School of Civil and Mechanical Engineering

Development of a Multi-Criteria Decision-Making Framework for Sustainable Road Transport Systems: Integrating Stakeholder-Cost-Environment-Energy Lifecycle Impacts

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DECLARATION

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The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number: HRE2016-0273.

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ABSTRACT

Road transport systems often face excessive lifecycle and operational expenditure (OPEX) overruns, traffic congestions, pollutant emissions, added fuel and vehicle operating costs to users, and road deterioration. These impacts occur gradually over the asset's lifecycle and could have been avoided by opting for a sustainable alternative at the decision stage. At the project-level, decision-makers have to practice consistency in investment decisions while evaluating interdependent and often conflicting ideas of economy, environmental impact and social performance of any new or existing road transport system and its two components: *roads* and *traffic*. Design, operation, maintenance and rehabilitation of the *road component* require holistic environmental, energy and monetary assessment of virgin and recycled material options.

Existing literature has shown that the environmental impact reduction performances of any alternate options using recycled materials are dependent upon the local material supply-chain, transport distance and other up/down-stream processes in all lifecycle stages of the complete roadworks. There is a lack of lifecycle analysis studies in road literature that account for impacts across pavement courses, roadside concrete kerbs, barriers and foundation works for the traffic signs and lighting systems in a concise work. Additionally, usage, construction, and maintenance activities are subjects that have not yet reached consensus among researchers and practitioners.

Transit solutions (e.g., public transport, car-free precincts, etc.) deal with the second component of *transport and traffic* fleet management. Prototype transport alternative(s) choice is complex and psychometric properties of user (passenger) satisfaction form any alternative travel mode is complicated by various underlying variables such as journey time, accessibility, travel quality, personal biases, and socio-economic factors, among others. New technically advanced autonomous vehicles (AVs) and shared mobility further complicates the situation. Even though past research has exhibited that vehicle emissions and user costs constitute the largest share of impacts across all lifecycle stages, high-resolution impact assessment models based on real-world traffic flow and acceleration-deceleration-time profiles need to be established. On the other hand, the integration of decision-making methods, e.g., lifecycle assessment, cost assessment, social analysis, still lacks.

This study aims to fill these gaps by proposing a multi-criteria decision-making framework with a multilevel of analysis. It analyses the non-linear traffic flow patterns for a case study transport system (5-lane dual carriageway road in Abu Dhabi), cost and environmental in/out-flows for a traditional approach and alternate approaches coupling the benefits of recycled materials and public transport-based traffic reduction strategies. Stakeholder opinions are also be included in the final deliverable by the user and expert surveys. Key attributes necessary to quantify cost, social (related to stakeholders) and environmental benefits are first selected by the decision-makers. User surveys identify hotspots in existing system and micro-simulation, lifecycle assessment and cost models are used to calculate empirical (quantitative) values. Qualitative values are then calculated after assigning the expert weights to cost, energy, and emissions. A combination of quantitative and qualitative data is used to boost decision-maker confidence in the proposed framework, direct applicability and a degree of policy control on the final output without compromising the overall transparency of the decision-making process. Results showed that an autonomous vehicle-based bus rapid transit service in conjunction with recycled materials for pavement courses and slag in roadside concrete works significantly reduced the lifecycle cost (51%), energy (56%) and pollutant (55% in global warming/climate change potential, 50% in photochemical ozone formation, 24% in particulate matter) burdens. The proposed framework also exhibited strong robustness against variations in indicator weights due to the changing priorities of different stakeholder groups.

This study contributes to the existing research by developing a theoretical foundation to analyse and compare the interrelated lifecycle impacts for road transport system. It also contributes by developing a detailed inventory data, which can be used by future researchers for predicting energy, cost, resource and emissions in/outflows. Researchers may also analyse the feasibility of design alternatives or performance enhancement of existing systems using the developed multi-level MCDM framework. On the industrial front, future applications may include: establishing stakeholder interaction protocols; standardised data schema for infrastructure projects; sustainability assessment and resource/cost/emissions reduction strategy.

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DEDICATION

To my parents, Muhammad Riaz Usman and Rubina Riaz,

the architects of my every success

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for staying true to her vows and being my strength and support system during the best and worst of times

To my sister, Zenab,

for understanding the sacrifices that the whole family has to make in the PhD journey

To my sister, Hira,

for being the source of my happiness and for her wit that helps me forget all worries

LIST OF PUBLICATIONS

The following publications have resulted from the work conducted as part of this research.

JOURNAL PUBLICATIONS

- Hasan, U., Whyte, A., AlJassmi, H., "Critical review and methodological issues in integrated life-cycle analysis on road networks", Journal of Cleaner Production, 206 (1), 541-558, 2019. DOI: 10.1016/j.jclepro.2018.09.148. (*Predominantly part of Chapter 2*).
- Hasan, U., Whyte, A., AlJassmi, H., "A review of the transformation of road transport systems: Are we ready for the next step in artificially intelligent sustainable transport?", Applied System Innovation, 3 (1), 2020. DOI: 10.3390/asi3010001. (*Predominantly part of Chapter 3*).
- Hasan, U., Whyte, A., AlJassmi, H., "A life-cycle decision-making framework to assess the need for autonomous mobility", Transport Research Procedia, 42, 32-43, 2019. DOI: 10.1016/j.trpro.2019.12.004. (*Predominantly part of Chapter 4*).
- Hasan, U., Whyte, A., AlJassmi, H., "Public bus transport service satisfaction: Understanding its value to urban passengers towards improved uptake", Case Studies on Transport Policy (manuscript under review). (*Predominantly part of Chapter 5*).
- Hasan, U., Whyte, A., AlJassmi, H., "Life-Cycle asset management in residential developments: Building on transport system critical attributes via a data-mining algorithm", Buildings, 9(1), 1-37, 2019. DOI: 10.3390/buildings9010001. (*Predominantly part of Chapter 6*).
- Hasan, U., Whyte, A., AlJassmi, H., "Life cycle assessment of roadworks in United Arab Emirates: Recycled construction waste, reclaimed asphalt pavement, warm-mix asphalt and blast furnace slag use against traditional

approach", Journal of Cleaner Production, 257, 120531, 2020. DOI: 10.1016/j.jclepro.2020.120531. (*Predominantly part of Chapter 7*).

- Hasan, U., Whyte, A., AlJassmi, H., "Microsimulation projection of current and future energy consumption and exhaust emissions from urban highway vehicles: Scenario analyses of reduction measures in Abu Dhabi", Applied Energy (manuscript under review). (*Predominantly part of Chapter 8*).
- Hasan, U., Whyte, A., AlJassmi, H., "A multi-criteria decision-making framework for sustainable road transport systems: Integrating stakeholder-cost-environment-energy for a highway case study in United Arab Emirates", International Journal of Project Management (manuscript under review). (*Predominantly part of Chapter 9*).

CONFERENCE PROCEEDINGS

- Hasan, U., Whyte, A., AlJassmi, H., Framework for delivering an AV-based mass mobility solution: integrating government-consumer actors and life-cycle analysis of transportation systems" In Proceedings of the 46th European Transport Conference, 10–12 October 2018; Dublin, Ireland, Association of European Transport, p. 18.

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NOMENCLATURE, ABBREVIATIONS, AND SYMBOLS

A list of nomenclature, abbreviation, and symbols used within the text of this thesis is described below in addition to their description alongside the first usage. The list has been prepared in the logical ascending alphabetical order.

a_{11}	=	Value of alternative "1" with respect to criteria "1"
a_{mn}	=	Value of alternative "m" with respect to criteria "n"
A	=	Ranking results based on the framework
AADT	=	Annual average daily traffic
AASHTO	=	American Association of State Highway and Transportation Officials
ACC	=	Adaptive cruise control
ADDoT	=	Abu Dhabi Department of Transport
ADM	=	Abu Dhabi Municipality
AHP	=	Analytic hierarchy process
AI	=	Artificial intelligence
AR	=	Alternative for roadworks
AT	=	Alternative for traffic fleet
AV	=	Autonomous vehicles
AVE	=	Average variance extracted
BAU	=	Business-as-usual
BRE	=	Building Research Establishment
BRT	=	Bus rapid transit
C_{ac}	=	Acquisition cost of materials and land
CAV	=	Connected automated vehicle
CBD	=	Central business district
CDE = CO_2eq.	=	Carbon dioxide equivalent
C_{en}	=	Energy costs
CFC	=	Chlorofluorocarbon
C_{in}	=	Initial cost
C_{ins}	=	Construction and installation costs
C_k	=	Cost criterion/KPI "k"
C_m	=	Routine minor maintenance costs
CML	=	Centre of Environmental Science
CNG	=	Compressed natural gas
CO	=	Carbon monoxide

C_{op} = Operational and usage cost.
COPERT = Computer Programme to calculate Emissions from Road Transport
CP_j^{BAU} = Car passengers for the BAU case
C_{rn} = Renewal cost
CS = Mode share of category "j" car
C_t = Cost for any particular year "t"
CT = Car traffic of category "j" car
C_t = Future cost in year "t"
CV = Coefficient of variation
d_i^- = Distance from negative-ideal solution
d_i^* = Distance from ideal solution
DoT = Department of Transport
E = Egalitarian
$E^F{}_{j,k,l}$ = Emission factors
EI = Environmentally insensitive
E_k = Energy consumption criterion/KPI "k"
EPA = Environmental Protection Agency – United States of America
EPD = Environmental product declarations
FBT = Frequency of bus travel
FCT = Frequency of car travel
FFD = Fossil fuel depletion
FHWA = Federal Highway Administration
FrCT = Frequent car/taxi travellers
FreqBus = Frequency of buses
GCC = Gulf Cooperation Council
GGBFS = Ground granulated blast furnace slag
GHG = Greenhouse gases
GJ = Gigajoule
g_r = Annual vehicle growth rate
GWP = Global warming potential
H = Hierarchist
HGV = Heavy goods vehicle
HMA = Hot-mix asphalt
HT = Human toxicity
i = Discount rate
I = Individualist

I^-	=	Negative-ideal solution
I^*	=	Ideal solution
I_{in}	=	Importance index
IPCC	=	Intergovernmental Panel on Climate Change
IR	=	Ionizing radiation
ISO	=	International Standards Organisation
ITS	=	Intelligent transportation system
IVE	=	International vehicle emissions
I_x	=	Index for predictor variable "x"
JRCP	=	Jointed reinforced concrete pavement
k	=	Vehicle class
KPI	=	Key performance indicator
ktonnes	=	Kilo-tonnes
l	=	Speed-time profile
LCA	=	Lifecycle assessment
LCC = C_l	=	Lifecycle cost
LCCA	=	Lifecycle cost analysis
LCI	=	Lifecycle inventory
LCIA	=	Lifecycle impact assessment
LDV	=	Light-duty vehicle
LEED	=	Leadership in Energy and Environmental Design
L_m	=	Road length
LNG	=	Liquid natural gas
LoS	=	Level of service
LRT	=	Light rail transit
LvlFare	=	Level of fare
M	=	Set of meaningful rules "R"
M&R	=	Maintenance and rehabilitation
MCDM	=	Multi-criteria decision-making
MJ	=	Megajoule
Mt	=	Million tonnes
N	=	Number of vehicles in year "t"
NetCov	=	Network coverage
NHTSA	=	National Highway Traffic Safety Administration
N_o	=	Initial number of vehicles in the year "t_o"
O_3	=	Ozone gas
OD	=	Stratospheric ozone depletion
OM&R	=	Operation maintenance and rehabilitation

OMD	=	Occasional multimodal travellers
OPC	=	Ordinary Portland cement
OR	=	Odds ratio
PaLATE	=	Pavement Lifecycle Assessment Tool for Environmental and Economic Effects
PCR	=	Product category rules
P_k	=	Pollutant emission criterion/KPI "k"
PLS	=	Partial least squares
PM	=	Particulate matter
PMF	=	Particulate matter formation
POxF	=	Photochemical oxidants formation
POzF	=	Photochemical ozone formation
PRT	=	Personalised rapid transport
PS	=	Pro-sustainability
PT	=	Public transport
PV	=	Present value
QoR	=	Quality of ride
$\tilde{R}$	=	Normalised decision matrix
$\tilde{r}$	=	Normalised value
RAP	=	Reclaimed asphalt pavement
R_{ci}^*	=	Relative closeness of any ideal solution
RCW	=	Recycled construction and demolition waste
RFID	=	Radio frequency identification
$\tilde{r}_{ij}$	=	Normalised matrix
RON	=	Research octane number
RUC	=	Road user cost
s	=	Traffic management scenario
SAV	=	Shared autonomous vehicle
SCAD	=	Statistics Centre – Abu Dhabi
SEM	=	Structural equation modelling
SETAC	=	Society of Environmental Toxicology and Chemistry
SMART	=	Sustainability Mobility and Accessibility Research and Transformation
S_m	=	"m" alternative for road transport system
SO_2eq.	=	Sulphur dioxide equivalent
TE_j	=	Traffic emissions for "j" pollutant,
TJ	=	Terajoule
tkm	=	Tonne kilometre

TOPSIS	=	Technique for Order Preference by Similarity to an Ideal Solution
u-base	=	Unbound aggregates base course
UNEP	=	United Nation Environmental Programme
$\tilde{V}$	=	Weighted normalised matrix
VAA	=	Vehicle Assist and Automation
VfM	=	Value for money
VIF	=	Variance inflation factors
VMT	=	Vehicle miles travelled
VOC	=	Vehicle operation cost
V_r	=	Salvage or residual value
Λ_x	=	Manifest variable matrix "x"
Λ_y	=	Manifest variable matrix "y"
WBS	=	Work breakdown structure
$\tilde{w}_j$	=	Relative weight
$\tilde{w}_j$	=	Weight of evaluation criterion "j"
WMA	=	Warm-mix asphalt
x^2	=	Chi square statistic
x_m	=	Antecedent variable
y_n	=	Consequent variable
α	=	Confidence
α_{min}	=	Minimum confidence
β	=	Path coefficient
Γ	=	Path coefficient matrix
Γ_{min}	=	Minimum interest value
δ	=	Residual value for variable "x"
ε	=	Residual value for variable "y"
ζ	=	Initial travel dataset
ζ_{ts}	=	Training dataset
ζ_{vs}	=	Validation dataset
η	=	Endogenous latent variable matrix
ξ	=	Exogenous latent variable for "x" matrix
σ	=	Support
σ_{min}	=	Minimum support
ψ	=	Responsible variable
℘	=	Partially addressed/*needs further work,*
✓	=	Used/addressed
✗	=	Unaddressed/Needed

↑	=	Recognised as the leading factor
1,4-DB equivalent	=	1,4 dichlorobenzene equivalent

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Today's road transport systems are subject to traffic congestions, pollutant emissions, high user time delay costs, increasing fuel and vehicle operational costs, deterioration of surface-assets and other costs, social and environmental burdens throughout the service life. The service life of any built asset starts from the conceptual stage to extraction of raw materials, construction, use, maintenance and rehabilitation (M&R) and the final end-of-life stage that itself may be composed of recycling and disposal (Norman, MacLean, & Kennedy, 2006). The problems associated with the current road transportation systems are mainly due to virgin material usage for construction and M&R and excessive traffic growth patterns. Bjornsson, de la Garza, and Nasir (2012) note that the two primary components of a road transport system are: *roadworks* and *traffic fleet* or *vehicles*. Figure 1.1 shows the two components and the various stages in the lifecycle of a road transport system.

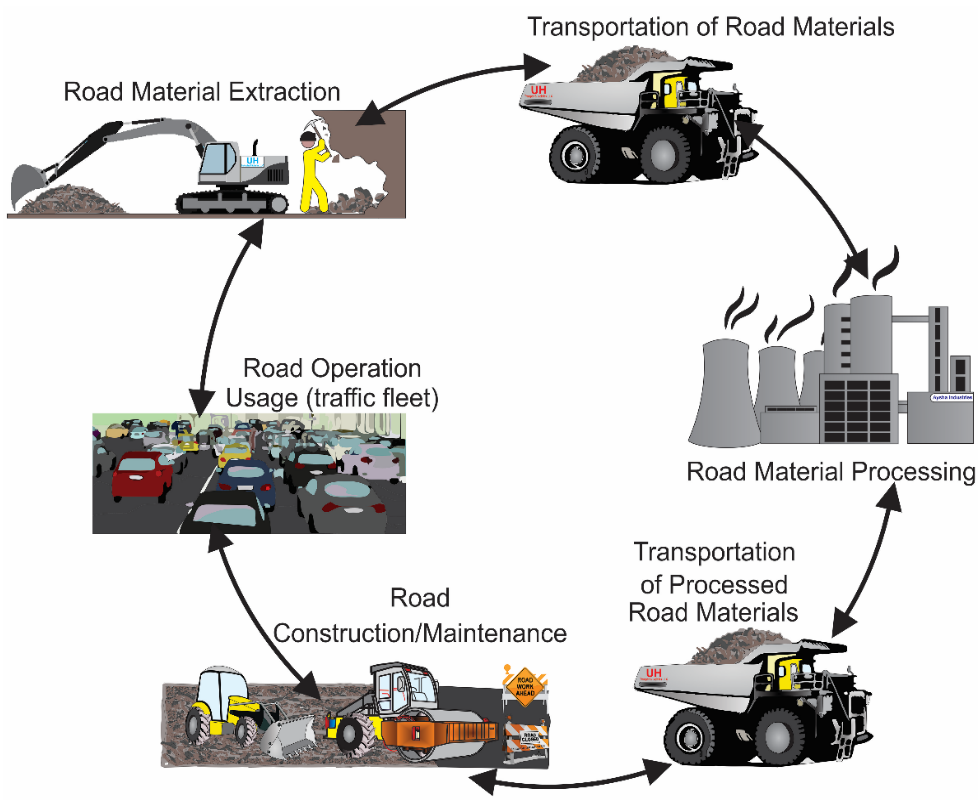


Figure 1.1 Lifecycle stages and components of a road transport system

Flexibility in establishing the lifecycle functional unit as a Pareto set that considers stakeholder preferences, cost and environment burdens across both components is significant for achieving system-wide sustainability. Lifecycle cost analysis (LCCA) is usually performed to calculate the several costs occurring throughout the service life, such as initial construction cost, routine maintenance cost, vehicle operation, user travel time, agency operation cost, transit service costs, and periodic rehabilitation, etc. Lifecycle assessment (LCA) is performed to calculate the environmental and social burdens in all stages of the asset's lifecycle. Generally, the LCCA and LCA research has been diverse across several decades since its initial exposure to road network projects, with studies proposing a variety of indicators and issues that must be tackled for true sustainability optimisation.

The potential of recycled material usage and industrial by-products for roadworks has been given considerable attention by researchers in recent years. Biswas (2014) investigated the environmental performance of recycled construction and demolition waste (RCW) as an alternative to virgin crushed gravel as pavement base material during the initial construction as well as base and sub-base material during maintenance of a 100m asphalt road in Australia, resulting in an overall greenhouse gas (GHG) reduction of 0.4 tonnes of CO_2 equivalent. Turk et al. (2016) and Bloom et al. (2017) also explored the partial and complete replacement of natural aggregate base course with RCW to varying degrees of GHG reduction. Bloom et al. (2017) assessed the environmental benefits of reclaimed asphalt pavement (RAP) usage during the maintenance and rehabilitation (M&R) stages of asphalt pavements in their United States-based study. The authors employed a 4% replacement of the asphalt binder content by RAP and observed a significant reduction in GHG emissions. However, effectively communicating benefits of sustainable road construction techniques, particularly, recycled material usage, and usage stage savings to the other decision-making stakeholders is also important for direct application in real-world situations (Batouli, Bienvenu, & Mostafavi, 2017).

These issues are arguably addressable by using appropriate decision-making frameworks that incorporate cost, environmental and social factors related to stakeholder (users and decision-makers) objectives and priorities. Any comprehensive framework aiming to address the issue of sustainability performance must acknowledge the process flow over the entire cycle of the supply chain (Reap et al., 2008), thereby reducing a "shifting of issues" from one stage or ecosystem to another, given the stages in a product's lifecycle consist of several intermingled loops. Thus, the overall cost, environmental and social impacts during the usage stage of the road transport system due to the *traffic fleet component* are critical for improving the sustainability performance of the road transport system.

The global escalating reliance on private mobility increases pollutant emissions, energy consumption, and municipal agency and user costs; the problem is most significant in cities (Currie & De Gruyter, 2018). The world's urban population will increase by 2.5 billion people, i.e., approximately 67% of the global population may live in urban areas by 2050 (United Nations, 2018), multiplying burdens on urban roads. Traffic congestions and resultant environmental issues are often alleviated by urban government agencies through the discouragement of motorised travel (e.g., promoting bicycle lanes), creating pedestrian zones or car-free precincts. This alternate strategy is commonly advocated in developed countries where climatic renditions can be more easily addressable. Unfortunately, in many developing countries, hot and humid climates strain the limits of the applicability of green transport solutions. Middle-eastern cities such as Abu Dhabi repeatedly experience hot climates (Gulf News Report, 2015; Maceda, 2018). Thus, policies may not be globalised, as modal shifts differ. Reducing cost and increasing efficiency of public transport offers alternate incentive to private car users and a sustainable transit mode (Hensher, 2007), yet, business models of the provided service and sustainability performance of supporting infrastructure require to be studied in conjunction with *whole system* analysed as a *multi-criteria* problem.

Prominence is given to mass-transit alternatives for diverting passengers towards sustainable public transport. Bus rapid transit (BRT) and light rail transit (LRT) are examples of such initiatives aimed at creating mode shifts from private automobiles by increasing network coverage, frequency, and service capacity. BRT offers a more affordable solution in terms of network coverage, affordability and service frequency (Mikhail et al., 2013). It is also less prone to cost overruns and flexible to the introduction of new corridors within an existing system-wide network at a relatively small cost. As pointed out by Hensher (2007), an efficient BRT system has the possibility of not only eliminating traffic gridlocks in CBDs but also occupies less space than LRT. This, together with low implementation cost has given rise to BRT's popularity in developing countries. However, its ability to attract passengers, notwithstanding its potential as a promising public transport system capable of handling heavy transit load, that needs business model (client-service-provider relation) factorisation as an ordinary public bus service.

It has been argued that preference of public bus as the travel mode is a complex issue elicited from a large set of underlying travel-related variables. Studies (Abenoza, Cats, & Susilo, 2017; Redman et al., 2013) have found that travellers base their mode choice on satisfaction from the level of service; value for passenger money; travel bias; and, quality attributes. Public transport authority planners can increase passengers' usage of public transport by retaining existent regular passengers as well as attracting new riders if the exact effects of these underlying factors on the study project area are identified towards solving the issue of user acceptance.

Public transport systems are designed to deliver low cost transit solutions while reducing environmental burdens. However, the supporting road infrastructure is generally designed much earlier and not in synergy with the whole system through a lifecycle approach. As the road ages, increasing traffic load and traffic management public transit strategies demand expansion and/or modification in the road design. These activities not only carry environmental and cost loads but also disturb the existing habitat and traffic flow (Galatioto et al., 2015). The advancements in road material recycling, stabilisation, greener construction and now, the entrance of automated vehicle technology in the mobility equation, offer new opportunities for sustainable optimisation of road transport systems. Yet, existing decision-making frameworks (Robèrt et al., 2017) for road projects lack an integrated sustainability-based approach capable of assessing the multi-criteria user and expert participation, cost and environmental attributes. This thesis compares past studies on mobility and road networks to present a multi-criteria decision-making framework, using insights from user preference; lifecycle analysis; and, expert opinion to enhance practicality.

Although, both LCCA and LCA have been used in the past to assess the sustainability performance of road transportation systems as stated in the studies reviewed here, some limitations in the extent of application were also noticed by some of the researchers that have reviewed two of the primary elements: roadworks (AzariJafari, Yahia, & Ben Amor, 2016; Jamshidi et al., 2017) and traffic (Guo et al., 2016; Yu, Lu, & Xu, 2013). Yet, a detailed analysis of roadworks and motorised traffic using the constructed road may aid government policy and transport system decision-makers in realising the city-wide sustainability goals. Demands in strategic management and decision analysis have created the need for a paradigm of integrated tools and frameworks utilising multi-criteria decision making (MCDM) methodology. The threshold of profit accumulation and benefit harvesting as MCDM objectives had been extended to sustainable transportation infrastructure systems. However, a majority of the studies conducted so far on the application of MCDM within transportation infrastructures have primarily focused on the cost versus benefit trade-off and the variability of budget (e.g. Wu and Flintsch (2009) and Bai, Labi, and Sinha (2011)). These factors highlight the need for a dynamic decision-making framework that integrates the sustainability triple-bottom-line cost, environmental and social impacts across all lifecycle stages and components of a road transport system.

1.2 RESEARCH SCOPE AND OBJECTIVES

Literature review (see Chapters 2–3) highlights that construction, OM&R of transportation infrastructures are not isolated activities and carry environmental loads, energy and resource burdens along with monetary implications. The evolution of technology has brought in new prospects of intelligent transportation systems and automated vehicles. The results obtained from the different state-of-art frameworks and models are often complex to interpret and on different scales. In order to identify, compare and select a sustainable transportation system, efficient decision-making approaches are required. It is essential to provide an assessment model that is simple, reliable, and practical and accommodates stakeholder confidence. Based on these arguments, the aim and research question that overarches this research project is:

"***How can the sustainability triple-bottom-line cost, environmental and stakeholder-related social impacts can be integrated towards a transparent, reliable and empirical decision-making framework that can also reflect project-based priorities for choosing the optimum road transport system alternatives?***"

The overarching research aim is further defined by the following fourteen objectives:

Review of Literature:

Objective 1: Perform a state-of-the-art assessment of the existing literature in the wider field of decision-making techniques (LCCA and LCA, etc.) for road transport systems to highlight the critical aspects, identify the hotspots in current processes which can be improved upon to increase the robustness of the frameworks and facilitate the government authority and private planning/consulting stakeholders to achieve whole-life cost and overall sustainability goals.

Objective 2: Transport vehicles and traffic constitute the second component of the road transport systems and carry a significant cost, social and environmental burdens over the service life. Perform a review of the recent advances in vehicle technology (e.g., autonomous and smart vehicles) and alternate fuels (CNG, electric, hybrid) to identify how these technologies can be applied to meet the stakeholder and sustainability objectives of a road transport system project.

Indentification of Key Parameters in Road Transport Systems:

Objective 3: Identify the key performance indicators (KPIs) for evaluating the cost, energy, social and pollutant emissions burdens of a road transport system that can be used for evaluating different alternatives.

Objective 4: Establish the expected features of a transport system in terms of user preferences.

Calculation of Lifecycle Impacts for Road:

Objective 5: Estimate the amount of energy consumed and pollutants emitted for conducting complete roadworks (including pavement courses, roadside concrete kerbs, barriers, and foundation works for traffic signals and lighting systems, etc.) in a conventional virgin material approach.

Objective 6: Calculate the expected burden mitigation in each stage when recycled materials are used.

Objective 7: Estimate the initial costs suffered by the local agency commissioning a road transport system project.

Objective 8: The contribution of recycled materials usage in the construction, M&R stages to the lifecycle cost of the road component in a road transport system.

Calculation of Lifecycle Impacts for Traffic fleet:

Objective 9: Calculate the impact of road M&R on the traffic fleet flow profile in terms of cost, environmental and energy consumption impacts.

Objective 10: The effect of different traffic management scenarios on the traffic flow profile of any case study transport system, and how does it translate to improvement across all KPIs.

Objective 11: Projection of how the current road transport systems can be changed due to the application of automation and alternate fuel technologies.

Objective 12: Calculate the expected cost variation, difference in energy consumption and change in pollutant emissions after applying different project alternatives.

Calculation of Multi-criteria Weightage and Lifecycle Impacts for the whole Road Transport System:

Objective 13: Incorporate the opinion of experts and decision-making stakeholders in the framework for ranking the preferences of alternatives for sustainability.

Objective 14: Estimate the consequences of greener alternatives (*combining recycled materials and traffic management strategies*) towards a road transport system in the simplistic terms of cost, energy consumption and pollutant emission.

1.3 SIGNIFICANCE AND ORIGINAL CONTRIBUTION OF THE THESIS

Integration of sustainability approaches to the entire transportation system, inclusive of the two primary components (*roads* and *vehicles/traffic fleet*) has been given limited exposure in literature, with the operation and usage stage rarely discussed in detail. Mass-transit proposals such as rapid bus transport to address the traffic fleet impacts, rarely consider the lifecycle sustainability aspect of supporting road networks and the associated exogenous parameters such as fuel consumption, time-delays, congestion and traffic flow and alternate approaches to construction and maintenance including use of recycled materials and industrial wastes. Automation is also a fairly new topic that has not yet been studied as an integral part of a transportation system along with its implication on the overall sustainability goals of a city government. Also, decision-makers are often not involved in the research analysis which further alienates research results from real-world applications. On the other hand, the users of a road transport system are also not involved in the decision-making process which affects the user adoption and success rate of any alternative, particularly, public transport based traffic management strategies. The main contribution and significance of this thesis are to develop a multi-level MCDM framework that:

- Involves decision-makers associated with the road transport system in establishing the KPIs for sustainability performance improvement.
- Users are involved to identify the hotspots in the current system.
- Detailed roadworks and vehicle cost, emission, and energy inventories are developed and utilised to calculate KPI performances.
- Priorities of stakeholders are included to offer a degree of control to the decision-makers and improve their confidence in the MCDM results.
- The proposed MCDM framework is based on detailed quantitative and qualitative data for all components of a road transport system in a transparent manner to ensure real-world applicability for the decision-making process.

1.4 OUTLINE OF THE THESIS

This thesis is divided into ten chapters based on the individual aspect of the research project discussed. Chapters 2 and 6 are published papers with the thesis candidate (author) acting as the first author. Chapters 3, 5, 7, 8 and 9 are currently under review or preparation for journal publication. Due to this format, some background and literature information may be repetitive across the chapters, which may also be read as individual contributory works.

An introduction to the research problem and issues related to road transport systems, scope, objectives, significance, and outline of the thesis are provided in Chapter 1. Chapter 2 focuses on a critical literature review of LCCA and LCA research published in the last decade (post-2008) towards the identification of research gaps. Chapter 3 reviews the state-of-art of the peer-reviewed literature published on the application of artificially intelligent and autonomous vehicles for road transport systems.

Chapter 4 specifies the methodology of this thesis by identifying the purpose and main components of the proposed MCDM framework through a multi-level approach. It details the tools for incorporating stakeholder-related social factors, lifecycle cost and environmental impacts with the policy priorities of decision-makers. Chapter 5 and Chapter 6 tackle the question of user adaptability by first identifying the hotspots in the current system for a case study road transport system in Abu Dhabi city. The user-preference data collected and analysed after developing a data mining algorithm. Research findings are then presented.

Chapter 7 applies lifecycle methodology to calculate the environmental impacts of a 3.5 km-long asphalt dual carriageway section case study in Abu Dhabi across all lifecycle stages: material extraction and production, material and equipment transport, construction, M&R, and end-of-life; assuming a 30 years lifetime. Environmental impact assessment is performed for air emissions and energy consumption by complete roadworks: earthworks, pavement courses, concrete works for traffic barriers, kerbs, parapets, traffic signs, and light systems. Actual field data for the road section using virgin materials and traditional asphalt production mix for pavement works and Portland cement concrete for the complete concrete works is used as the baseline case. The impact of using recycled asphalt pavement, construction waste and slag is then analysed as alternate cases. Routine maintenance and periodic rehabilitation by milling and repaving wearing course (<4.5 cm depth) every 5 years is also analysed. The environmental assessment considers all indicators from the ReCiPe midpoint method.

Chapter 8 presents the assessment of energy consumption and exhaust pollutant emissions from vehicle operations on the above dual-carriageway section over the period from 2015–2045. High-resolution traffic microsimulation models are developed using actual traffic counts, vehicle exhaust emissions and fuel consumption data. All vehicle types from passenger cars, minibus, and coach, light- and heavy-duty trucks are modelled. Traffic growth models and advancements in vehicle fuel technology and Euro emission-control engine standards are used to project future traffic data. These are then utilised to assess the impact reduction potential of traffic management scenarios: business-as-usual, public bus transport case, public bus rapid transit service case and a traffic demand-responsive autonomous vehicle-based bus rapid transit service case, at the vehicle level.

Chapter 9 applies the proposed MCDM framework to integrate the results of Chapters 5 – 8. It compares the sustainability performances of the eight different alternatives coupling the benefits of recycled materials for roadworks and public transport-based traffic management strategies for improving the sustainability performance of the case study highway transport system in Abu Dhabi city across established KPIs. Chapter 10 summarises the findings of the thesis and directions for future work.

1.5 REFERENCES

Abenoza, R. F., Cats, O., & Susilo, Y. O. (2017). Travel satisfaction with public transport: Determinants, user classes, regional disparities and their evolution. *Transportation Research Part A: Policy and Practice, 95*, 64-84. DOI: 10.1016/j.tra.2016.11.011.

AzariJafari, H., Yahia, A., & Ben Amor, M. (2016). Life cycle assessment of pavements: reviewing research challenges and opportunities. *Journal of Cleaner Production, 112*, 2187-2197. DOI: 10.1016/j.jclepro.2015.09.080.

Bai, Q., Labi, S., & Sinha, K. (2011). Trade-off analysis for multiobjective optimization in transportation asset management by generating pareto frontiers using extreme points nondominated sorting genetic algorithm II. *Journal of Transportation Engineering, 138*(6), 798-808. DOI: 10.1061/(ASCE)TE.1943-5436.0000369.

Batouli, M., Bienvenu, M., & Mostafavi, A. (2017). Putting sustainability theory into roadway design practice: Implementation of LCA and LCCA analysis for pavement type selection in real world decision making. *Transportation Research Part D: Transport and Environment, 52*, 289-302. DOI: 10.1016/j.trd.2017.02.018.

Biswas, W. K. (2014). Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia. *The International Journal of Life Cycle Assessment, 19*(4), 732-744.

Bjornsson, H. C., de la Garza, J. M., & Nasir, M. J. (2012). A decision support system for road maintenance budget allocation. *Computing in Civil and Building Engineering, 2000*, 702 - 709. DOI: 10.1061/40513(279)92.

Bloom, E., Canton, A., Ahlman, A. P., & Edil, T. (2017). *Life cycle assessment of highway reconstruction: A case study*. Paper presented at the Transportation Research Board 96th Annual Meeting, Washington DC, United States.

Currie, G., & De Gruyter, C. (2018). Exploring links between the sustainability performance of urban public transport and land use in international cities. *Journal of Transport and Land Use, 11*(1), 325–342. DOI: 10.5198/jtlu.2018.957.

Galatioto, F., Huang, Y., Parry, T., Bird, R., & Bell, M. (2015). Traffic modelling in system boundary expansion of road pavement life cycle assessment. *Transportation Research Part D: Transport and Environment, 36*, 65-75. DOI: 10.1016/j.trd.2015.02.007.

Gulf News Report. (2015, 27th October). Gulf will be too hot for humans by 2070: study. *Gulf News*.

Guo, X., Fu, L., Ji, M., Lang, J., Chen, D., & Cheng, S. (2016). Scenario analysis to vehicular emission reduction in Beijing-Tianjin-Hebei (BTH) region, China. *Environmental Pollution, 216*, 470-479. DOI: 10.1016/j.envpol.2016.05.082.

Hensher, D. A. (2007). Sustainable public transport systems: Moving towards a value for money and network-based approach and away from blind commitment. *Transport Policy, 14*(1), 98-102. DOI: 10.1016/j.tranpol.2006.10.004.

Jamshidi, A., Kurumisawa, K., Nawa, T., Jize, M., & White, G. (2017). Performance of pavements incorporating industrial byproducts: A state-of-the-art study. *Journal of Cleaner Production, 164*, 367-388. DOI: 10.1016/j.jclepro.2017.06.223.

Maceda, C. (2018, 28th August). UAE temperatures hit near 50 degrees Celsius. *Gulf News*. Retrieved (4/11/2018) from www.gulfnews.com/uae/weather/uae-temperatures-hit-near-50-degrees-celsius-1.2271557.

Mikhail, C., Stephanie, P., Zoe, E., William, E., & Juan, M. (2013). Infrastructure and automobile shifts: positioning transit to reduce life-cycle environmental impacts for urban sustainability goals. *Environmental Research Letters, 8*(1), 015041.

Norman, J., MacLean, H. L., & Kennedy, C. A. (2006). Comparing high and low residential density: Life-cycle analysis of energy use and greenhouse gas emissions. *Journal of Urban Planning and Development, 132*(1), 10-21. DOI: 10.1061/(ASCE)0733-9488(2006)132:1(10).

Reap, J., Roman, F., Duncan, S., & Bras, B. (2008). A survey of unresolved problems in life cycle assessment. *The International Journal of Life Cycle Assessment, 13*(5), 374-388. DOI: 10.1007/s11367-008-0009-9.

Redman, L., Friman, M., Gärling, T., & Hartig, T. (2013). Quality attributes of public transport that attract car users: A research review. *Transport Policy, 25*(Supplement C), 119-127. DOI: 10.1016/j.tranpol.2012.11.005.

Robèrt, K.-H., Borén, S., Ny, H., & Broman, G. (2017). A strategic approach to sustainable transport system development - Part 1: Attempting a generic community planning process model. *Journal of Cleaner Production, 140*, 53-61. DOI: 10.1016/j.jclepro.2016.02.054.

Turk, J., Mauko Pranjić, A., Mladenovič, A., Cotič, Z., & Jurjavčič, P. (2016). Environmental comparison of two alternative road pavement rehabilitation techniques: cold-in-place-recycling versus traditional reconstruction. *Journal of Cleaner Production, 121*, 45-55. DOI: 10.1016/j.jclepro.2016.02.040.

United Nations. (2018). World urbanization prospects. Retrieved (22/04/2018) from https://esa.un.org/unpd/wup. UN Department of Economic and Social Affairs.

Wu, Z., & Flintsch, G. (2009). Pavement preservation optimization considering multiple objectives and budget variability. *Journal of Transportation Engineering, 135*(5), 305-315. DOI: 10.1061/(ASCE)TE.1943-5436.0000006.

Yu, B., Lu, Q., & Xu, J. (2013). An improved pavement maintenance optimization methodology: Integrating LCA and LCCA. *Transportation Research Part A: Policy and Practice, 55*, 1-11. DOI: 10.1016/j.tra.2013.07.004.

CHAPTER 2

LITERATURE REVIEW OF STUDIES ON ROAD TRANSPORT SYSTEMS

2.1 ABSTRACT

Lifecycle management of road network projects traditionally emphasise *material production* and *construction* stages, with less attention given to *usage stage* and functionality improvement. Increasingly there is a need to address: inconsistencies in cost attribute selection; adjusting for uncertainties and costs; clarifying system boundaries; data sources; functional units and regional or temporal applicability of lifecycle frameworks. The current study focuses on a critical literature review of LCCA and LCA research published in the last decade (post-2008) towards the identification of research gaps. Accurately analysing all lifecycle stages, feedback loops, future cash, and resource flows, and interlinking performance with overall sustainability can aid the decision-making process towards sustainable alternatives for constructing new or rehabilitating existing roads. This review finds that the use of recycled materials, base/sub-base stabilisers, and asphalt binder replacement has the potential of energy saving (≥ 34% or 3.1 TJ), mitigating landfill disposal issues, and greenhouse gas load reduction (≥ 35% CDE[1]). Lack of real world LCCA-LCA application and stakeholder prejudice against recycled material usage are addressable by better stakeholder (decision-makers and road users) engagement via a social component. The proposed enhancements identified in this chapter can increase LCA/LCCA attraction to policy-makers, planners, and users and ultimately ensure a more sustainable asset.

2.2 INTRODUCTION

Due to unprecedented population growth and the ongoing influx of people and businesses towards urban areas, roads often face traffic congestions causing time-delays, pollutant emissions, added fuel and vehicle operational costs, noise pollution and deterioration of the road networks. Issues such as limitation of funds, lack of political/social interest and subjectivity of opinion dominate the decision-making

[1]CDE = Carbon dioxide equivalent emission values, direct emissions only of CO_2, CH_4 and CO.

process to create and maintain infrastructure in perpetuity. Principles of control and system-style lifecycle engineering management are generally under applied. Traditionally, project studies are often conducted during the feasibility stage of an asset's design and much emphasis is placed upon the initial costs. However, the whole costs of low-specification design, construction without adequate quality management systems and sporadic rather than controlled inspection, as well as unstructured operation maintenance and rehabilitation (OM&R) regimes continue to cause concern (Hood et al., 2018). Significant monetary benefits exist where cost analyses are performed for the entire life of a road network asset (e.g., pavements, highways, bridges and other roadside components) towards increased investment and long-term benefit to users.

Lifecycle cost analysis (LCCA) is the conventional procedure for the evaluation of the financial benefits and returns from any investment by analysing its future expenditures along with the initial costs. Whilst the application of LCCA in road construction has been given considerable attention during the past decades, only limited practical application has been attained so far (Cabeza et al., 2014). Coupled with the principle of cost-effectiveness, is the idea of sustainability which adds to the traditional balance of time, quality and cost of construction investment. Adding sustainability into the equation introduces the comprehensive criteria of evaluating road investment decisions, either for "new" road networks or "rehabilitation" of deteriorating assets, against environmental, social, and even political and administrative perspectives. Road projects can then be sustainably and cost-effectively procured, designed, constructed, managed and maintained and then reintegrated or recycled. It means that if the sustainability justifications are added to the economical or monetary criteria, the needs of users can be better met and further benefits may be achieved if the analysis is performed for the entire life cycle of the road network assets.

Lifecycle assessment (LCA) is a known methodology for evaluating environmental impacts related to energy consumption, greenhouse gas and pollutant emissions of processes and products (ISO 14040, 2006). Any integrated design and management of a typical road network project generally consider three main subjects: identifying the main problem that requires an investment; the embedded hidden issues; and, the problem-solving process or methodology (Figure 2.1). The success of any road network project, therefore, depends upon the cumulative efficiency of these three primary components, to balance cost and environmental targets and (government) agency's adherence to code and standards' legislation.

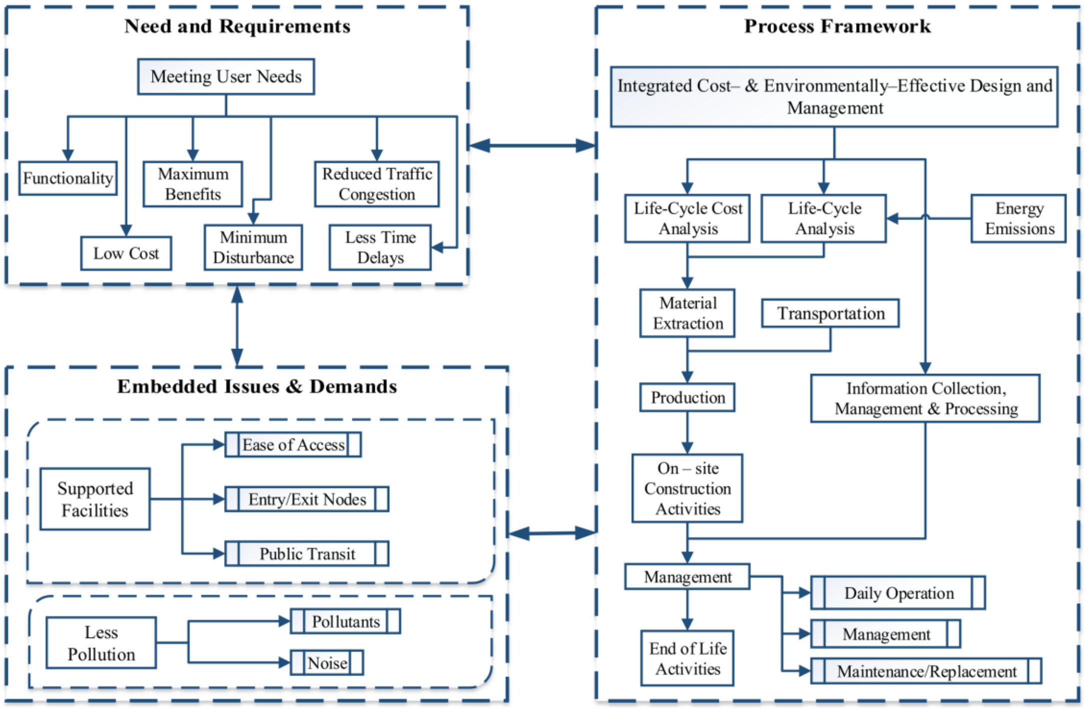


Figure 2.1 Schematic of processes in infrastructure design and management

Integration of the two road infrastructure design and management assessment approaches, LCCA and LCA, and the direction of respective cost and environmental burdens alongside the effect of *vehicle-surface interactions* on fuel consumption and wear and tear of tyres during the usage stage of a pavement require acknowledgement within an analysis framework. It is also essential for government authority decision-makers to consider all design and management aspects, such as; traffic congestion; cost and environmental risks; road ownership and user costs; vehicle operation and ownership cost; currency fluctuations; and, environmental loads during a whole-life of the road asset. However, researcher projects tend to be limited in the number of aspects and scope of the lifecycle stages considered (AzariJafari, Yahia, & Ben Amor, 2016).

The purpose of the current study is to provide a state-of-the-art review and analysis of the existing literature in the wider field of LCCA and LCA of road network projects to highlight the *critical aspects*, identify the *hotspots* in current processes which can be improved upon to increase the robustness of the frameworks and facilitate the government authority and private planning/consulting stakeholders to *achieve whole-life cost and overall sustainability goals*. Once the critical aspects are identified for achieving the overall system sustainability of road and transport projects; the energy, human capital, and other resources can optimised to reduce excessive environmental burdens towards cleaner production of road network projects. The literature review *methodology* adopted here consists of collecting peer-reviewed research papers published in the last decade, after 2008 (through Google Scholar and ScienceDirect databases), to review the latest research work conducted on lifecycle management of road network projects. The adopted methodology is roughly based on Guo, Hu, and Dai (2018), expanded to include the most recent and definitive research published on road networks elements; inclusive of pavements, highway (roadside) components and bridges to capture the wider extent of the transport and road research field.

The articles were filtered based on the road elements and lifecycle stages addressed relative to respective cost, pollutants, and energy consumption across large-scale projects comparing critical indicators, scope, and framework of peer-reviewed studies to uncover findings that may improve the cost and environmental performance of these road assets. Two sub-stages in the processing stage, LCCA, and LCA of individual studies are discussed in the context of stakeholder needs, the embedded issues in the study system boundary, and the frameworks proposed for problem solution. This is a significant contribution of the current study as it addresses the three (cost, environmental and social) sustainability issues of road network assets to cover the extent of perceived process problems in management of road network projects.

The main purpose of this chapter is to review the state of existing literature and identify the critical processes and stages for effective asset management and lifecycle assessment of road network projects towards the overall cost, social and environmental sustainability. Researchers have performed individual extensive reviews of studies on the use of recycled materials (Anthonissen, Van den bergh, & Braet, 2016; Balaguera et al., 2018; Gautam et al., 2018) in road projects, attributes for lifecycle costs (Babashamsi et al., 2016), LCA as a project procurement and planning tool (AzariJafari et al., 2016; Butt, Toller, & Birgisson, 2015), significance of traffic/transit load and patterns in the overall lifecycle impact of road networks (Inyim et al., 2016) and the social and policy concerns (Jiang et al., 2017; Santos, Behrendt, & Teytelboym, 2010). On the other hand, studies on quantifying/minimising the environmental burden, e.g., particulate matter pollutants (Pant & Harrison, 2013) and fuel consumed by the traffic (Rahman et al., 2017) were reviewed by other researchers.

This chapter further develops on the findings of these studies to propose cleaner production of road networks as a policy issue; highlight the significance of lifecycle environmental and socio-economic burden from the vehicles and the use of recycled materials to promote sustainable development. It also presents an overall picture of the energy, cost and resource inflows and outflows across the whole-life of road networks in addition to the critical attributes, data resources for lifecycle analyses, common mitigation, recycling, and mixing strategies utilised and standards of practices.

2.3 PROCESS FRAMEWORK: LCCA IN ROAD NETWORK PROJECTS

Researchers considering the practical application of LCCA for the design and rehabilitation of road and infrastructure projects such as Zimmerman et al. (2010) defined this whole-cost application as an evaluation of all anticipated costs incurring during the desired service life of the asset so that different alternatives can be compared and assessed through equivalent parameters, and a feasible course of actions deduced.

2.3.1 Conceptual basis and stages in LCCA

The reliability of any LCCA-based (whole-cost) framework or model is influenced by the accuracy of the data collected as well as the projection of any future costs that may occur in the considered lifecycle of the asset. The exact determination of future expenditures can often be uncertain due to market variables and risks such as recession and variations in the velocity of distant cash flows (Galí, 2015). Economists as well as asset managers, when accounting for alternate investments during the planning and design of an asset, often discount future costs after *n* years with a constant or variable discount rate to give a more realistic magnitude of the asset's operational, maintenance, user and social costs (including environmental costs) in terms of the present value "PV" (Goh & Yang, 2009). Equation (2.1) shows this relation for the initial costs of C_{in} and costs C_t for a year t if the discount rate is i (American Standard for Testing of Materials (ASTM), 2015).

$$PV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t}; \text{ for } C_t = C_o(1+e)^t; \qquad \text{Equation (2.1)}$$

LCCA results for any road design alternative are influenced by the fluctuations in the discount rate and may even be further influenced by local currency inflation and risks (Wu, Yuan, & Liu, 2017). Discount rates applied by the private agencies usually reflect risk-free annual return rate (akin to government treasury bonds), while public agencies base it on their cost of raising capital. An empirical rule of thumb (Equation (2.2)) provided by the Royal Institution of Chartered Surveyors acknowledges these factors and may be included in off-the-shelf packages or any LCCA spreadsheet developed for the analysing lifecycle costs occurring at various stages in a road project's life (Whyte, 2015).

$$\begin{aligned}\text{Discount rate} &= (\textit{Treasury bond return rate} - \textit{Inflation}) \\ &+ \left[0.5 \times (\textit{Average equity return} - \textit{Treasury bond})\right]\end{aligned} \qquad \text{Equation (2.2)}$$

Additionally, Equation (2.3) is used to determine the escalated rates in the future.

$$A = PV\left\{\frac{\left[i(1+i)^n\right]}{\left[(1+i)^n - 1\right]}\right\} \qquad \text{Equation (2.3)}$$

$$C_l = C_{ac} + C_{en} + C_{ins} + C_{op} + C_m + C_{rn} - V_r \qquad \text{Equation (2.4)}$$

The lifecycle cost (C_l) of a road asset can, therefore, be given by Equation (2.3) (Whyte, 2015); where: acquisition cost of materials and land is C_{ac}; C_{en} represents energy costs; construction and installation costs are C_{ins} and C_{op} is the asset operational and usage cost. Routine minor maintenance costs are C_m, C_{rn} is the renewal cost, and any salvage or residual value is represented by V_r. The costs are converted to present worth by using Equation (2.1). This means that the traditional inputs to any LCCA model are fixed, discrete values, discounted to equivalent units to produce preconceived results. The conversion or discounting of future expenditures to present value or worth is a procedure in which the results of a cost analysis over the long-term are uncertain when selecting the best alternative, solely based on an investment-return methodology.

Generally, the common elements of LCCA models developed for road project investment decisions tend to observe a multi-tier procedure (Figure 2.2), whereas the critical economic indicators are not generally prioritised. Input variables, such as initial costs, operation and occupancy costs, maintenance and repair costs, social and hidden costs, externalities and incomes, analysis period, end-of-life costs and compensation for inflation, depreciation of money with time are fixed, based upon past studies and traditional LCCA approaches (Wennström & Karlsson, 2016) to address cost optimisation problems of road maintenance and pavement design. The need for construction of new roads or rehabilitation of an existing pavement structure forms the basis on which the objectives of a functional product[2] are developed and the scope and boundary of the project are established. The lifecycle inventory data for the specific road design alternatives, i.e., available resources and manpower are assessed next to perform cost computations for the road projects.

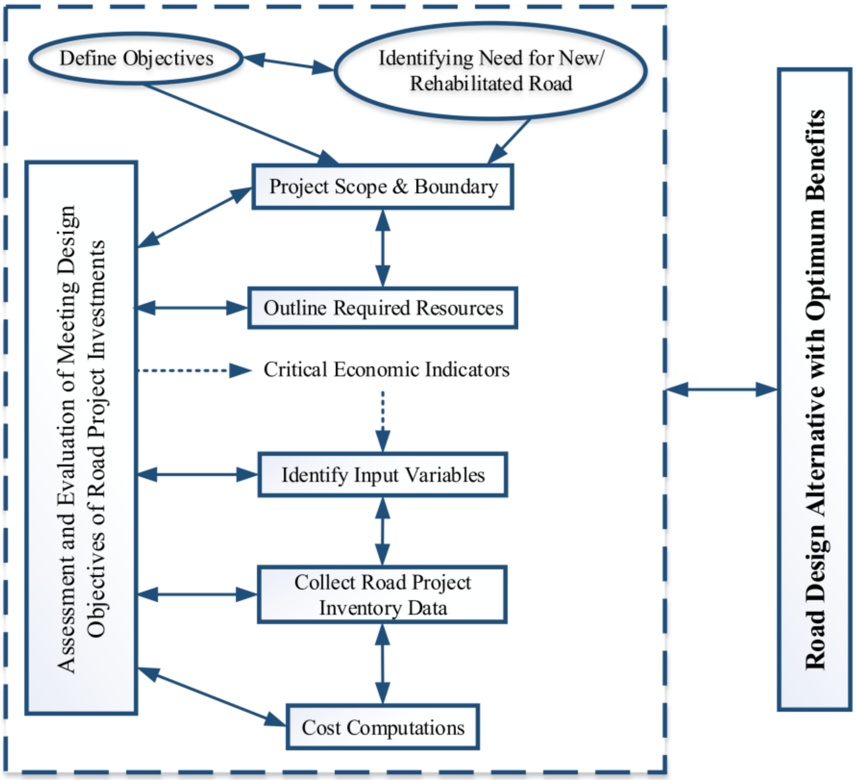


Figure 2.2 Stages in a conventional LCCA for investment decision-making on road projects

2.3.2 Cost aggregation: Future cash-flows

The inflows and outflows of resources and critical variables occurring during any of the several stages within a project's estimated lifecycle are synthesised in a database, and the costs for a practicable range of "fit-for-purpose" alternatives are calculated. Whilst costs to mitigate and address technical measures to find environmental compliances for noise and particulate matter are assessed generally, environmental

[2] The term product used herein is intended to include both goods and services, and is also used in such context by the ISO 14040 guideline (2006). A product system model, therefore, represents the processes involved during the entire lifecycle of a product, and respective inflows-outflows of capital, resources and energy.

benefit and energy inflows-outflows are reserved for LCA consideration (Section 2.4). After compensating for uncertainties and discounting costs, preferred fit-for-purpose alternatives are then categorised based upon cost, benefit, and feasibility contributions. The alternative with the optimum benefits can then be deduced based upon the impact categorisation produced by the LCCA. It should be noted that LCCA does not yield a direct fixed alternative or prioritise the implemented option (Alqahtani & Whyte, 2013, 2016). Nonetheless, LCCA does aid decision-makers in assessing the need-cost-benefit paradigm for the road asset. The following text covers the recent state of the art studies conducted on the development of LCCA frameworks specifically targeted towards pavements, highways and bridge projects. The discussion below covers the LCCA (whole-cost) application across various stages within the asset's lifecycle and the different frameworks proposed in the existing research literature.

2.3.3 Stakeholder expenses: Costs to users

The concept of getting the most benefits for the least amount of investment is not a novel idea within the domain of road network projects. Researchers (Jingning, 2015; Mirza & Ali, 2017) have advocated the intermingling of LCCA-effective design and OM&R practices with those of value engineering to improve the decision-making paradigm. Further argument by Alqahtani and Whyte (2016) advocates for the calculation of indirect socio-economical, environmental and road-user indirect costs, such as accessibility and comfort; accident and safety; time-delays; and, vehicle operating costs due to congestions, detours and work zone conditions. The road network user costs (Equation (2.5)) have to be added to the assets' lifecycle cost estimates, calculated based on Equation (2.3), for best estimation of the stakeholder expenses.

$$\text{User costs} = C_{\textit{time-delay costs}} + C_{\textit{vehicle opreration costs}} \qquad \text{Equation (2.5)}$$

2.3.4 Stakeholder expenses: Budgetary costs of road agencies

Due to the limitation of the funds available to many municipal agencies, private financing of public infrastructures provides an alternate option. However, in order to attract the private investors, the economic feasibility evaluation should address the involved uncertainties (both cost estimation- and performance-related) and risks (financial and payment, pre- and post-contractual and political risks) when evaluating the potential returns (Giang & Pheng, 2015), as direct correlation between risks and return exists. It is also noteworthy at this stage that the investment goals of private investors may not necessarily align with the political, publicity and administrative objectives of the government municipal authority; and, maybe more inclined towards materialising solid client retention and consumer market expansion.

One notable example, for road and transport projects, is the case of Public Transport Authority of Western Australia, where approximately 65% of public transit and road projects were approved by government stakeholders, despite projecting a negative net present value, a potential rejection marker for private investors (Whyte, 2015). The government authorities seeking partnership with private investors may fail to convey their objective of maximum social benefits to the investors while campaigning for a higher initial cost for a later return, nonetheless, user retention of road projects through expanding transit clients may be more comprehensible. This client or passenger attraction is probably achievable by passenger engagement and need identification so that the government or private capital can be best targeted towards providing services that, not only results in whole-life social benefits from the road and transit asset, but also expand clientele of the services provided by involving users in the decision-making process (Hasan, Whyte, & Al Jassmi, 2018b). Supplementary studies targeting this specific objective of identifying client needs (Hasan, Whyte, & Al Jassmi, 2018a) should, therefore, be performed prior to any design or lifecycle study to ensure the success of the project.

2.3.5 Maintenance and rehabilitation (M&R) costs

The application of an LCCA framework on M&R projects addressing deteriorating road network elements was explored in a study by Choi et al. (2015) on highway M&R works. The authors collected extensive data containing 190,000 roads datasets from the Texas Department of Transportation's pavement information management system regarding 39,000 highway sections and 103 influencing factors to perform regression and cluster analysis. The study noted the sensitivity of LCCA analyses to cost indicators and traffic loading and underlying road network peculiarities. Mobility trends, i.e., mode choice of passengers (Hasan et al., 2018b), fluctuate over the road network lifecycle. In order for any transit system to act as a quality service providing a platform to its consumers, the infrastructure that supports it must be well-maintained.

Cost of maintaining the road network is dependent upon several factors attributed to its contributing elements; e.g., age and thickness of pavement, provision of highways and bridges (facilitating high-speed corridors), perceived traffic congestion during maintenance activities, temporal variations, political, administrative and investment objectives as well as average annual average daily traffic load.

2.3.6 Frameworks and critical parameters for LCCA

Researchers have long investigated pavements and other elements of a road network and adopted LCCA to compare design alternatives. However, these LCCA studies are somewhat diverse and present an eclectic mix of parameters deemed critical for achieving cost optimisation when designing or maintaining the road network assets. The breadth of published literature is still lacking in succinct guidelines and indicator databases comparable across the different studies and so, towards the state of the art analyses presented here, Table 2.1 provides a summary of the key LCCA studies detailing multiple iterations and combinations for road networks projects towards system transparency and a mirroring of stakeholder objectives.

Table 2.1 Summary of commonly cited studies on LCCA of various elements of road network projects

Researchers	**Issues addressed**				**Cost parameters**						**Uncertainty**					**Time and traffic**			**Design parameters**					
	Traffic congestion	Cost-risk relation	Pollution	Added–value analysis	Initial cost	Ownership and OM&R	Political & administrative	Return rate & LoS	Future cash-flow	Hidden, social & user	Discount rate	Sensitivity analysis	Lack of past data	Standardised guidelines	Rate of inflation	LCCA time horizon	Longer useful life	Traffic load (AADT)	Thickness	Age and deterioration	Precipitation/freeze-thaw	Annual average temperature	Limited funds	Modular integrated systems
Chen and Ni (2018) **Maintenance & surface roughness: highways**	ᑭ	×	×	ᑭ	✓	↑	✓	✓	✓	✓	✓	×	✓	✓	×	✓	✓	✓	✓	↑	×	×	↑	×
Lee, Thomas, and Alleman (2018) **Rehabilitation: highways**	ᑭ	ᑭ	×	×	✓	✓	×	×	ᑭ	↑	✓	×	✓	✓	×	✓	✓	✓	✓	×	×	×	✓	×
Batouli, Bienvenu, and Mostafavi (2017) **Construction & extension: highway**	✓	×	✓	ᑭ	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	ᑭ	✓	ᑭ	✓	✓	✓	×	×	✓	×
Celauro et al. (2017) **Construction & maintenance: roads**	×	×	✓	✓	✓	✓	×	×	✓	×	✓	×	×	×	ᑭ	✓	×	×	✓	✓	×	×	✓	×

Trigaux et al. (2017) **Construction & maintenance: urban roads**	×	×	✓	✓	✓	✓	×	₽	✓	✓	✓	✓	×	×	✓	✓	✓	✓	₽	✓	×	×	₽	↑
Simões, Almeida-Costa, and Benta (2017) **Preventive maintenance: roads**	×	×	✓	✓	✓	↑	✓	₽	✓	✓	✓	×	×	×	✓	✓	✓	✓	✓	✓	×	✓	✓	×
Wu, Yuan, and Liu (2017) **Preventative maintenance: pavements**	✓	✓	×	×	✓	✓	✓	×	₽	✓	✓	✓	₽	×	✓	✓	×	✓	✓	✓	×	×	×	×
Jannat and Tighe (2016) **Maintenance & rehabilitation: highway**	₽	×	₽	×	✓	✓	×	₽	✓	×	✓	×	✓	✓	×	✓	✓	✓	✓	✓	×	×	✓	×
Wennström and Karlsson (2016) **Rehabilitation: pavement**	×	×	×	×	✓	✓	×	×	✓	✓	×	×	×	×	×	×	×	✓	×	×	×	×	×	×
Choi et al. (2015) **Rehabilitation: highway**	×	×	×	×	×	×	×	×	×	×	×	✓	×	✓	×	×	✓	↑	×	↑	↑	↑	×	×
Han and Do (2015) **Maintenance simulation: highways**	₽	✓	✓	✓	×	✓	↑	✓	✓	✓	✓	×	✓	✓	×	✓	✓	✓	×	✓	×	×	✓	×
Qiao et al. (2015) **Maintenance and climate change cost: highways**	×	×	↑	×	✓	✓	✓	₽	✓	✓	✓	✓	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×

Du et al. (2014) **Procurement: bridges**	×	×	✓	✓	₽	×	×	×	×	×	×	✓	×	×	×	✓	✓	×	×	₽	×	×	×	×
Goh and Yang (2014) **Sustainability cost: highways**	✓	×	✓	×	×	×	×	×	×	×	×	×	×	×	✓	×	×	×	×	×	×	×	×	×
Mirzadeh et al. (2014) **Construction and rehabilitation: roads**	✓	✓	×	✓	✓	↑	✓	✓	✓	✓	₽	✓	×	×	✓	✓	✓	✓	✓	₽	×	×	₽	×
Noori et al. (2014) **Reflective cracking mitigation: roads**	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×	✓	✓	✓	✓	✓	×	×	×	×
Safi, Sundquist, and Karoumi (2014) **Procurement: bridge**	×	×	×	✓	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Goh and Yang (2009) **Sustainability: roads**	×	×	✓	×	×	✓	×	×	×	✓	✓	✓	×	×	×	×	✓	×	×	×	×	×	×	×

Key: ✓ *= used/addressed,* ₽ *= partially addressed, needs further work,* × *= Unaddressed/Needed,* ↑ *= recognised as the leading factor*

2.3.7 Summary and gaps from the reviewed roads LCCA frameworks

Real world project-level analysis of the 18 studies cited above, finds adherence to numerous respective (varied) guidelines and industry norms from around the world, as key to an LCCA methodology for roads. The following text in this section provides the author's synthesis of the extensive literature reviewed above. For simplification of analysis complexity, it is suggested that any proposed LCCA framework should include prominent items from the key variable groups identified in the table above. The exact variable selection is dependent upon the complexity of the project, expert appraisal, and severity of the required cost optimisation endeavours. Following these guidelines, a detailed document analysis of the above-published literature by the author shows that:

- *Ownership and OM&R costs* form part of a cost parameter matrix in a majority of the essential roads' studies (~75%). The cost to acquire the road network asset on part of the municipal agency is critical for the decision-makers analysing completeness cost of the project, however, consistency in cost analysis needs to be maintained to include the OM&R cost, as a higher acquisition cost may be justifiable by a reduction in the future management and operation expenditure later.
- *Risks* associated with road network investments are explored in only three studies where they are the primary focus of the analysis. Capital investments are affected by several interdependent factors such as temporal variations, traffic growth patterns, fluctuations in discount rates and deterioration of pavement material which creates an inherent cost risk perceivable by decision-makers. Transparency of any applied LCCA framework is susceptible to an appropriate acknowledgement of the involved risks in the cost allotment to different project design alternatives.
- *Uncertainty and market fluctuations* were acknowledged in almost all (~80**%**) of the key road's whole cost studies. Recommendations made on the basis of an LCCA framework are not only susceptible to the adopted *discount rate* (acknowledged in ~70% of research) and *inflation rate* (considered in ~40%) of the analysis currency, but, also susceptible to uncertainty as a result of a lack of historical data or low "quality" data collected for analysis. On the other hand, an abundance of past data of construction and rehabilitation activities can present a

variety of options to the decision-makers for any potential road network projects. Due to perceived misalignment between various government and public stakeholders on the best course of action, a general lack of trust and uncertainty on LCCA results is still noted to exist in real world projects.

- *User costs and hidden social costs* were generally addressed (60%), however, more emphasis was placed on agency-side costs of ownership and maintenance (75%). Nonetheless, user costs may be critical for future studies; recent work by Wennström and Karlsson (2016) attributed a majority of costs towards the road users as illustrated in Figure 2.3. Decisions to constrain the scope of analysed variable constructs to agency-side parameters may be attributed to a general lack of data at the various lifecycle stages of the asset under consideration.

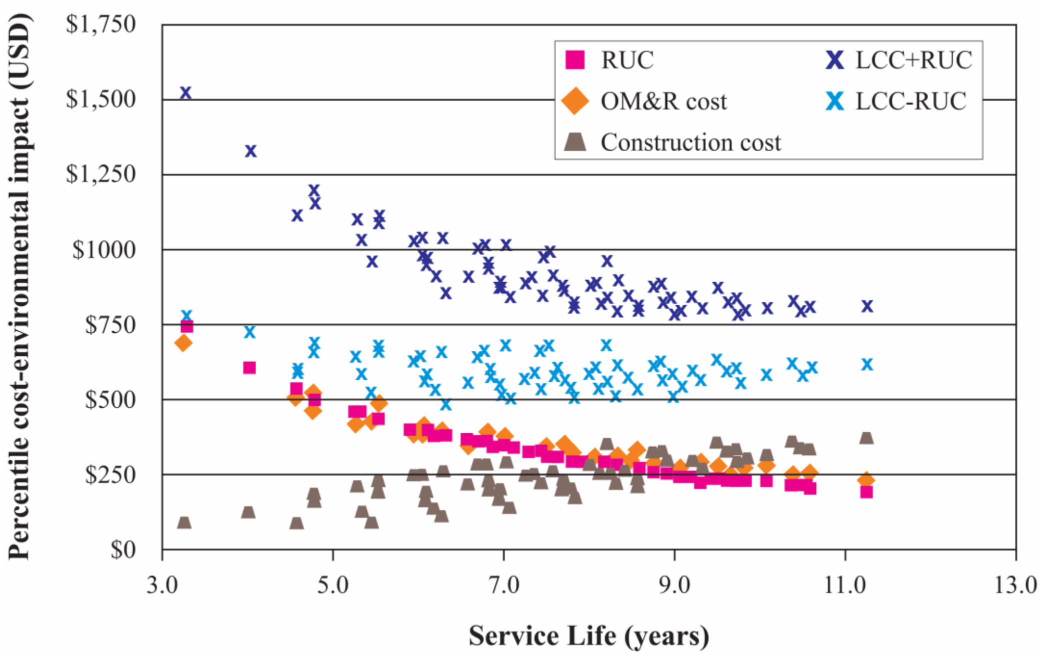


Figure 2.3 Percentile trade-off between cost-environment of road projects (adapted from Wennström and Karlsson (2016))

- *Political and administrative issues cost* and *dollar-value (i.e., fiscal translation) of pollutant generation* (taking lead in only one study) need to be included in the LCCA framework as environmental sustainability not only mirrors overall design objectives of embedded projects' needs but also increase the robustness of the LCCA process. Partially inspired by the marginal monetary utility maximisation principles of economics, optimising the per-dollar value of road networks is an important parameter for municipal authorities, and so easily comprehensible by the general public. The dollar value of pollutants generated as a result of human activities (i.e., roads here) per tonne of GHG, human productivity lost and costs in recuperating from adverse health impacts affect the robustness of any LCCA framework and can greatly help to rank valuation of the different project alternatives.

- Implemented LCCA processes also need to be attentive to *future cash-flows*, *traffic load patterns*, *limited funds* available to the agency, the *time horizon* of the analysis and cost associated with different aspects of each primary road network element. Constrained budgets and sustainability goals of municipal agencies necessitate the use of transparent frameworks accounting for cash-returns and dynamic traffic flows in addition to maintaining (limited) controls on mass mobility to achieve future-proofing.

Generally, government authorities commissioning the design and performing decisions on maintenance and operation of road assets need decision support tools throughout the assets' lifecycle to optimise the costs. LCCA considers all costs occurring during the effective project life, however, these costs need to be properly discounted to net present value and market fluctuations, uncertainties and risks should be acknowledged in project-specific LCCA models or spreadsheets developed to compare the cost components. These factors may also be significant when comparing the use of recycled materials (Hasan et al., 2016a) during any stage in the road assets' lifecycle, often motivated by environmental goals and reducing "eco-loading" of the construction activities. For example, Whyte (2015) compared virgin materials (virgin limestone, hot/warm-mix asphalt) against recycled materials in a heavily trafficked Western Australia road. The general conclusions proposed more environmentally friendly options as slightly cheaper provided the application cannot be precluded by haulage. As these costs largely target the *ownership, operation, maintenance and rehabilitation costs* to the *government agency*; costs to road users in terms of direct vehicle operation cost, value of time lost in congestion around construction zones or under-capacity roads incapable of handling large traffic loads, not least the indirect impact on human health and environmental toxicity, need to be accounted for (further discussed in Section 2.4.4). Nonmonetary scores such as the environmental and social benefits may produce a larger difference between the virgin and recycled material options, often justified through LCA analysis tools.

2.4 PROCESS FRAMEWORK: LCA IN ROAD NETWORK PROJECTS

Lifecycle assessment (LCA), initially coined by SETAC in 1990 (Fava et al., 2014), is the methodological evaluation of environmental weightings of a product by systematic quantification of impacts such as resource consumption and depletion, eutrophication, climate change, ozone depletion, noise pollution and other direct and indirect implications of human activities on the ecosystem (ISO 14040, 2006; SAIC, 2006; Svoboda, 2006) generated over the entire lifecycle; or "cradle to cradle/grave".

2.4.1 Conceptual basis and phases in lifecycle assessments

The conceptual basis for LCAs has been developed over decades with the I/O evaluation of net energy analysis and then assessing production processes both directly and indirectly responsible for the generation of energy and waste emissions (Green & Lepkowski, 2006). LCA adopts a lifecycle perspective to quantify the resource and energy consumption and wastes (e.g., GHG) emitted in the environment, which increases interest in developing an LCA-based framework for built assets (Sharma et al., 2011). The process framework largely based upon SETAC and ISO 14040 (2006) asserts that the sustainability assessment of a product must acknowledge impact across three dimensions; economic, environmental and social. Four distinctive systematic phases of an iterative LCA approach are: outlining goal and scope, compilation of lifecycle inventory (LCI), lifecycle impact assessment (LCIA) and the last phase of interpretation.

Goal and scope outlining involves the identification and report of the extent of a product system including the processes expected later in its lifecycle. A familiar feature of this phase in the description of a functional unit[3], system boundaries[4], categories of impact (e.g., social, economic and environmental) and alternative scenarios. *LCI compilation* is the tabulation and quantification of the collected information regarding the energy and resource exchanges (inflows-outflows) with the

[3] As defined by ISO 14040 (2006), "A functional unit is a measure of the performance of the functional outputs of the product system", and may use quantification of materials or the service provided, e.g., a road is intended for transportation of people and goods and may have extended sub-functions of providing less congested, quicker, smoother and easier transportation depending upon its design.

[4] Recommended cut-off criteria for constraining the elements to be modelled for representation of a product system, based on energy/resources, and environmental impacts.

environment and waste emissions over the project's life in a product system. After the compilation, the *LCIA phase* involves the conversion of inventory into systematic estimates of environmental impacts weighted and evaluated based upon analytical indicators. The last phase of *interpretation* is actually an iterative process in practice, in the sense that it follows and precedes the three other LCA phases after every consecutive iteration of the assessment process. Even though the primary focus of LCA is to provide analysts with quantitative data on environmental impacts associated with the processes upstream, decision-makers are often encouraged to conclude recommendations based upon LCIA and inventory data in conjunction with the sub-functions and impact categories and not just the magnitude of the energy/resource flow and waste generation.

2.4.2 Data collection, quality check, material control, and product declarations

One of the primary challenges in the real-world application of any LCA methodology is defining the scope, source, and quality of the LCIA inventory data that needs to be collected for identifying the environmental burden generated across the different stages of a road network asset. Industrial confidentiality related to upstream case-specific historical data and the cost of gathering high quality and detailed LCA data for a construction project (Treloar, Love, & Crawford, 2004) may be challenging for any road agency in applying LCA for the decision-making process. On the other hand, uncertainties in the collected LCIA data may be detrimental to the calculated environmental performance of the different alternatives for the road asset case study being analysed by the road management agency. These issues with data collection, quality check, and system boundaries were further highlighted by Yu, Wang, and Gu (2018). They note that as the existing pavement LCA studies rely on different energy intensity values data resources to calculate the energy consumption associated with concrete and/or asphalt pavement production, the estimated values may lead to fluctuations. Moreover, scarcity of certain construction materials and local resource depletion concerns in a case study region, transportation distance, mixing techniques, equipment, and heating, etc., may also influence the corresponding calculations.

Such issues, identified prior to the conduction of an LCA study increases the stakeholder confidence and ensures adequate decision-making process for best road alternative selection. Primary data sources should be used where possible and missing data may be complemented by secondary resources from peer-reviewed literature as prevalent in the research on road materials (Moretti et al. 2017). The system boundary, including the selection of road lifecycle stages, may be based upon the standardised performance data sheets such as environmental product declaration standards. Environmental product declarations (EPDs) are international third-party verified standardised (CEN EN 15804, 2013; ISO 14025, 2006; ISO 21930, 2017) datasheets for the environmental performance of different impact categories regulated by product category rules (PCRs); i.e.; climate change (global warming potential) value, ozone depletion value and acidification potential etc.; of the road alternatives. In a standardised LCA methodology, the government road management agency defines the PCRs *prior to* conduction of an LCA. Studies such as Baker et al. (2016) have used Type III, product-specific EPDs to define LCA boundary report the LCA study results.

2.4.3 Construction material selection: LCA approach in pre-construction stages

The traditional aim behind conducting LCAs is to improve the overall performance of a product in terms of environmental impacts, and as such an earlier estimate in design and construction procurement procedures may produce benefit. Pavements, highways, and bridges form a critical portion of the road networks. Therefore, they account for a significant part of energy/resource consumptions, emission of GHGs such as CO_2, CO, NO_x, O_3 and black carbon and other volatile organic compounds generated by the road network projects.

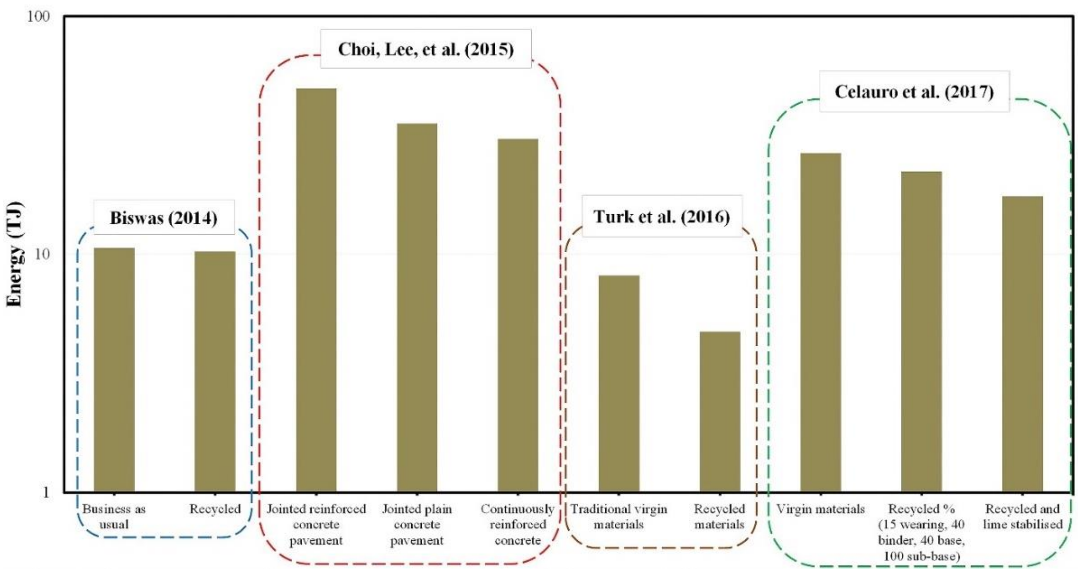


Figure 2.4 Lifecycle energy burdens of roads (log scale)

Fuglestvedt et al. (2008) have observed that the global radiative forcing corresponding to the pavements alone for the year 2000 were 150 mW/m^2 and since industrial times, road networks may have accounted for approximately 31% and 15% of the total ozone and carbon dioxide forces due to human activities, from material extraction and production stages to the final salvage or reuse. Figure 2.4 above, highlights some of the key energy burden work. Biswas (2014) in his study comparing the use of recycled materials against virgin materials in road construction in Australia, found that 180.6 tonnes of CDE and 10.67 TJ energy was consumed during an urban pavement's lifecycle, while Choi et al. (2015) found 4390.774 tonnes CDE for a JRCP pavement consuming 49.8 TJ energy.

Figure 2.4 and Figure 2.5 incorporate a recent study by Turk et al. (2016) which found the use of recycled material as a decreasing factor in energy consumption (by 3.4 TJ) and global warming (by 20 tonnes of CDE). The potential is further realised in the later study by Celauro et al. (2017), where different options with a gradually increased replacement of virgin materials by the recycled options demonstrated improved performance in energy usage (Figure 2.4) and carbon load (Figure 2.5) categories.

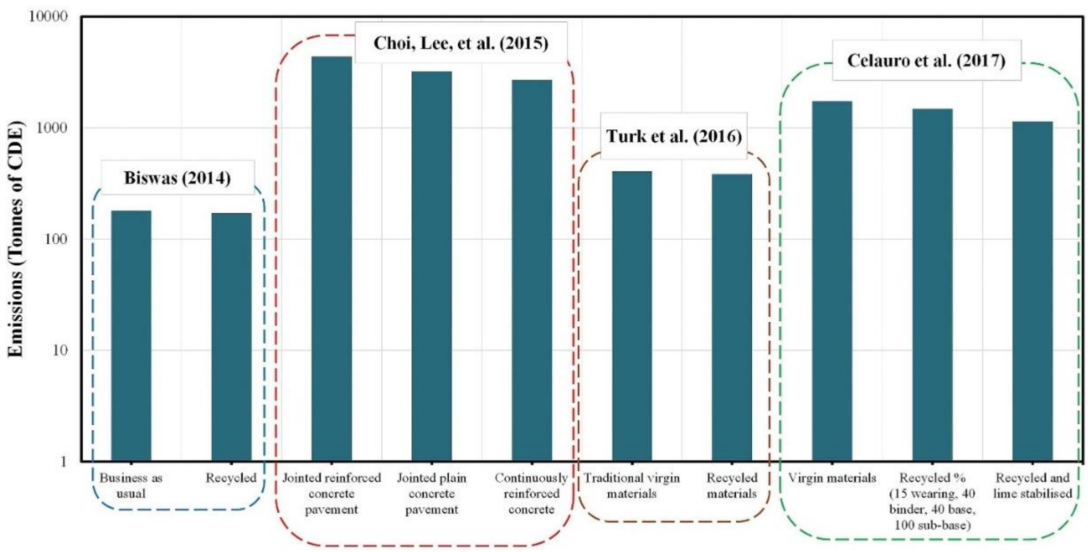


Figure 2.5 Lifecycle global warming potential of road (log scale)

2.4.4 Applying LCA in construction, usage, M&R stages emissions

Past trends in developed countries such as the United States have exhibited around 17% increase (EPA, 2016) in the transportation sector GHG emissions in the year 2014 compared to the 1990 appraisals. The EPA (2016) study found the transportation sector as the second highest polluter in the USA. Similar results have been estimated for developing countries (Dang & Sui Pheng, 2015; Sadri, Ardehali, & Amirnekooei, 2014) as well as G8 and European countries (Andersen et al., 2013). The operation of road networks and respective fossil fuel consumption costs escalate the financial and environmental impacts from the relatively lower early-stage burdens, making roads a hot topic in green infrastructure initiatives. Several factors contribute to the energy consumption and waste emissions associated with the operation of road networks.

Usage stage impacts to road users and mass mobility implications of any early-stage decisions as well as the larger system-wide effects, critical to end-consumers, need to be addressed. This aspect is specifically significant for the real-world success of any LCA-based endeavour for high traffic volume roads as the construction and OM&R activities have been noted to account for less than 5% of the consumed energy during the whole-life of a road network, whereas the usage stage traffic volume can account for more than 95% (Araújo, Oliveira, & Silva, 2014; EAPA/Eurobitume, 2004).

The study by Araújo et al. (2014) on use of recycled materials in pavement construction, operation and maintenance noted that depending upon traffic volume, the GHG emissions due to traffic operating on the roads are 1000 times larger, with energy consumption 700 times higher, during usage stage compared to the construction stage. This alone intensifies the importance of accounting for the usage stage in LCAs. However, it should be noted that this dominance of usage stage impacts in the LCA results is influenced by the traffic volumes supported by the road. For example, in the study by Santos, Ferreira, and Flintsch (2015) comparing low (AADT ~ 300) and high (AADT ~ 2000) traffic volumes, usage stage only accounted for 10-21% of the emissions, whereas material choice and construction methodology dominated the lifecycle impacts of the studied pavements.

In addition, in-place recycling of pavement material may further increase the environmental benefits during construction and rehabilitation stages. Turk et al. (2016) have found that cold in-place recycling can reduce the acidification load by 18% and energy consumption by 16% during pavement construction and maintenance on a high traffic (AADT ~ 2500) Slovenia road without significantly compromising on the service life. Recycling construction waste as road aggregates has gained popularity (Hasan, 2015). However, the mechanical properties and stability of roads constructed with recycled materials could be of concern to the different stakeholders because of its status as fit-for-purpose (Hasan et al. 2016b).

The technical performance of using recycled materials as pavement base layer was analysed in another study on low traffic volume roads by Lopez-Uceda et al. (2018) with recycled pavement aggregates and Portland cement-fly ash binder mix. They found that the mixed recycled aggregate base exhibited 2.5 MPa tensile strength and 20 MPa compressive strength and may only be suitable for constructing roads with heavy vehicle AADT < 50. Moisture resistance, fatigue, rutting and stiffness of pavements constructed or rehabilitated with recycled materials was studied by Dinis-Almeida et al. (2016) and Pasandín & Pérez (2017). They found that even though recycled aggregates increase the absorptive behaviour (demanding more bitumen content), the mixtures exhibited adequate tensile strength, fatigue resistance and moisture resistant similar to the virgin material sample, even for warm-mix asphalt pavements. Furthermore, Miliutenko, Björklund, and Carlsson (2013) note that hot in-place recycled can be applied for low-heavy traffic road types and showed an additional 3 GJ equivalent/tonne and 0.02 tonne CDE of asphalt waste savings compared to in-plant recycling.

2.4.5 Frameworks and critical attributes for LCA

Researchers utilising different LCA frameworks have identified contributors like the construction material used, traffic volume and delays, quality of pavement or road design among others over the entire lifecycle of any road network project. Compared to the infancy of LCA and the uncertainties in its functional units, boundary, and inventories, LCCA has been widely researched and, often, been a part of roadworks and pavement policy-making under various regulatory agency guidelines (Rangaraju, Amirkhanian, & Guven, 2008). Integrating LCCA tools within the LCA toolbox can aid decision-makers further by assigning an economic perspective along with the environmental context, bringing the question of resource and energy conservation into the picture of cost-benefit, thus combining two dimensions of sustainability.

A review by AzariJafari et al. (2016) recognised the diversity of the alternates available to the decision-makers assessing investment incentives from pavement projects. Inconsistency of LCA frameworks, applied across several components of the larger transit system as well as different stages of the pavements themselves were noted. However, an integrated LCA modelling approach to handle the broader life-span of the projects can still yield value-added future-proofing results. Reviews are often specifically aimed at addressing research challenges, with less emphasis on the real-world case studies; yet, this state-of-the-art review notes that work completed highlights the inconsistent selection of functional units and lifecycle stages in different research as among the primary challenges for future wider research or any eventual industry application. The sensitivity of LCA recommendations to the material choices and construction strategies, environmental burdens arising later in the road project's lifecycle (e.g., lighting requirements, carbonation, and albedo) were also credited to the type of material used during construction and rehabilitation. Depending upon the system boundary definition, noise is also sometimes included among the environmental burdens (Sánchez et al., 2018). Conversely, other researchers (Oltean-Dumbrava, Watts, & Miah, 2013) have instead included in road LCA studies as part of the social indicators.

Furthermore, the source and quality of LCA data (as well as the consistency, transparency, and flexibility of applying the LCA recommendations to different design alternatives for diversified road network projects) may also influence the adoption rate of the LCA frameworks by the decision-makers. Table 2.2 below summarises this work's LCA road secondary research and provides key variables' weightings thus far.

Table 2.2 Scope and methodology of selected LCA-based studies on road network projects

Study reference	Road element typology	Functional unit	System boundary	Scenarios analysed	LCI database and resources
Moretti et al. (2018)	Asphalt concrete road	3.75 m wide dual lane, 1 m × 4 m cross-section, 1.5 m wide shoulders	- Raw material extraction - Production and processing - Construction	**Trench *vs.* embankment** road sections. **30-100 km** transportation **distances**.	- *Material transportation:* European Commission (2012, 2014). - *Asphalt:* Moretti et al. (2017). - *Cement production:* AITEC (2016). - *Bitumen & fuel:* Eurobitume (2011). - *Aggregates:* Officina dell'Ambiente (2013) and UNPG (2012).
Bloom et al. (2017)	Urban highway re-construction of asphalt pavement	2.4 km	- Raw material extraction - Production and processing - Construction	**Recycled**: aggregates; pavement (base course & HMA); asphalt shingles (**partially replaced binder**); slag and fly ash (**partially replaced Portland cement**).	- *Quantity take-offs:* Local agencies. - *Environmental impacts:* Compared outputs from two emissions modelling software; PaLATE (option 1) and SimaPro (option 2).
Celauro et al. (2017)	Asphalt pavement (urban road)	1 km, single carriageway. 30 years analysis period	- Production and processing - Construction - Maintenance and rehabilitation	Five scenarios **varying**: **virgin**, **recycled *and* lime stabilised** materials. Maintenance plans: **repaving wearing** course ***vs.*** maintenance of **all courses**.	- *Unit materials:* Regional Council Office for Infrastructure and Mobility (2013). - *Emissions calculation:* Local resources and PaLATE.
Chen et al. (2017)	Cement and asphalt roads	No specifically defined	- Raw material extraction - Production and processing - Construction	Low to high volume traffic roads	- *Aggregate & asphalt emission:* Zhang & Liu (2015) and Wang & Wei (2015). - *GHG factors:* Regional data and Zhao et al. (2016)

Karlsson et al. (2017)	Urban road re-construction	7.5 km 3-lane road	- Construction - Maintenance and rehabilitation	Two alternatives: **reconstruction** of **the entire road** ***vs.*** only **reconstructing end** and **start**.	- *GHG emissions and energy use:* Goedkoop et al. (2009), Lundberg et al. (2013) and Toller et al. (2014). - *Material & environmental factors:* Stripple (2001) and local resources.
Butt and Birgisson (2016)	Asphalt road (theoretical cases)	1km, 3.5m lane construction, maintenance (after 15 years). 25 years life	- Production and processing - Construction - Maintenance and rehabilitation	Four scenarios: **Two unmodified asphalt mix aggregates** ***vs.*** **adding warm mix asphalt**.	- *GHG emissions:* Local data, EAPA/ Eurobitume (2004), Klöpffer (2006). - *Energy consumption:* ECRPD (2010), Sheehan et al. (1998) & Stripple (2001).
Butt et al. (2016)	Asphalt road	1 km, 3.5 m wide. 1 km, 4 m wide. 20 years life	- Raw material extraction - Production and processing - Construction	Two case studies with different pavement cross-sections.	- *Asphalt production energy use:* Local contractors. - *Fuel, electricity and other material consumption data:* Stripple (2001).
Turk et al. (2016)	Regional asphalt concrete road rehabilitation	40,000 sq. m pavement (20 years life) serving 2500 AADT	- Raw material extraction - Production and processing - Construction	Traditional **virgin materials** ***vs.*** **recycled** (stabilised asphalt concrete) materials.	- *Fuel, binder, aggregates, stabiliser and material transport:* GaBi 4.0. - *Cement:* Josa et al. (2004), EPD (2015) & Ammenberg et al. (2015). - *Asphalt:* Mladenovič et al. (2015).
Anastasio uet al. (2015)	Urban concrete pavement with an asphalt overlay	7.3 wide dual-lane low traffic 1 km road and 40 years' service life	- Raw material extraction - Production and processing - Construction - M&R - End-of-life	Various scenarios comparing different percentages of recycled and virgin materials.	- *Material consumption:* Marceau, Nisbet, and Van Geem (2007) and Eurobitume (2011). - *Greenhouse gas emissions:* IPCC (2008)

Choi et al. (2015)	Rigid highway pavement rehabilitation	1 km long & 14.8 m wide. 50 years life span	- Production and processing - Construction - M&R - End-of-life	**Continuous-reinforced concrete** (30 years' life) ***vs.*** **jointed plain concrete** (20 years) ***vs.*** **jointed reinforced concrete** (15 years).	- Unit cost data collected and miscellaneous data sources through Carnegie Mellon University (2011).
Santos, Ferreira, and Flintsch (2015)	Typical Portuguese flexible pavement	1 km of 4 main (3.75 m) lanes & outer, inner shoulders (3 m, 1.5 m). 40 years analysis period	- Raw material extraction - Production and processing - Construction - M&R - Operation & use - End-of-life	**Two** classes of **AADT**, **16** types of **hot-mix asphalt** and **asphalt concrete** pavement structures and the **3 foundation types** from the Portuguese pavement design catalogue.	- *Fuel:* Dones et al. (2007). - *On-road vehicles, construction equipment & material:* EPA (2009). - *HMA production:* US EPA (2004). - *Aggregates:* Jullien et al. (2012). - *Bitumen and bituminous emulsion:* Eurobitume (2011).
Biswas (2014)	Asphalt road	100 m, over 100 years	- Raw material extraction - Production and processing - Construction - M&R	**Virgin materials *vs.* recycled** (only as: concrete rubble for base, crushed limestone sub-base and recycled asphalt wearing course).	- *Limestone and hot-mix bitumen:* Whyte (2015). - *Equipment and energy data:* RMIT (2007) database. - *Recycled and crushed rock base:* Mitchell (2012) and RMCG (2010).
Du et al. (2014)	Bridge procurement	Whole bridge (dimensions based on scenarios) over 100 years life	- Raw material extraction - Production - Construction - End-of-life	Five bridge design options.	- *Material and quantity data:* local contractors. - *Environmental inventory data:* From Ecoinvent v2.2 public database for the local conditions.
Yu and Lu (2014)	Overlay pavement section	10 km, 4 lanes	- Pavement albedo in operation & use	**Portland cement concrete *vs.* hot-mix asphalt overlays**.	- Based on empirical relations proposed by Bird et al. (2008), Muñoz et al. (2010) & Susca (2012).

Yu and Lu (2012)	Rehabilitation of Portland cement concrete pavement	1 km overlay. 40-year service life	- Raw material extraction - Production and processing - Construction - Operation & use - End-of-life	**Hot-mix asphalt *vs.* Portland cement concrete *vs.* crack seat overlays**.	- *Material:* Marceau et al. (2007), Stripple (2001) and Meil (2006). - *Material transport:* Wang (2011). - *Construction equipment*: EPA NONROAD 2008 model. - *Fuel consumption:* EPA (2005) and Amos (2006).
Wang et al. (2012)	Rehabilitation of rural road segments	Not explicitly defined as compared rolling resistance effect for different case studies	- Raw material extraction - Production and processing - Construction - Operation and usage	**34,000 AADT** (2-lanes) ***vs.* 3,200 AADT** (4-lanes) **asphalt** roads ***with* capital preventive maintenance** strategies; ***vs.* 86,000 AADT** (2-lanes) ***vs.* 11,200 AADT** (2-lanes) **concrete** roads ***with* concrete pavement restoration.**	- *Cements, aggregates and concrete:* Stripple (2001), Meil (2006), Dones et al. (2007) & Marceau et al. (2007). - *HMA and rubberised hot-mix asphalt:* Stripple (2001) and Meil (2006) and USLCI database by NREL (2011). - *Oil manufacturing and feedstock:* Dones et al. (2007).
Cass and Mukherjee (2011)	Highway concrete pavement rehabilitation	Per lane mile of CO_2 equivalent	- Equipment - Raw material extraction - Production and processing - Construction	Two modelling approaches; **with *and* without SimaPro** in the emissions calculations.	- *Material and equipment inventories:* Field data using Info Tech. Inc.'s Field Manager software. - *Emissions:* SimaPro 7 and e-Calc emissions calculator.
Lee et al. (2010)	Asphalt highway road surface	4.7 km long section	- Raw material extraction - Production and processing - Construction	**Traditional** *AASHTO* pavement design ***vs.* recycled** (foundry sand subbase, fly ash stabilised pavement material base).	- *Emissions and inventory:* PaLATE and EPA (2009). - FHWA's RealCost v2.5 for cost calculation.

The potential for uptake of a (newly) developed LCA framework based upon the real world studies tabulated above (Table 2.2) is particularly important for advocating the practicable usage of sustainable approaches such as the use of recycled materials for construction and maintenance of road network projects. Research has shown that utilising recycled and waste material for road construction reduces environmental impacts, landfill pressure and extraction costs but that, negative perception by stakeholders, regarding the poor performance of such materials and high cost, hinders large-scale practical application (Huang, Bird, & Heidrich, 2007). The critical review study by Wang et al. (2018) attempted to provide extensive coverage and a summary of significant findings in the current recycling technologies for road network projects. Several of the tabulated authors above claim that recycled material inclusion during construction and maintenance activities remains promising for reducing energy load and GHG emissions compared to use of virgin materials.

Leachate generated from constructed road base using recycled techniques and feedstock energies were minimal when paralleled with overall lifecycle benefits. However, recycling techniques such as terminal blend, dry and wet rubberised and recycled asphalt mixing; and, use of slag and fly ash as pavement stabilisers were often deemed critical to meet the cost and environmental goals of municipal authorities. In addition, the cost performance and variation in the environmental impacts from the use of recycled materials during the entire lifecycle, particularly the usage stage need to be identified. More studies based on real-world data and problem handling for actual road network and transit system projects are helpful for government and public stakeholders to correctly visualise the benefits of recycled materials. Necessarily, it raises the question of accurately comparing the various mixing techniques, materials, recycling ratios and construction strategies across different alternatives.

This state-of-the-art analysis of past research via the document-analysis, secondary research approach presented goes towards developing an LCCA/LCA framework to aid the decision-making process. The selected pool of key literature has been reviewed in Table 2.2 to reflect the critical aspects of LCA methodology, use of recycled and alternate materials and the establishment of LCA inventories. The crucial recycling techniques and data resources that may be useful to any future studies or industry applications are summarised in the above table. Comparison of functional units and system boundaries complemented by the required datasets is also provided to aid the decision-makers, project planners and managers and various public and private actors interested in the sustainable design and management of road networks.

2.4.6 Summary and gaps from the reviewed LCA frameworks

The studies presented in Table 2.2 attempted to analyse the (cost and) environmental load reduction performance of the strategies adopted by the local authorities for the construction and management of road networks. For the application of any LCA frameworks in road network projects, specifically, to move further towards real-world use, the following paragraphs aim to recapitulate the current state of research and provide suggestions.

- A general *lack of dynamic user traffic patterns* and *"consumer" impact assessment* are argued here to represent serious constraints to the future application(s) of LCA frameworks. Likewise, very few research papers attempted to *integrate the system-wide impacts* across all lifecycle stages, which is argued here as needed due to the considerably long-term usability of road networks. Unless proper integration can be achieved in the framework and reasoning behind indicator, functional unit, and system boundary, becomes more transparent, LCA recommendations of project alternatives remain open to subjective interpretation which can deter uptake.
- *Selective analysis* of lifecycle stages occurred inherently in a majority of studies albeit *only one study* (Santos, Ferreira, & Flintsch, 2015) considered feedback loops, energy and GHG feeds from the entire road lifecycle. Recycling or end-of-life was the second-most neglected stage; only *three studies* included environmental load from this stage. Frequent M&R schedules of the deteriorating road surfaces were addressed by *four studies*, while the extraction of raw materials was added to the framework parameters in *nine studies*. Production and processing benefits of recycled against virgin materials were examined in *eleven studies* and construction stage(s) was considered by all of the studies except the pavement albedo study where it was out of the research scope. Nowadays, real-world scenario representations and improvements of stakeholder confidence in LCA frameworks, require that parameters from all stages of the road lifecycle are needed to capture the magnitude of cost and environmental benefits of recycling.
- *For a comprehensive LCA framework* considering all stages (Santos et al., 2015), a majority of the data was either assumed based on existing literature or calculated

from an amalgamation of regional and foreign unit costs, emissions and energy feed datasets. Regarding the foreign datasets, significant research is available along with calculators from European and US-based resources, which may be applicable to other regions. However, this may produce a methodological challenge in the applicability and sensitivity of results.

- *Shortages of local and actual case and region-specific data resources for some regions around the world* hinder the application of LCA frameworks in both research and industry projects as majority of the existing datasets and lifecycle frameworks are developed from US and European case studies and the difference between the system advancements, production/construction laws, norms and regulations, and technical process are varied between regions (Santos et al., 2017). However, this may be resolved by collecting local LCI resources and comparing the data flexibility of existing studies for missing datasets to deduce how they (in isolation or collectively) can be applied to handle the missing data.
- *Asphalt recyclability* is arguably one of the most significant findings of most studies leading to loss of stored feedstock energy with wear and tear. Repaving or on-site recycling of asphalt rephrases the asphalt vs. concrete recyclability archetype analysis due to the difference in perceived usability as sub-base for the new road constructed over the completely deteriorated structure.
- *Energy feeds, cost and emissions from transferal waste resources* such as blast furnace slag and fly ash to partially replace cement binders in concrete or asphalt-concrete pavements are argued here as key aspects. Some researchers (Hoy et al., 2017; Silva, de Brito, & Dhir, 2015) suggest that recycling and reuse of materials may result in some strength loss due to aging, such that extracted recycled materials required to be stabilised by industrial wastes (Hasan et al., 2015). It is argued here that any future developed LCA frameworks should acknowledge positive mapping of transferred waste reuse credits, and require explicit recognition that recycling waste outputs divert away from landfill sites.

2.4.7 Normalisation and weighting for LCA interpretation

Due to the diversity in material choices available for road construction, ranging from virgin materials (asphalt and concrete), mixing technique (hot, warm and cold); several environmental impacts of varying magnitudes and units are generated across different lifecycle stages. For example, climate change is generally expressed as "kgCO_2 equivalent", while acidification is expressed as "kgSO_2 equivalent" and normalisation provides a common reference point (Stranddorf et al., 2005) for planners.

Table 2.3 Annual normalisation factors for some environmental impact categories (adapted from Bengtsson and Howard (2010) and Huijbregts et al. (2017))

Environmental impact categories (unit)	**Normalisation factors**		
	Global	**Europe**	**Australia**
Climate change (*kgCO_2 equivalent/year*)	$3.36x10^{13}$	$4.49x10^{12}$	$6.21x10^{11}$
Ozone depletion (*kg CFC-11 equivalent/year*)	$2.29x10^{8}$	$1.02x10^{7}$	$4.17x10^{4}$
Fossil fuel depletion (*kg of oil equivalent/year*)	$7.84x10^{12}$	$7.23x10^{11}$	-
Acidification (*kgSO_2 equivalent/year*)	$2.56x10^{11}$	$1.79x10^{10}$	$2.67x10^{9}$
Terrestrial eco-toxicity (*kg 1,4-DB equivalent/year*)	$4.96x10^{10}$	$6.50x10^{9}$	$1.90x10^{9}$
Freshwater eco-toxicity (*kg 1,4-DB equivalent/year*)	$2.77x10^{10}$	$5.43x10^{9}$	$3.71x10^{9}$
Marine eco-toxicity (*kg 1,4-DB equivalent/year*)	$4.11x10^{12}$	$1.18x10^{12}$	$2.62x10^{14}$
Human toxicity (*kg 1,4-DB equivalent/year*)	$8.83x10^{12}$	$2.08x10^{12}$	$6.96x10^{10}$
Eutrophication (*kg P equivalent/year*)	$1.76x10^{9}$	$1.93x10^{8}$	$1.39 x10^{8}$
Particulate matter (*kg PM equivalent/year*)	$8.55x10^{10}$	$6.93x10^{9}$	$9.82x10^{8}$
Photochemical oxidation (*kg NMVOC equivalent/year*)	$3.45x10^{11}$	$2.64x10^{10}$	$1.61x10^{9}$

The normalisation values that are used for interpreting the LCIA results for the different geographical regions around the world are presented in Table 2.3, as a concise reference point for future works. The values and units are based upon the data from the updated ReCiPe model.

It may be further argued that the current environmental objectives of the country may assess the environmental consequences of the construction decision differently due to the perceived importance of each impact category and may prefer assigning scores or weightings, based on expert opinions. For example, some of the environmental categories occurring during the lifecycle stages of a road project are illustrated below in Figure 2.6 (Bengtsson, Howard, & Kneppers, 2010). Compared to the normalisation factors, the weighting values are highly dependent upon the specific objectives of a regional agency, socio-demographics of the expert panel used for assigning the weighting values and the sampling size. In general, impact weighting generation and prioritisation use the methods available for MCDM such as the analytic hierarchy process (AHP) and fuzzy rankings.

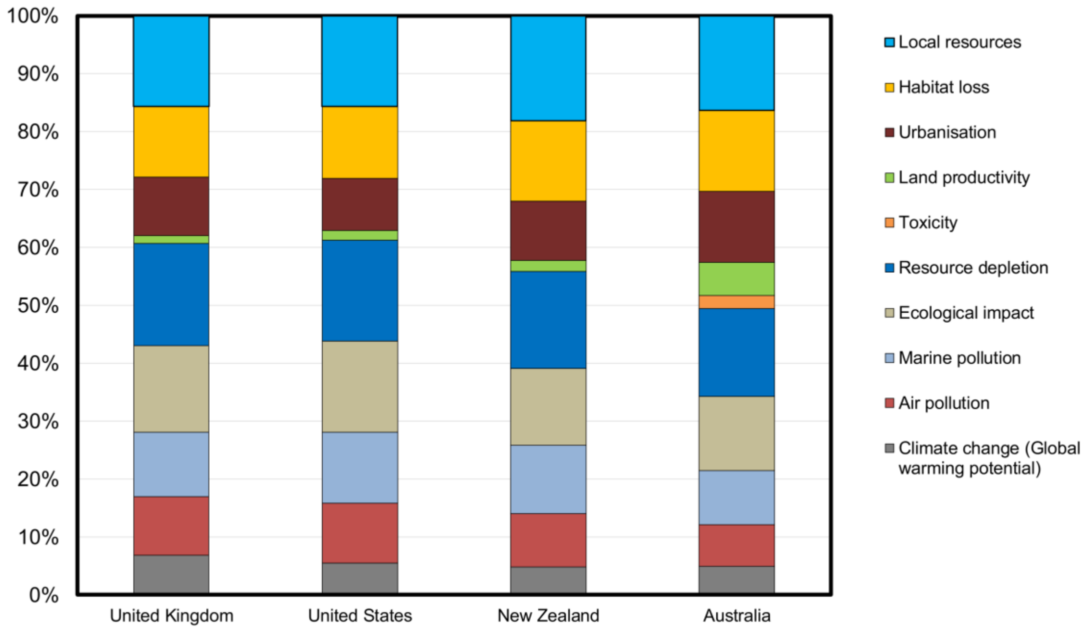


Figure 2.6 The average weighting factors for some of the lifecycle impact categories (adapted from Lippiatt (2007), Bengtsson et al. (2010) and Abbe & Hamilton (2017))

2.5 Requirements, needs, and demands: The social component

Growth in population inherently requires residents' mobility and accessibility within a city that is serviced by its extensive road networks. Traditionally these road networks are designed to facilitate rapid personal travel and are built around private automobile transit. For example, Chester, Horvath, and Madanat (2010) have stated that the infrastructure in most cities in the United States is centred on automobile travel. As urban road networks mature, agencies are forced to seek a trade-off between high maintenance of existing facilities versus road network expansion costs due to increased usage. Indeed Chester et al. (2010) further propose developing growth models based on historical data to highlight the transferal occurrences where investment focus of urban agencies shifts to maintaining existing road networks from constructing new and alternate strategies extrapolated from present usage. The limited maintenance funds of municipal agencies are stretched by the elevated road network deteriorations due to traffic congestion and pavement surface wear and tear. This inhibits the functionality, durability, and ability of road networks as the maximum benefit provided to the users. Linear combinations of all cost and environmental components across the modules of the road projects need to be balanced against the user mobility and benefit to users.

Transport agencies encourage mode shift towards public transport to reduce private automobile travel and increase the functionality and benefit-provision performance of road networks (Gray, Laing, & Docherty, 2016). In order to achieve this, the municipal transport agencies should focus upon perceiving transit as a competitive service that provides users with a quality service, supported by efficient road networks. Amirgholy, Shahabi, and Gao (2017) noted that, similar to any consumer product, quality public transport service and supporting road network comes at high capital and environmental cost to the management public authority agency. Any future study on lifecycle management of road network projects must then evaluate the supported transit and related mobility modules as a marketing and consumer behavioural problem. In this way, a dynamic LCCA/LCA package integrating user needs, mobility trends, road network projects, and mass-transit, can aggregate multi-level cost, energy, and environmental flows. Thus not only will such a tool indicate increases in the functionality and user adoption of the project alternatives proposed by the municipal agencies, but also make the sustainable design and management of road network projects conceivable to the decision-makers, project planners and other stakeholders.

2.6 CONCLUSION AND FUTURE RESEARCH DIRECTIONS

Due to the limited capital funds available to municipal authorities and the higher effect of cost uncertainties on profit compared to environmental performance, the importance of cost parameters requires highlighting during decision-making. The diversity of initial cost optimisation literature in the earliest reported studies on road network project assessment is a testament to the relative importance of initial cost. Since the 1970s, whole-life approaches to optimise cost over entire project life have been extensively discussed and several LCCA frameworks have been proposed.

This state of the art review chapter summarised the existing literature attributes to overcome the issue of real-world adoption and subsequently links and consistency with the respective environmental analyses. National and international interest in reducing environmental burdens and energy input loads of construction projects has generated LCA tools as a knowledge quantification toolbox. LCA has been used in a number of road network projects to examine and enhance the cost and environmental future-proofing performance of design, operation, maintenance, and recycling decisions. Due to this reason, both cost and environmental frameworks have been reviewed in this study recognising that in the future LCCA frameworks must be embedded in the more holistic LCA frameworks.

The current review study examined 36 (extensively) and 97 (supporting) lifecycle cost, and environmental articles, from peer-review journals targeting research on design, management, and recycling of actual real-life road assets. The findings show that:

1. The interest of stakeholders and researchers in "sustainable" road and transit has increased in recent years. However, a majority of studies were conducted in limited geographical contexts (USA and Europe) or constrained focus to only a few stages of the road system lifecycle. Regarding the cost component, several attributes have been proposed by research to achieve cost optimisation of road network projects through LCCA-based comparison of design alternatives (refer to Section 2.3.6).
2. User and embedded social costs of road network projects are significantly higher than the initial capital investments and should be given preference (Figure 2.3 results above). User adoption, dynamic traffic growth patterns, future cash-flows, and user-accorded benefits should be targeted to present the local authority transport planners with the opportunity of reducing the analysis uncertainties due to decision-makers and user prejudice. The challenges and future research directions are elaborated in Section 2.3.7.
3. The time period of analysis examining lifecycle burdens of different project alternatives for roads and the highly subjective nature of the somewhat intangible benefits obtained as a result of investments, no matter how difficult to quantify with a deterministic approach, must also be incorporated and measured explicitly.
4. The use of *recycled and industrial waste materials* has demonstrated potential in increasing cost performance, environmental benefits and resource savings compared to the use of virgin materials, mechanical and fit-for-purpose performance of pavements build with recycled materials should also be investigated for the traffic, distress and fatigue levels.

5. A side benefit of utilising recycled and waste materials in road projects is preventing groundwater contamination and leachate generation in the aquifers located close to landfills, particularly in developing countries.
6. The GHG emissions from construction design alternatives of road network projects utilising recycled materials were comparatively less than virgin materials' utilisation, for example, (Celauro et al., 2017) revealed a maximum of 34.5% CDE reduction (as Figure 2.5 in Section 2.4.3).
7. Resource and energy loads of pavements constructed by material mixes containing lime-stabilised and recycled materials (Celauro et al., 2017) was 34.21% or 3.1 TJ lower than virgin materials alternatives as shown in Figure 2.4 of Section 2.4.3.
8. The *LCIA results* may be presented in a more comprehensible form using normalisation factors and expert-assigned weighting scores in the *interpretation* phase. Stakeholder interest can be addressed through meeting user needs, agency objectives and proper stakeholder engagement through the incorporation of the social component into LCA tools (as discussed in Section 2.5).

The eight items above represent the way forward for a real-world application of lifecycle analysis in road network projects.

2.7 REFERENCES

Abbe, O., & Hamilton, L. (2017). *BRE global environmental weighting for construction products using selected parameters from EN15804*. Hertfordshire, UK: BRE Global Ltd.

US EPA (2004). AP-42: Compilation of air pollutant emission factors: Preliminary document. Retrieved (4/11/2018) from http://www.epa.gov/ttn/chief/ap42/ch11/index.html.

Alqahtani, A., & Whyte, A. (2013). Artificial neural networks incorporating cost significant Items towards enhancing estimation for (life-cycle) costing of construction projects. *Construction Economics and Building, 13*(3), 51-64.

Alqahtani, A., & Whyte, A. (2016). Evaluation of non-cost factors affecting the life cycle cost: an exploratory study. *Journal of Engineering, Design and Technology, 14*(4), 818-834.

American Standard for Testing of Materials (ASTM). (2015). Standard practice for measuring life-cycle costs of buildings and building systems. Vol. E917 - 15, pp. 23. West Conshohocken, PA: ASTM International.

Amirgholy, M., Shahabi, M., & Gao, H. O. (2017). Optimal design of sustainable transit systems in congested urban networks: A macroscopic approach.

Transportation Research Part E: Logistics and Transportation Review, 103, 261-285. DOI: 10.1016/j.tre.2017.03.006.

Ammenberg, J., Baas, L., Eklund, M., Feiz, R., Helgstrand, A., & Marshall, R. (2015). Improving the CO_2 performance of cement, part III: The relevance of industrial symbiosis and how to measure its impact. *Journal of Cleaner Production, 98*, 145-155. DOI: 10.1016/j.jclepro.2014.01.086.

Amos, D. (2006). *Pavement smoothness and fuel efficiency: An analysis of the economic dimensions of the Missouri Smooth Road Initiative*. Retrieved (4/11/2018) from www.library.modot.mo.gov/RDT/reports/Ri05040/or07005.pdf. Missouri, USA.

Anastasiou, E. K., Liapis, A., & Papayianni, I. (2015). Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials. *Resources, Conservation and Recycling, 101*, 1-8. DOI: 10.1016/j.resconrec.2015.05.009.

Andersen, O., Jensen, C. S., Torp, K., & Yang, B. (2013). *EcoTour: Reducing the environmental footprint of vehicles using eco-routes.* Paper presented at the 14th International Conference on Mobile Data Management (MDM). Milan, Italy: IEEE.

Anthonissen, J., Van den bergh, W., & Braet, J. (2016). Review and environmental impact assessment of green technologies for base courses in bituminous pavements. *Environmental Impact Assessment Review, 60*, 139-147. DOI: 10.1016/j.eiar.2016.04.005.

Araújo, J. P. C., Oliveira, J. R., & Silva, H. M. (2014). The importance of the use phase on the LCA of environmentally friendly solutions for asphalt road pavements. *Transportation Research Part D: Transport and Environment, 32*, 97-110.

Associazione Italiana Tecnico Economica Cemento - AITEC. (2016). *Environmental product declaration: Average Italian cement*. Retrieved (4/11/2018) from www.gryphon.environdec.com/data/files/6/11845/epd880it%20Average%20Italian%20cement.pdf. Rome, Italy.

AzariJafari, H., Yahia, A., & Ben Amor, M. (2016). Life cycle assessment of pavements: Reviewing research challenges and opportunities. *Journal of Cleaner Production, 112*, 2187-2197. DOI: 10.1016/j.jclepro.2015.09.080.

Babashamsi, P., Md Yusoff, N. I., Ceylan, H., Md Nor, N. G., & Salarzadeh Jenatabadi, H. (2016). Evaluation of pavement life cycle cost analysis: Review and analysis. *International Journal of Pavement Research and Technology, 9*(4), 241-254. DOI: 10.1016/j.ijprt.2016.08.004.

Baker, M. B., Abendeh, R., Abu-Salem, Z., & Khedaywi, T. (2016). Production of sustainable asphalt mixes using recycled polystyrene. *International Journal of Applied Environmental Sciences, 11*(1), 183-192.

Balaguera, A., Carvajal, G. I., Albertí, J., & Fullana-i-Palmer, P. (2018). Life cycle assessment of road construction alternative materials: A literature review. *Resources, Conservation and Recycling, 132*, 37-48. DOI: 10.1016/j.resconrec.2018.01.003.

Batouli, M., Bienvenu, M., & Mostafavi, A. (2017). Putting sustainability theory into roadway design practice: Implementation of LCA and LCCA analysis for pavement type selection in real world decision making. *Transportation Research Part D: Transport and Environment, 52*, 289-302. DOI: 10.1016/j.trd.2017.02.018.

Bengtsson, J., & Howard, N. (2010). *A life cycle impact assessment method - Part 2: Normalisation*. Retrieved (4/11/2018) from www.bpic.asn.au/download/4ImpactAssessment-Part2Normalisation171212.pdf. Canberra, Australian Capital Territory.

Bengtsson, J., Howard, N., & Kneppers, B. (2010). *Weighting of environmental impacts in Australia*. Retrieved (4/11/2018) from www.bpic.asn.au/download/5Weightings120111a.pdf. Canberra, Australian Capital Territory.

Bird, D. N., Kunda, M., Mayer, A., Schlamadinger, B., Canella, L., & Johnston, M. (2008). Incorporating changes in albedo in estimating the climate mitigation benefits of land use change projects. *Biogeosciences Discuss., 2008*, 1511-1543. DOI: 10.5194/bgd-5-1511-2008.

Biswas, W. K. (2014). Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia. *The International Journal of Life Cycle Assessment, 19*(4), 732-744.

Bloom, E., Canton, A., Ahlman, A. P., & Edil, T. (2017). *Life cycle assessment of highway reconstruction: A case study*. Paper presented at the Transportation Research Board 96th Annual Meeting, Washington DC, United States.

Butt, A. A., & Birgisson, B. (2016). Assessment of the attributes based life cycle assessment framework for road projects. *Structure and Infrastructure Engineering, 12*(9), 1177-1184. DOI: 10.1080/15732479.2015.1086388.

Butt, A. A., Birgisson, B., & Kringos, N. (2016). Considering the benefits of asphalt modification using a new technical life cycle assessment framework. *Journal of Civil Engineering and Management, 22*(5), 597-607. DOI: 10.3846/13923730.2014.914084.

Butt, A. A., Toller, S., & Birgisson, B. (2015). Life cycle assessment for the green procurement of roads: a way forward. *Journal of Cleaner Production, 90*, 163-170. DOI: 10.1016/j.jclepro.2014.11.068.

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews, 29*, 394-416. DOI: 10.1016/j.rser.2013.08.037.

Carnegie Mellon University. (2011). EIO-LCA: Free, fast, easy life cycle assessment. Retrieved (4/11/2018) from www.eiolca.net.

Cass, D., & Mukherjee, A. (2011). Calculation of greenhouse gas emissions for highway construction operations by using a hybrid life-cycle assessment approach: case study for pavement operations. *Journal of Construction Engineering and Management, 137*(11), 1015-1025.

Celauro, C., Corriere, F., Guerrieri, M., Lo Casto, B., & Rizzo, A. (2017). Environmental analysis of different construction techniques and maintenance activities for a typical local road. *Journal of Cleaner Production, 142*, 3482-3489. DOI: 10.1016/j.jclepro.2016.10.119.

CEN EN 15804. (2013). Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. In (Vol. EN 15804:2012+A1:2013 (E), pp. 65). Brussels, Belgium: European Committee for Standardisation.

Chen, J., Zhao, F., Liu, Z., Ou, X., & Hao, H. (2017). Greenhouse gas emissions from road construction in China: A province-level analysis. *Journal of Cleaner Production, 168*, 1039-1047. DOI: 10.1016/j.jclepro.2017.08.243.

Chen, S.-H., & Ni, F. M.-W. (2018). Explore pavement roughness under various funding for the Taiwan provincial highways using LCCA. *International Journal of Pavement Engineering*, 1-8. DOI: 10.1080/10298436.2018.1429610.

Chester, M., Horvath, A., & Madanat, S. (2010). Parking infrastructure: Energy, emissions, and automobile life-cycle environmental accounting. *Environmental Research Letters, 5*(3), 034001. DOI: 10.1088/1748-9326/5/3/034001.

Choi, K., Kim, Y. H., Bae, J., & Lee, H. W. (2015). Determining future maintenance costs of low-volume highway rehabilitation projects for incorporation into life-cycle cost analysis. *Journal of Computing in Civil Engineering*, 04015055.

Choi, K., Lee, H. W., Mao, Z., Lavy, S., & Ryoo, B. Y. (2015). Environmental, economic, and social implications of highway concrete rehabilitation alternatives. *Journal of Construction Engineering and Management, 142*(2), 04015079. DOI: 10.1061/(ASCE)CO.1943-7862.0001063.

Dang, G., & Sui Pheng, L. (2015). *Infrastructure investments in developing economies: The case of Vietnam* (1 Ed.). Singapore: Springer Singapore.

Dinis-Almeida, M., Castro-Gomes, J., Sangiorgi, C., Zoorob, S. E., & Afonso, M. L. (2016). Performance of warm mix recycled asphalt containing up to 100% RAP. *Construction and Building Materials, 112*, 1-6. DOI: 10.1016/j.conbuildmat.2016.02.108.

Dones, R., Bauer, C., Bolliger, R., Burger, B., Faist Emmenegger, M., Frischknecht, R., Tuchschmid, M. (2007). *Life cycle inventories of energy systems: Results for current systems in Switzerland and other UCTE countries*. Dübendorf, Switzerland.

Du, G., Safi, M., Pettersson, L., & Karoumi, R. (2014). Life cycle assessment as a decision support tool for bridge procurement: environmental impact comparison among five bridge designs. *The International Journal of Life Cycle Assessment, 19*(12), 1948-1964. DOI: 10.1007/s11367-014-0797-z.

EAPA/Eurobitume. (2004). *Environmental impacts and fuel efficiency of road pavements*. Retrieved (29/10/2018) from www.eapa.org/usr_img/position_paper/fuel_efficiency_report.pdf.

ECRPD. (2010). *Energy conservation in road pavement design, maintenance and utilisation*. Retrieved (29/10/2018) from www.ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/ecrpd_publishable_report_en.pdf.

EPA. (2005). *Emission Facts: Average carbon dioxide emissions resulting from gasoline and diesel fuel*. Washington, DC.

EPA. (2009). Gasoline and diesel industrial engines-emission factor documentation for AP-42 Section 3.3. Retrieved (29/10/2018) from www3.epa.gov/ttn/chief/ap42/ch03/final/c03s03.pdf.

EPA. (2016). *Inventory of US greenhouse gas emissions and sinks: 1990-2014*.

EPD. (2015). Environmental product declaration: Blast furnace cement (CEM III) produced in Europe. Retrieved (29/10/2018) from www.cembureau.be/sites/default/files/documents/CEMBUREAU%20%20EPD%20CEM%20III%20%20Feb%202015.pdf. European Cement Association.

Eurobitume. (2011). Life cycle inventory: Bitumen (online). Retrieved (29/10/2018) from www.eurobitume.eu/hse/sustainability.

European Commission. (2012). *Commission regulation (EU) no. 459/2012 of 29 May 2012 amending regulation (EC) no. 715/2007 of the European Parliament and of the Council and Commission regulation (EC) no. 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6)*. Brussels, Belgium: European Union.

European Commission. (2014). *Strategy for reducing heavy-duty vehicles fuel consumption and CO_2 emissions*. Brussels, Belgium: European Union.

Fava, J. A., Smerek, A., Heinrich, A. B., & Morrison, L. (2014). The role of the Society of Environmental Toxicology and Chemistry (SETAC) in life cycle assessment (LCA) development and application. In W. Klöpffer (Ed.), *Background and Future Prospects in Life Cycle Assessment* (pp. 39-83). Dordrecht: Springer Netherlands.

Fuglestvedt, J., Berntsen, T., Myhre, G., Rypdal, K., & Skeie, R. B. (2008). Climate forcing from the transport sectors. *Proceedings of the National Academy of Sciences, 105*(2), 454-458. DOI: 10.1073/pnas.0702958104.

Galí, J. (2015). *Monetary policy, inflation, and the business cycle: An introduction to the New Keynesian Framework and its applications* (2nd Ed.). New Jersey, US: Princeton University Press.

Gautam, P. K., Kalla, P., Jethoo, A. S., Agrawal, R., & Singh, H. (2018). Sustainable use of waste in flexible pavement: A review. *Construction and Building Materials, 180*, 239-253. DOI: 10.1016/j.conbuildmat.2018.04.067.

Giang, D. T. H., & Pheng, L. S. (2015). Critical factors affecting the efficient use of public investments in infrastructure in Vietnam. *Journal of Infrastructure Systems, 21*(3), 05014007. DOI: 10.1061/(ASCE)IS.1943-555X.0000243.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A., Struijs, J., & Zelm, R. (2009). ReCiPe 2008, PRé Consultants. *University of Leiden, Radboud University, RIVM, Nijmegen. Den Haag, the Netherlands: VROM (Dutch Ministry of Housing Spatial Planning and Environment)*.

Goh, K. C., & Yang, J. (2009). Developing a life-cycle costing analysis model for sustainability enhancement in road infrastructure project. *Rethinking Sustainable Development: Planning, Infrastructure Engineering, Design and Managing Urban Infrastructure*, 324-331.

Goh, K. C., & Yang, J. (2014). Managing cost implications for highway infrastructure sustainability. *International Journal of Environmental Science and Technology, 11*(8), 2271-2280.

Gray, D., Laing, R., & Docherty, I. (2016). Delivering lower carbon urban transport choices: European ambition meets the reality of institutional (mis)alignment. *Environment and Planning A: Economy and Space, 49*(1), 226-242. DOI: 10.1177/0308518X16662272.

Green, R. J., & Lepkowski, W. (2006). A forgotten model for purposeful science. *Issues in Science and Technology, 22*(2), 69-73.

Guo, S., Hu, J., & Dai, Q. (2018). A critical review on the performance of Portland cement concrete with recycled organic components. *Journal of Cleaner Production, 188*, 92-112. DOI: 10.1016/j.jclepro.2018.03.244.

Han, D., & Do, M. (2015). Life cycle cost analysis on pavement inspection intervals considering maintenance work delay. *KSCE Journal of Civil Engineering, 19*(6), 1716-1726. DOI: 10.1007/s12205-014-1229-0.

Hasan, U. (2015). *Experimental study on bentonite stabilisation using construction waste and slag.* (M.Phil.). Curtin University, Perth, Western Australia, Australia.

Hasan, U., Chegenizadeh, A., Budihardjo, M., & Nikraz, H. (2015). A review of the stabilisation techniques on expansive soils. *Australian Journal of Basic & Applied Sciences, 9*(7), 541-548.

Hasan, U., Chegenizadeh, A., Budihardjo, M. A., & Nikraz, H. (2016a). Experimental evaluation of construction waste and ground granulated blast furnace slag as alternative soil stabilisers. *Geotechnical and Geological Engineering, 34*(6), 1707-1722. DOI: 10.1007/s10706-016-9983-z.

Hasan, U., Chegenizadeh, A., Budihardjo, M. A., & Nikraz, H. (2016b). Shear strength evaluation of bentonite stabilised with recycled materials. *Journal of Geoengineering, 11*(2), 59-73.

Hasan, U., Whyte, A., & Al Jassmi, H. (2018a). Life-cycle asset management in residential developments building on transport system critical attributes via a data-mining algorithm. *Buildings, 9*(1). DOI: 10.3390/buildings9010001.

Hasan, U., Whyte, A., & Al Jassmi, H. (2018b). Public-transport system management: Improving service satisfaction and sustainable uptake. *Manuscript submitted.*

Hood, C., Laing, R., Gray, D., Napier, L., Simpson, A., & Tait, E. (2018). *The application of major road infrastructure to support and drive sustainable urban mobility.* Paper presented at the 1st International Conference on New Horizons in Green Civil Engineering (NHICE-01), Victoria, BC, Canada.

Hoy, M., Rachan, R., Horpibulsuk, S., Arulrajah, A., & Mirzababaei, M. (2017). Effect of wetting–drying cycles on compressive strength and microstructure of recycled asphalt pavement – Fly ash geopolymer. *Construction and Building Materials, 144*, 624-634. DOI: 10.1016/j.conbuildmat.2017.03.243.

Huang, Y., Bird, R. N., & Heidrich, O. (2007). A review of the use of recycled solid waste materials in asphalt pavements. *Resources, Conservation and Recycling, 52*(1), 58-73. DOI: 10.1016/j.resconrec.2007.02.002.

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., . . . van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment, 22*(2), 138-147. DOI: 10.1007/s11367-016-1246-y.

Inyim, P., Pereyra, J., Bienvenu, M., & Mostafavi, A. (2016). Environmental assessment of pavement infrastructure: A systematic review. *Journal of Environmental Management, 176*, 128-138. DOI: 10.1016/j.jenvman.2016.03.042.

IPCC. (2008). *Climate change 2007: The physical science basis. Contribution of Working Group I, II and III to the Fourth Assessment Report of the IPCC* (Core Writing Team, R. K. Pachauri, & A. Reisinger Eds.). Geneva, Switzerland: Intergovernmental Panel on Climate Change.

ISO 14025. (2006). Environmental labels and declarations – Type III environmental declarations – Principles and procedures. Vol. 14025:2006, pp. 25. Geneva, Switzerland: International Organization for Standardization.

ISO 14040. (2006). Environmental management – Life cycle assessment – Principles and framework. Vol. 14040:2006(E), pp. 20. Geneva, Switzerland: International Organization for Standardization.

ISO 21930. (2017). Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services. Vol. 21930:2017, pp. 80. Geneva, Switzerland: International Organization for Standardization.

Jannat, G., E., & Tighe, S. L. (2016). *Investigating life cycle cost analysis to identify a sustainable pavement maintenance and rehabilitation strategy: A case study on Ontario highways.* Paper presented at the Efficient Transportation-Managing the Demand-2016 Conference and Exhibition of the Transportation Association of Canada, Toronto, Ontario.

Jiang, B., Liang, S., Peng, Z.-R., Cong, H., Levy, M., Cheng, Q., Remais, J. V. (2017). Transport and public health in China: The road to a healthy future. *The Lancet, 390*(10104), 1781-1791. DOI: 10.1016/S0140-6736(17)31958-X.

Jingning, Y. (2015, 14-15 June 2015). *The evaluation model of the bridge approach design scheme based on the life.* Paper presented at the 2015 8th International Conference on Intelligent Computation Technology and Automation (ICICTA).

Josa, A., Aguado, A., Heino, A., Byars, E., & Cardim, A. (2004). Comparative analysis of available life cycle inventories of cement in the EU. *Cement and Concrete Research, 34*(8), 1313-1320. DOI: 10.1016/j.cemconres.2003.12.020.

Jullien, A., Proust, C., Martaud, T., Rayssac, E., & Ropert, C. (2012). Variability in the environmental impacts of aggregate production. *Resources, Conservation and Recycling, 62*, 1-13. DOI: 10.1016/j.resconrec.2012.02.002.

Karlsson, C. S. J., Miliutenko, S., Björklund, A., Mörtberg, U., Olofsson, B., & Toller, S. (2017). Life cycle assessment in road infrastructure planning using spatial geological data. *The International Journal of Life Cycle Assessment, 22*(8), 1302-1317. DOI: 10.1007/s11367-016-1241-3.

Klöpffer, W. (2006). The hitch hiker's guide to LCA - An orientation in LCA methodology and application. *The International Journal of Life Cycle Assessment, 11*(2), 142-142. DOI: 10.1065/lca2006.02.008.

Lee, E.-B., Thomas, D., & Alleman, D. (2018). Incorporating road user costs into integrated life-cycle cost analyses for infrastructure sustainability: A case study on Sr-91 corridor improvement project (Ca). *Sustainability, 10*(1), 179. DOI: 10.3390/su10010179.

Lee, J., Edil, T., Tinjum, J., & Benson, C. (2010). Quantitative assessment of environmental and economic benefits of recycled materials in highway construction. *Transportation Research Record: Journal of the Transportation Research Board* (2158), 138-142.

Lippiatt, B. C. (2007). *Building for environmental and economic sustainability technical manual and user guide (BEES 4.0)*. Washington, DC: National Institute of Standards and Technology, Technology Administration, U.S. Department of Commerce.

Lopez-Uceda, A., Ayuso, J., Jiménez, J. R., Galvín, A. P., & Del Rey, I. (2018). Feasibility study of roller compacted concrete with recycled aggregates as base layer for light-traffic roads. *Road Materials and Pavement Design*, 1-13. DOI: 10.1080/14680629.2018.1483257.

Lundberg, K., Miliutenko, S., Birgirsdottir, H., Toller, S., Brattebø, H., & Potting, J. (2013). *LICCER model guidelines report* (4.1).

Marceau, M., Nisbet, M. A., & Van Geem, M. G. (2007). *Life cycle inventory of Portland cement concrete*. Skokie, Illinois.

Meil, J. (2006). *A life cycle perspective on concrete and asphalt roadways: Embodied primary energy and global warming potential*. Ottawa, ON.

Miliutenko, S., Björklund, A., & Carlsson, A. (2013). Opportunities for environmentally improved asphalt recycling: the example of Sweden. *Journal of Cleaner Production, 43*, 156-165. DOI: 10.1016/j.jclepro.2012.12.040.

Mirza, S., & Ali, M. S. (2017). Infrastructure crisis – A proposed national infrastructure policy for Canada. *Canadian Journal of Civil Engineering, 44*(7), 539-548. DOI: 10.1139/cjce-2016-0468.

Mirzadeh, I., Butt, A. A., Toller, S., & Birgisson, B. (2014). Life cycle cost analysis based on the fundamental cost contributors for asphalt pavements. *Structure and Infrastructure Engineering, 10*(12), 1638-1647. DOI: 10.1080/15732479.2013.837494.

Mitchell, C. (2012). *Aggregate carbon demand: The hunt for low carbon aggregate.* Paper presented at the 16th Extractive industry geology conference, Portsmouth, UK.

Mladenovič, A., Turk, J., Kovač, J., Mauko, A., & Cotič, Z. (2015). Environmental evaluation of two scenarios for the selection of materials for asphalt wearing courses. *Journal of Cleaner Production, 87*, 683-691. DOI: 10.1016/j.jclepro.2014.10.013.

Moretti, L., Mandrone, V., D'Andrea, A., & Caro, S. (2018). Evaluation of the environmental and human health impact of road construction activities. *Journal of Cleaner Production, 172*, 1004-1013. DOI: 10.1016/j.jclepro.2017.10.250.

Moretti, L., Mandrone, V., D'Andrea, A., & Caro, S. (2017). Comparative "from cradle to gate" life cycle assessments of Hot Mix Asphalt (HMA) materials. *Sustainability, 9*(3), 400.

Muñoz, I., Campra, P., & Fernández-Alba, A. R. (2010). Including CO_2-emission equivalence of changes in land surface albedo in life cycle assessment. Methodology and case study on greenhouse agriculture. *The International Journal of Life Cycle Assessment, 15*(7), 672-681. DOI: 10.1007/s11367-010-0202-5.

Noori, M., Tatari, O., Nam, B., Golestani, B., & Greene, J. (2014). A stochastic optimization approach for the selection of reflective cracking mitigation techniques. *Transportation Research Part A: Policy and Practice, 69*, 367-378. DOI: 10.1016/j.tra.2014.09.006.

NREL (2011). *United States life cycle inventory database*. National Renewable Energy Laboratory.

Officina dell'Ambiente. (2013). *Dichiarazione Ambientale di Prodotto (EPD) delle materie prime seconde o aggregati di origine industriale*. Italy

Oltean-Dumbrava, C., Watts, G., & Miah, A. (2013). Transport infrastructure: Making more sustainable decisions for noise reduction. *Journal of Cleaner Production, 42*, 58-68. DOI: 10.1016/j.jclepro.2012.10.008.

Pant, P., & Harrison, R. M. (2013). Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: A review. *Atmospheric Environment, 77*, 78-97. DOI: 10.1016/j.atmosenv.2013.04.028.

Pasandín, A. R., & Pérez, I. (2017). Fatigue performance of bituminous mixtures made with recycled concrete aggregates and waste tire rubber. *Construction and Building Materials, 157*, 26-33. DOI: 10.1016/j.conbuildmat.2017.09.090.

Qiao, Y., Dawson, A. R., Parry, T., & Flintsch, G. W. (2015). Evaluating the effects of climate change on road maintenance intervention strategies and life-cycle costs. *Transportation Research Part D: Transport and Environment, 41*, 492-503. DOI: 10.1016/j.trd.2015.09.019.

Rahman, S. M., Khondaker, A. N., Hasan, M. A., & Reza, I. (2017). Greenhouse gas emissions from road transportation in Saudi Arabia - A challenging frontier. *Renewable and Sustainable Energy Reviews, 69*, 812-821. DOI: 10.1016/j.rser.2016.11.047.

Rangaraju, P. R., Amirkhanian, S., & Guven, Z. (2008). *Life cycle cost analysis for pavement type selection*. Washington, DC.

Regional Council Office for Infrastructure and Mobility. (2013). *New official regional price list for public works*. Sicilian Region

RMCG Consultants for Business, C. a. E. (2010). *Sustainable aggregates for South Australia—CO_2 emission factor study*. Victoria, Australia.

RMIT. (2007). *Life cycle assessment tools in building and construction*.

Sadri, A., Ardehali, M. M., & Amirnekooei, K. (2014). General procedure for long-term energy-environmental planning for transportation sector of developing countries with limited data based on LEAP (long-range energy alternative planning) and EnergyPLAN. *Energy, 77*, 831-843. DOI: 10.1016/j.energy.2014.09.067.

Safi, M., Sundquist, H., & Karoumi, R. (2014). Cost-efficient procurement of bridge infrastructures by incorporating life-cycle cost analysis with bridge management systems. *Journal of Bridge Engineering, 20*(6), 04014083.

SAIC, S. A. I. C. (2006). *Life cycle assessment: Principles and practice*. Retrieved (25/08/2019) from www.semanticscholar.org/paper/Work-Assignment-Manager-Curran-Gutierrez/5f99a6900925d095d6251092ce771e07a5df3d42/pdf. Cincinnati, OH

Sánchez, M., López-Mosquera, N., Lera-López, F., & Faulin, J. (2018). An extended planned behavior model to explain the willingness to pay to reduce noise pollution in road transportation. *Journal of Cleaner Production, 177*, 144-154. DOI: 10.1016/j.jclepro.2017.12.210.

Santos, G., Behrendt, H., & Teytelboym, A. (2010). Part II: Policy instruments for sustainable road transport. *Research in Transportation Economics, 28*(1), 46-91. DOI: 10.1016/j.retrec.2010.03.002.

Santos, J., Ferreira, A., & Flintsch, G. (2015). A life cycle assessment model for pavement management: Road pavement construction and management in Portugal. *International Journal of Pavement Engineering, 16*(4), 315-336. DOI: 10.1080/10298436.2014.942862.

Santos, J., Thyagarajan, S., Keijzer, E., Flores, R. F., & Flintsch, G. (2017). Comparison of life-cycle assessment tools for road pavement infrastructure. *Transportation Research Record: Journal of the Transportation Research Board, 2646*, 28-38. DOI: 10.3141/2646-04.

Sharma, A., Saxena, A., Sethi, M., Shree, V., & Varun. (2011). Life cycle assessment of buildings: A review. *Renewable and Sustainable Energy Reviews, 15*(1), 871-875. DOI: 10.1016/j.rser.2010.09.008.

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., & Shapouri, H. (1998). *Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus* (NREL/SR-580-24089). Retrieved (25/08/2019) from www.osti.gov/servlets/purl/658310.

Silva, R. V., de Brito, J., & Dhir, R. K. (2015). The influence of the use of recycled aggregates on the compressive strength of concrete: A review. *European Journal of Environmental and Civil Engineering, 19*(7), 825-849. DOI: 10.1080/19648189.2014.974831.

Simões, D., Almeida-Costa, A., & Benta, A. (2017). Preventive maintenance of road pavement with microsurfacing – An economic and sustainable strategy. *International Journal of Sustainable Transportation, 11*(9), 670-680. DOI: 10.1080/15568318.2017.1302023.

Stranddorf, H. K., Hoffmann, L., & Schmidt, A. (2005). *Impact categories, normalisation and weighting in LCA* (Vol. 78). Luxembourg: Danish Ministry of the Environment - Environmental Protection Agency.

Stripple, H. (2001). *Life cycle assessment of road. A pilot study for inventory analysis*. Gothenburg, Sweden.

Susca, T. (2012). Enhancement of life cycle assessment (LCA) methodology to include the effect of surface albedo on climate change: Comparing black and white roofs. *Environmental Pollution, 163*, 48-54. DOI: 10.1016/j.envpol.2011.12.019.

Svoboda, S. (2006). Note on life cycle analysis. In *Pollution prevention in a corporate strategy* (pp. 9). Ann Arbor, Michigan: National Pollution Prevention Centre for Higher Education, University of Michigan Press.

Toller, S., Kotake, M., & Nyholm, S. (2014). Klimatkalkyl version 2.0 – Beräkning av infrastrukturens klimatpåverkan och energianvändning i ett livscykelperspektiv (in Swedish) (Klimatkalkyl version 2.0 – calculation of the infrastructure's impact on climate change and energy use in a life cycle perspective). *Trafikverket, Sweden*.

Treloar, G. J., Love, P. E., & Crawford, R. H. (2004). Hybrid life-cycle inventory for road construction and use. *Journal of Construction Engineering and Management, 130*(1), 43-49.

Trigaux, D., Wijnants, L., De Troyer, F., & Allacker, K. (2017). Life cycle assessment and life cycle costing of road infrastructure in residential neighbourhoods. *The International Journal of Life Cycle Assessment, 22*(6), 938-951. DOI: 10.1007/s11367-016-1190-x.

Turk, J., Mauko Pranjić, A., Mladenovič, A., Cotič, Z., & Jurjavčič, P. (2016). Environmental comparison of two alternative road pavement rehabilitation techniques: cold-in-place-recycling versus traditional reconstruction. *Journal of Cleaner Production, 121*, 45-55. DOI: 10.1016/j.jclepro.2016.02.040.

Union Nationale des Producteurs de Granulats – UNPG. (2012). Module d'informations environnementales de la production de granulats recyclés. Paris, France: Union Nationale des Producteurs de Granulats.

Wang, C., & Wei, Y. (2015). A study on calculation method of CO_2 emission discharged from the producing of asphalt. *Northern Traffic, 6*, 90-93.

Wang, M. Q. (2011). Greenhouse gases, regulated emissions, and energy use in transportation. Retrieved (25/08/2019) from www.transportation.anl.gov/software/GREET/. Argonne National Laboratory.

Wang, T., Lee, I.-S., Kendall, A., Harvey, J., Lee, E.-B., & Kim, C. (2012). Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. *Journal of Cleaner Production, 33*, 86-96. DOI: 10.1016/j.jclepro.2012.05.001.

Wang, T., Xiao, F., Zhu, X., Huang, B., Wang, J., & Amirkhanian, S. (2018). Energy consumption and environmental impact of rubberized asphalt pavement. *Journal of Cleaner Production, 180*, 139-158. DOI: 10.1016/j.jclepro.2018.01.086.

Wennström, J., & Karlsson, R. (2016). Possibilities to reduce pavement rehabilitation cost of a collision-free road investment using an LCCA design procedure. *International Journal of Pavement Engineering, 17*(4), 331-342.

Whyte, A. (2015). *Integrated design and cost management for civil engineers*. New York, USA: CRC Press.

Wu, D., Yuan, C., & Liu, H. (2017). A risk-based optimisation for pavement preventative maintenance with probabilistic LCCA: A Chinese case. *International Journal of Pavement Engineering, 18*(1), 11-25. DOI: 10.1080/10298436.2015.1030743.

Yu, B., & Lu, Q. (2012). Life cycle assessment of pavement: Methodology and case study. *Transportation Research Part D: Transport and Environment, 17*(5), 380-388. DOI: 10.1016/j.trd.2012.03.004.

Yu, B., & Lu, Q. (2014). Estimation of albedo effect in pavement life cycle assessment. *Journal of Cleaner Production, 64*, 306-309. DOI: 10.1016/j.jclepro.2013.07.034.

Yu, B., Wang, S., & Gu, X. (2018). Estimation and uncertainty analysis of energy consumption and CO_2 emission of asphalt pavement maintenance. *Journal of Cleaner Production, 189*, 326-333. DOI: 10.1016/j.jclepro.2018.04.068.

Zhang, Y., & Liu, W. (2015). Analysis of energy consumption and CO_2 emission of asphalt pavement construction materials in construction period. *Highway, 1*(2015), 100-107.

Zhao, J., Zheng, Z., Cao, Z., & Yao, J. (2016). Spatial and causal analysis of discrepancies in CO_2 emission factors for cement production among provinces in China. *Resources Science, 38*, 1791-1800.

Zimmerman, K., Smith, K., & Grogg, M. (2010). *Applying economic concepts from an LCCA to a pavement management analysis*. Paper presented at the 89th Annual Meeting of the Transportation Research Board, Washington, DC.

CHAPTER 3

LITERATURE REVIEW ON APPLICATION OF AUTONOMOUS VEHICLES AND TECHNOLOGY FOR ROAD TRANSPORT SYSTEMS

3.1 ABSTRACT

The efficient interconnectivity of municipalities has become an intrinsic feature of smart cities, yet public transport systems are rarely optimised to reduce environmental burdens in different facets of their operations. Mobility is already experiencing a revolution as rapid computing, advanced communications, computers, and servers with big data capacities, efficient networks of sensors and signals are developing value-added applications such as intelligent spaces and autonomous vehicles. Another new technology that is both promising and might even be pervasive for faster, safer and more environmentally-friendly public transport is the development of autonomous vehicles (AVs). This chapter aims to understand the state of the current research on the artificially intelligent transportation system (ITS) and AVs through a critical evaluation of peer-reviewed literature. Findings revealed that the majority of existing research (around 82% of studies) focused on AVs. Results show that AVs can potentially reduce more than 80% of pollutant emissions per mile if powered by alternate energy resources. Not only can private vehicle ownership be cut down by bringing in ridesharing but the average vehicle miles travelled (VMT) should also be reduced through improved PT. The main benefits of AV adoption were reported in the literature to be travel time, traffic congestion, cost and environmental factors. Findings revealed barriers such as technological uncertainties, lack of regulation, unawareness among stakeholders and privacy and security concerns, along with the fact that lack of simulation and empirical modelling data from pilot studies limit the application. AV–PT was also found to be the most sustainable strategy in dense urban areas to shift the heavy trip load from private vehicles.

3.2 INTRODUCTION

Buzz around autonomous mobility, intelligent transportation system and smart cities has propelled the ventures of personal and public transit into new domains. In its early purview, concept of autonomous vehicles was integrated with urban bus transit in the form of the United States DoT's Vehicle Assist and Automation (VAA) programme (tested with 1 m spaced permanent magnetic markers over 3 mile route in maintenance yard) and California's PATH, a completely automated highway bus fleet in 2003. While the VAA tests on buses were performed in 2014 by operating an equipped bus for 6-8 hours/day, completely autonomous bus transit operations have yet to be developed as most current systems require drivers with the partially automated speed or lane controls (Liu, Fagnant, & Zhang, 2016). At present, automated vehicles are categorised by the NHTSA (IHS Automotive, 2014; NHTSA, 2013; Santos et al., 2011) according to their automation functionality into five levels of increasing automation (ranging from zero automation to a completely unmanned autonomous vehicle). For example, the VAA programme demonstrated a Level 2 in Oregon, precision docking and lane adherence by the steering automation, while manned braking and throttling of on-transit bus. Figure 3.1, prepared after Liu (2016), covers the state of research on the autonomous transportations systems in urban areas around the world based upon the vehicular size, capacity and operational features.

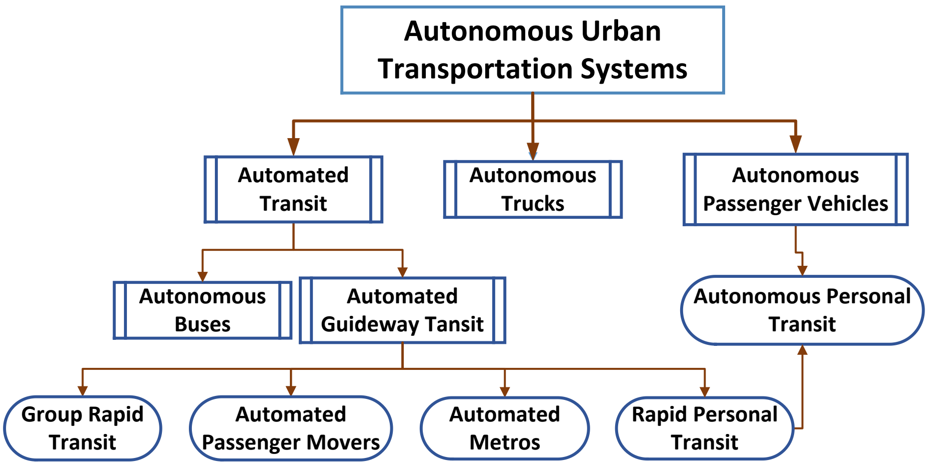


Figure 3.1 Mode classification of autonomous transport systems

On the note of autonomous buses, CityMobil2 is an innovative public transportation project, tested at the University La Sapienza in Rome to investigate the feasibility of autonomous public transit by studying shared and on-demand mobility on automated guideway transit, road user interactions and bus user experiences, where a considerably positive outlook from the public was observed. Automated guideway transit was defined by Liu (2011) and Liu et al. (2016) as a mode of urban transportation where dedicated tracks are used for the operation of completely autonomous vehicles. In the case of autonomous personal transportation, companies such as Volvo and Nissan have expressed interest in commercially marketing autonomous vehicles by the year 2020 (Massey, 2012; Nissan Motor Company, 2013). While according to Google co-founder Sergey Brin, autonomous vehicles may be a reality on U.S roads within the next five years (O'Brien, 2012) or so. Researchers such as Wang (2006) and Fagnant and Kockelman (2015) proposed that operation of autonomous personal cars may result in safer and less congested travel. As already evidenced by the increased fuel savings, road capacity, accident aversion and lower emissions due to the introduction of some level of automation (e.g., assisted parking and adaptive cruise control) in newer cars. Apart from fully automated cars such as MIT's fully autonomous Land Rover LR3 Talos (Leonard et al., 2008), shared autonomous vehicles (SAVs) has also been researched as an extension of the emerging e-hail or car-sharing (Greenblatt & Shaheen, 2015). Fagnant and Kockelman (2014) simulated the behaviour of these SAVs and observed that technological barriers of completely operational and affordable autonomous vehicles, as well as regulations regarding commercial automated taxi service licensing, are still to be drafted.

In the domain of on-demand mobility, Tang, Wang, and Miao (2006) have respectively expressed the ability of an overall intelligent transportation system (ITS) in improving user behaviour, air quality, travel time, productivity and safety propelled by the revolution in the fields of electronics, robotics, information technology and cybernetics. Due to logical and temporal constraints, accurate recognition and distinction between objects and humans on a road are most critical for autonomous vehicles on urban roads followed by complex manoeuvre, blocked routes, congested traffic operations and obeying traffic rules (Kuwata et al., 2009), as well as the overall sustainability of commissioning AVs from public investments.

The purpose of the current chapter is to perform a critical review of peer-reviewed research in the field of vehicular automation to map the status of autonomous transport, specifically to ask the question of how driverless vehicles are changing the way we think of mobility. The question of smart cities and technological transformation of road systems is also closely linked with the triple-bottom-line sustainability approach: social, cost and environment. The study is intended to serve as a platform for a pilot study on the exploration of artificially intelligent urban green transport with the city of Abu Dhabi as a case study. Keywords: autonomous cars, green transport, smart cities, intelligent urban transportation and ITS, were entered and the studies returned from Google Scholar and ScienceDirect were analysed, described in the following sections.

3.3 DIMENSIONS OF ARTIFICIALLY INTELLIGENT TRANSPORT SYSTEMS

This section discusses the primary dimensions of artificially intelligent transport systems (Figure 3.2) across the existing literature as on-demand mobility, shared autonomous vehicles, autonomous public bus transport, lane control, and vehicular guidance systems. The benefits of artificially intelligent transport systems for travel time reduction, easing congestions and incident management are also discussed in this section. A general finding was that the majority of existing studies on the performance evaluation of such systems largely focused on programming and technological aspects, public and transport law and profit generation. Although demand management was also extensively studied recently, little attention is paid to the long-term impact of implementing artificially intelligent transport systems and the resulting travel pattern variations particularly in the context of sustainability performance evaluations.

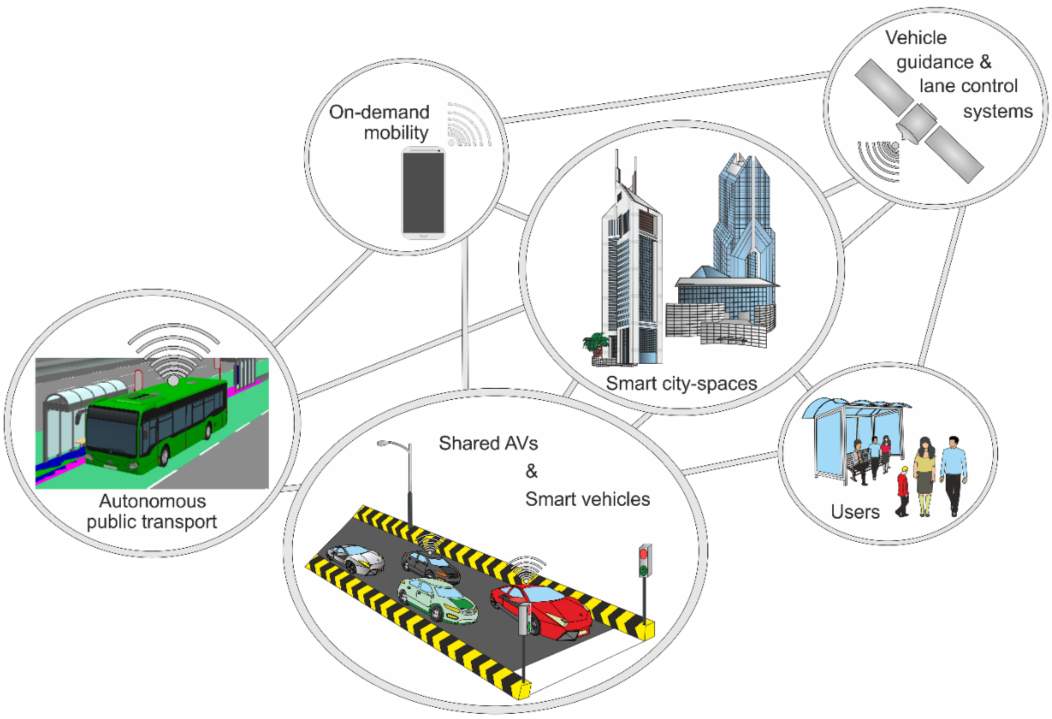


Figure 3.2 Dimensions of a connected AI transport system: on-demand mobility, smart city-spaces, users, public transport and vehicle guidance systems

3.3.1 On-demand mobility solutions

The popularity of on-demand mobility (e.g., Uber, Lyft, Hailo, etc.) has been increasing recently. These programmes are aimed to replace private automobile trips from vehicle ownership to a rental service that is run on-demand. Fagnant and

Kockelman (2014) have commented on the increasing popularity of these services, for example, the users in United States double every year or two. Greenblatt and Shaheen (2015), reviewed automated on-demand mobility and associated environmental impacts. They found that around eighty percent or more GHG emissions and energy use reduction may be observed with the use of autonomous vehicles. They also proposed that social benefits (lower VMTs and ownership reduction), environmental load suppression, land-use, and mass transit benefits may be achievable through on-demand mobility. Adding AVs may result in further reduction as smaller and more efficient SAVs become a reality as these vehicles may result in overcoming ride-sharing obstacles of users travelling to a reserved spot to access rental cars.

3.3.2 Shared autonomous mobility solutions

Preceded by existing commercial Car-sharing rental services (e.g., ZipCar and Car2Go), probably one of the most widely researched applications of autonomous vehicles as a solution to urban transit problems is the SAV. The concept of shared car mobility came from the relatively low ratio between the number of private vehicles owned and the actual number of vehicles in use during a typical day. Santos et al. (2011) suggested that approximately 10% of vehicles (models > 10 years) are on road on a representative day, which became slightly higher (17%) when newer vehicles (models ≤ 10 years) were considered.

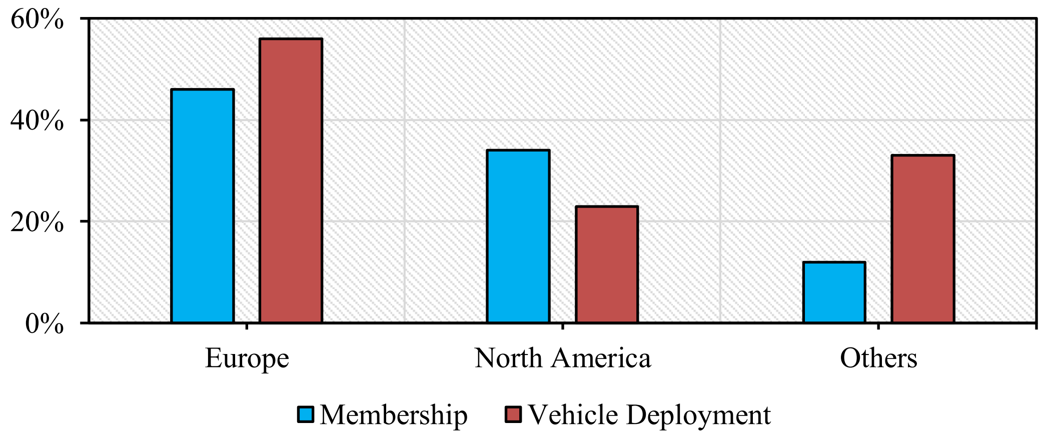


Figure 3.3 Percentile membership and vehicle deployment distribution of shared vehicle services

Buying more cars is not the mobility solution for the present trip demands in most areas and a transitioning towards a subscribed or pay-as-you-go vehicle in suitable areas may have more economical and environmental viability as the vehicle kilometres travelled are reduced. Shaheen and Cohen (Summer 2013) found that ride-sharing users increased to be 890,000 in U.S. by 2013 from 12,000 in 2002. A follow-up survey, Shaheen and Cohen (2016), found that around 104,000 shared vehicles are currently serving 4.8 million users across 1,531 cities globally, with the fleet distribution in Figure 3.3, with Mexico and Italy accounting for the highest (131:1) and second-highest (107:1) member-vehicle ratios.

To the end of on-demand autonomous mobility or aTaxis as dubbed by Kornhauser (2013) complementing passenger transit in urban centres, a number of research works have been commissioned. For example, the replacement of private cars in metropolitan areas by SAV taxi services was analysed by Ford (2012) and Kornhauser (2013) where passengers were required to travel to taxi stations, similar to the Car2Go services. Rigole (2014) in the metropolitan Stockholm region, focused on developing a framework to assist in dynamically allocating SAVs. This was achieved through the use of present road network depiction, private commute-demand, and multi-criteria evaluation (i.e. fleet size, travelling and waiting times), rerouting vacant vehicles based on varying values of these variables. Lifecycle assessment was performed to evaluate the environmental burdens of both traditional (diesel and petrol) and electric cars. Their results showed that by only utilising under 10% parking spots and private vehicles, SAV transport system can provide highly efficient "door-to-door" services. However, these results are exceedingly hampered by the decision of users to accept ride-sharing. On average around 15% increase in passenger travel times was expected along with lower traffic congestion and environmental impacts, which greatly increased as ride-sharing was replaced with vacant car drives between trips. Results are compatible with the market need for a shared vehicle which gave rise to projects such as ZipCar (Holmes, 2015) and is supported through Android/iPhone apps for identifying vehicle location. Affordability has been cited (Liu et al., 2016) as the primary driving force for the popularity of ZipCar with millennials and especially in densely populated urban areas, with approximately 470 cities supported by 10,000 cars or so. Therefore, potential application of SAVs on the mobility spectrum is promising.

Evaluation of the benefits of on-demand autonomous vehicles was conducted by Fagnant and Kockelman (2015). Approximately 8.7% of the distances travelled by the 56,000 SAVs every day were found to be vacant, reduced to 4.5% by allowing for carsharing. Three market penetration rates: 10%, 50%, and 90%; with vehicle miles travelled (VMT) per AV 10% higher at 90% and 20% higher at 10% market penetration were used, for representing the introduction of new technology and probably a more accepting public perception over the years. The study used discount rate and dollar-value of passenger vehicle time based upon the cost data (17 USD/person-hr) and, the 2020 traffic flow patterns, of Schrank, Eisele, and Lomax (2012), as baseline. Results illustrated benefits in the form of reduced demand for parking, fuel savings and lowered congestion levels. Shladover, Su, and Lu (2012) proposed that congestion may fell in freeways by approximately 60% if market penetration is assumed at 90%. The study proposed that a careful evaluation of market penetration and public perception is the key to the efficient operation of SAVs.

3.3.3 Autonomous public bus transport

Personalised rapid transport (PRT) is currently being researched as a sustainable transit solution with the use of electric autonomous single cabin vehicles in a pilot study by Masdar Institute of Science and Technology, Abu Dhabi (Alessandrini et al., 2015). However, the future vision of public transport in smart cities is expected to harness the potential promised by automation, as discussed earlier.

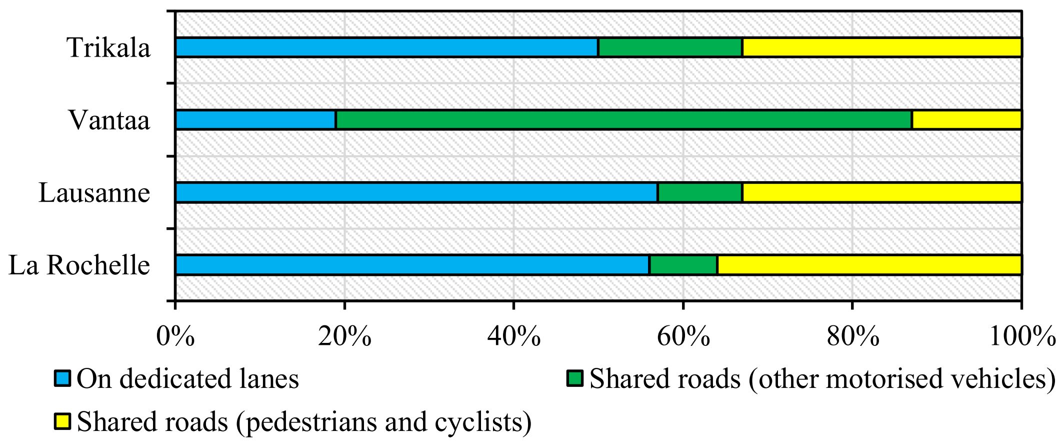


Figure 3.4 Stakeholder response distribution towards autonomous bus mode choices

The initial feedback received from the VAA field tests included lesser stress experienced by drivers and the ability of the steering system to aid the drivers in complex manoeuvre through narrow rights-of-way. Stakeholder responses from the CityMobil2 project (Alessandrini & Mercier-Handisyde, 2016) has shown as overwhelmingly predisposal towards autonomous vehicles, with the exception of

Vantaa respondents, operating on dedicated lanes as illustrated in Figure 3.4 (Alessandrini & Mercier-Handisyde, 2016).

The potential for automated buses to change the fundamental nature of public transport has been promising but design sensibility and accounting for the social implications are considerably important for planners. Understanding that the technological Darwinism has produced an overt emphasis over advanced mobility, projects such as Atkin's Venturer in Bristol for testing sensors and communication networks of primarily AV buses, ARUP's UK Autodrive, and the 8 million GBP government and consortium members led three years "Innovate UK" urban deliveries project in Greenwich. One of the most notable projects on driverless vehicles is the safer, cleaner and innovative transport being researched by the Transport Research Laboratory's GATEway (Greenwich Automated Transport Environment) project which uses 8-10 passengers' capacity vehicles. In all phases of trials, public engagement and feedback were collected to further ascertain the public perception regarding autonomous vehicles, further discussed in the perception section of this study.

3.3.4 Lane control, remote sensing and vehicular guidance system

A common feature of paved roads is lane control, such as painted boundaries, markers, and road signs. ITS application for lane control, dynamic message signs and remotely radio-frequency identification (RFID)-type controllable sensors have been cited by researchers (Wang, Zeng, & Yang, 2006) as a critical feature of modern cities. Better communication between ITS sensors and AVs may be observed which can reduce average vehicle mileage, crashes and congestions. Big data and machine learning can result in intelligent control, traffic pattern recognition, embedded markers (similar to barcodes), cognition of road users and adapting according to traffic behaviour. According to Wang (2005), agent-based control of transport management on an on-demand basis may be a more cost-effective and reliable alternate to traffic control while providing flexibility. Wang (2006) commented that instead of traditional reliance on traffic lights, cooperative intelligent-space technology may be implemented at intersections over ad-hoc networks. Sustainable ITS controlled transport systems may also account for social and climatic variations (Builder & Bankes, 1991; Wang & Tang, 2004) through a comprehensive agent-based model.

There are many sensor-based vehicle guidance systems currently available for partially automated assistance in navigation, crash aversion and warnings in lane departures such as adaptive cruise control (ACC). Shladover et al. (2012) estimated that the affective capacities of road lanes may be increased by up to 80%, depending upon market share. KPMG and Centre for Automotive Research (2012) found that traffic congestion reduction depend on automated driving and active vehicle-environment sensing from road sensors. For instance, vehicle to road (e.g., traffic signals) and vehicle to vehicle communications to increase system performance and improve operational safety, and may also improve system-wide sustainability performance.

3.3.5 Traffic congestion and travel time reduction

So far, it has been discussed that the majority of travel time and environmental burdens to users on a road network come from the supported traffic (Huang, Bird, & Bell, 2009) and a transit system may considerably reduce the emissions (Zhou et al., 2010). The cost of user time delays has been found by Rister and Graves (2002) as a significant contributor to the total road operation cost. Gupta, Kalmanje, and Kockelman (2006) and Litman (2013) have proposed that if the demand-management strategies are not carefully developed, the miles travelled by road users are expected to greatly increase. Traffic flow patterns are expected to fluctuate if effective vehicle-environment communication and autonomous vehicles are to become a reality in future smart cities. Research on connected automated vehicles (CAVs), has been proposed in the 2015 Automated Vehicles Symposium (Arem et al., 2016) to heavily rely on their impact on network routing, traffic control, and bottleneck capacity recognition. Utilisation of adaptive cruise control and ITS-based monitoring of traffic flow has been reported by Atiyeh (2012) to increase traffic speeds (8-13%) and fuel savings (23-39%).

Similar to the agent-based model for ITS road systems, described earlier, another study on agent-based modelling for SAVs was conducted by Fagnant and Kockelman (2014). They studied the environmental benefits of SAVs comparative to the traditional privately-owned vehicles by mimicking trips based on real-time travelling profiles, departure and destination times, and origin and destinations in a grid-based urban setting. The case study model, run over 100 days, was equipped with the relocation of unused vehicles (observed for some vehicles when the model was run), varying fleet size, service and trip generation distribution, and congestion levels.

Relocation of SAVs resulted in 11% higher travel as vacant vehicles moved, showing dependence on user concentration, but may replace 10 times of privately owned vehicles. Nonetheless, model predicted that it may be more suitable for reducing traffic congestion if a dynamic SAV relocation strategy is applied followed by use of alternate source of energy and newer vehicles in the network to reduce environmental loads.

3.4 BARRIERS: THE QUESTION OF SUSTAINABILITY

3.4.1 Cost and environment

Cities around the world are constantly pursuing energy independence and climate conservation. Luers et al. (2007) projected that in order to avoid climatic changes, GHG emissions must be considerably reduced. While Shaheen and Lipman (2007) found the transport sector to be the primary source of emissions (14%) globally and as such, the sustainability problems in road projects should be addressed. Although, there have been various programmes, e.g., Green Highway Partnership and Greenroads (Clevenger, Ozbek, & Simpson, 2013; Green Highways Partnership, 2007; Muench et al., 2011), for promoting partnership and innovation in sustainable transportation planning. Recycling of pavement materials (Whyte, 2012), e.g., ~99% in Japan (Kawakami et al., n.d.), and introduction of newer materials such as warm-mix asphalt (Barros & Dmytrow, 2009) have increasingly become popular. However, as Clyne (2010) commented, the impacts on performance of pavements are still uncertain.

The implementation of ITS as a tool for increasing sustainability of urban roads is uncertain. A lifecycle assessment study of Tupper et al. (2012) on the urban South Carolina interstate found that an ITS strategy can reduce CO_2 emissions (992 tonnes over 2 years) more than five times than any of the Greenroads recommended greener construction stage strategies, explained earlier. The study emphasised over the importance of ITS as a sustainability tool, especially since the fuel consumption reductions from ITS were 30 times higher than all four strategies combined over 8 years of repaving. They further iterated that despite the emphasis of transportation agencies on strategies such as WMA (Brown, 2008; Walker, 2009), ITS can potentially provide higher savings. It should be noted that the study did not account for the cost parameter of sustainability, nonetheless, these environmental savings were noted for the implementation of only one ITS strategy. Further application of strategies such as intelligent transportation spaces, automated transit gateways, and AVs may result in higher savings. For example 4,000 USD/year/AV from social benefits of parking, fuel efficiency, travel time and crash aversion as Fagnant and Kockelman (2015) reported.

3.4.2 Policy and technological shortcomings

Due to the substantial uncertainties associated with the long-term impacts of big data and autonomous vehicles policy drafting is difficult. Srinivasan, Smith, and Milakis (2016), through a metropolitan case study from the Netherlands, found that despite the uncertainties associated with AV implementation, there is a need for encouraging systematic approach-based pilot projects to study the long-term impacts. Researchers such as Liu et al. (2016) asserted the need for developing a consensus on the transformation of the traditional transport systems through vehicle automation technologies. Future research on autonomous vehicles, particularly autonomous public transport should address how these alternate vehicle technologies can be adopted to reduce overburden on personalised transit and achieve city-wide sustainability goals of municipal authorities in congested and heavy traffic density cities around the world.

3.4.3 Public perception

Manufacturers like Google currently plan to release AVs by the year 2020 (Greenblatt & Shaheen, 2015), which may result in safer and more efficient use of road. Even though Google has logged over 1.1 million kilometres (Anthony, 2014) through AVs on public roads in California, high costs limit the spread of autonomous cars on the consumer market (Economist Technology Quarterly, 2012; KPMG & Centre for Automotive Research, 2012). A challenge that may be addressed through autonomous public transport if public perception is duly considered and initiatives to promote a general understanding of autonomous public transport (e.g., buses) – mainly safety features are conveyed to the users. Adoption of closely travelling autonomous buses on dedicated lanes may increase the capacity of lanes (Tientrakool, Ho, & Maxemchuk, 2011), which may in return fuel savings as less brake-accelerate manoeuvre will be needed. Preliminary data from the CityMobil2 automated bus project has revealed that there is currently positive attitude from the general public, as Figure 3.5 (Alessandrini & Mercier-Handisyde, 2016) illustrates.

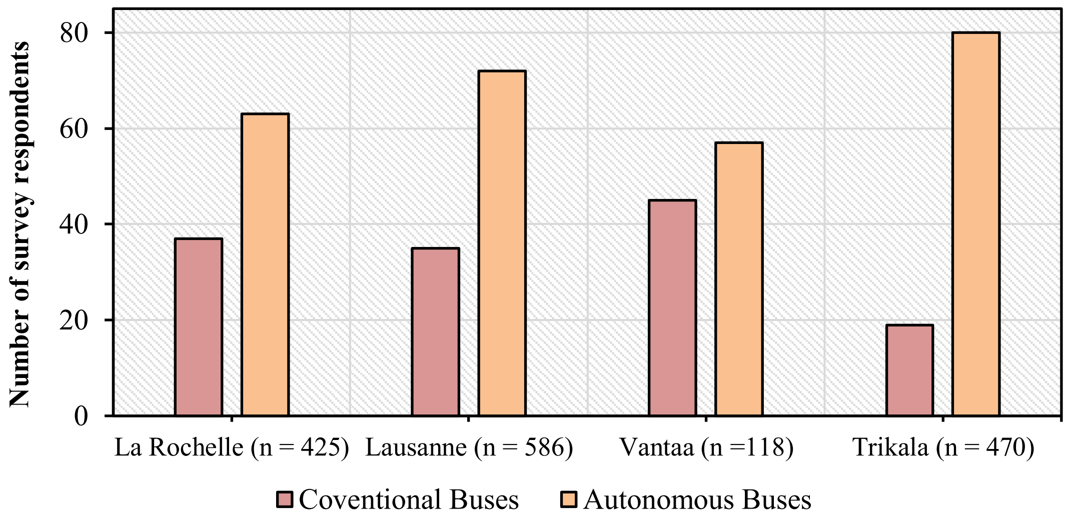


Figure 3.5 Public responses on mode choices: conventional vs. autonomous buses under the same route parameters

Information sharing initiatives such as Sustainability Mobility and Accessibility Research and Transformation (Zielinski, 2015) are aimed at carefully analysing the trade-offs between sustainability and innovative urban mobility. Other programmes such as the global mobility start-up database Mobi (Liu et al., 2016) and smartphone app-powered commercial door-to-door shuttle service of Transdev also aim to provide multi-modal solution to the urban transport problem. Nevertheless, most government agencies have yet to catch up to the automated transit technology. For example as Liu et al. (2016) report, the vagueness in the Federal Transit Administration and ITS Joint Program Office-led on-demand mobility programme's description of newer multi-modal mobility concepts and absence of autonomous mobility from the U.S. DoT strategic plan (U.S. Department of Transport, 2015). Due to the decreasing reliance of millennial travellers on single-occupancy vehicles and trip load divergence towards public transport, researchers (Alessandrini et al., 2015; Lesh, 2015; Liu et al., 2016; and Polzin, 2016) have commented that transport agencies should also focus on: long-term autonomous transit, SAVs, connected AVs and exclusive right-of-way for AVs. Moreover, building upon the success of projects like Morgan Town People mover (Raney & Young, 2004), ideas like automated bus rapid transit, an automated vehicle serving >15 travellers on dedicated lanes (Liu, 2016; United States Government Publishing Office, 2011), may become the new mode choice for mass transit.

3.5 Future research directions: Stakeholder engagement and integrating multiple criteria for sustainable adoption of AVs

Although at present the procurement and purchase costs of private and public AVs may be a concern (López-Lambas and Alonso, 2019) for practical implications, the research covered in this chapter shows that these high initial costs may be offset by life-cycle ownership costs, specifically fuel cost savings. Environmental impacts notwithstanding, the travel time and ride comfort factors may be the primary drivers of AV adoption for public transport and ride-sharing transit systems, and as such, should be focused in future research. It is also uncertain how the mode choice of travellers shall be affected by the introduction of ITS and AV-based transportation systems, specifically as an alternate public transit service.

Similarly, the detailed impact of AV–PT, private AV cars and SAVs on the daily operation of traffic fleet as well as life-cycle implications need to be empirically calculated. Scenario analyses of various AV adoption methods and fuel sources should be performed with the simultaneous engagement of stakeholders (government, users and private sectors). Researchers (Lopes and Duarte, 2013; Santos et al., 2015) have highlighted that the multi-criteria impacts covered in the sustainability triple-bottom-line approach should be utilised to asses the overall impact of real-world adoption. Even with the uncertainties associated with the deployment and operation of autonomous public transport, it might be apt for the decision- and policy-makers to consider AVs as part of the sustainability investigations of urban public transportation solutions. The actual implication of AV adoption on the exisiting traffic fleet may be investigated through detailed traffic simulation modelling to estimate the benefits compared to the conventional vehicles for public transit. Given that multiple qualitative and quantitative criteria of cost, environment, social acceptance (i.e., potential need/demand by users), stakeholder preference, etc., are to be integrated to calculate the actual benefit using detailed data inventory, a multi-crite approach may be utilised for feasibility assessment.

3.6 Conclusion

The situation of future transport systems is complicated by the social, environmental, political, and more so, budgetary, constraints of transportation agencies, making sustainability the primary concern. Literature review on intelligent transport systems and autonomous vehicles, to explore the future outlook, was conducted in this chapter. Results showed that automated urban mass transit may also be a promising alternative to personalised travel, where users can either subscribe or operate on a pay-as-you-go basis without the need for a driver or attendant for the service operation. The expected benefits of AV–PT are the reduction of land-use, cessation of traffic congestion, low user costs, fewer time delays and environmental burdens, mobility solutions to elderly and disabled people in the form of efficient and safe transport. The integration of shared mobility solutions with automated gateways and autonomous PT systems has also been investigated in the literature to certain degrees. Traffic simulation, analytical reviews and stated-preference surveys and limited filed data have been used to perform scenario analysis of various AV-based PT and ITS strategies in the existing transport literature. However, the review also found that the majority of literature lacked in concise integration of stakeholder engagement, real-world traffic data, cost and emission models and detailed traffic simulation modelling for life-cycle implications of ITS and AV transport.

Results also show that barriers regarding the technical, technological and policy-making exist for the practical, large-scale implementation of automated transit. Fragmentation of the government agencies involved, the distance between the research and stakeholder spectrums and divided public opinion further complicates the situation. The sustainability triple-bottom-line approach may be used for determining the long-term impacts of autonomous transit. As such, this study, which acts as a platform for describing the current state and need for a life-cycle analysis method for evaluating the application of autonomous rapid PT, identifies that there may be a potential for autonomous bus rapid transit (BRT) services to increase the productivity, energy and fuel savings capacity, as well as safety, of the urban transportation systems.

3.7 REFERENCES

Alessandrini, A., Campagna, A., Delle Site, P., Filippi, F., & Persia, L. (2015). Automated vehicles and the rethinking of mobility and cities. *Transportation Research Procedia, 5*, 145-160.

Alessandrini, A., & Mercier-Handisyde, P. (2016). *CityMobil 2 experience and recommendations* (pp. 52). Retrieved (25/08/2019) from www.citymobil2.eu/en/upload/Deliverables/PU/CityMobil2%20booklet%20web%20final_17%2011%202016.pdf.

Anthony, S. (2014). Google's self-driving car passes 700,000 accident-free miles, can now avoid cyclists, stop at railroad crossings. *ExtremeTech*. Retrieved (25/08/2019) from www.extremetech.com/extreme/181508-googles-self-driving-car-passes-700000-accident-free-miles-can-now-avoid-cyclists-stop-for-trains.

Arem, B. v., Abbas, M. M., Li, X., Head, L., Zhou, X., Chen, D., Orosz, G. (2016). Integrated traffic flow models and analysis for automated vehicles. In G. Meyer & S. Beiker (Eds.), *Road Vehicle Automation 3* (1 ed., pp. 249-258). Switzerland: Springer International Publishing.

Atiyeh, C. (2012). Predicting traffic patterns, one Honda at a time. MSN Auto.

Barros, C. B., & Dmytrow, S. (2009). Weather-mix asphalt: Warm approach works in California, where climates of all kinds play. *Roads & Bridges, 47*(4), 26-28.

Brown, D. (2008). Warm mix: The light is green. *Hot Mix Asphalt Technology, 13*(1), 20-32.

Builder, C. H., & Bankes, S. C. (1991). Artificial societies: A concept for basic research on the societal impacts of information technology. In (pp. 26). Santa Monica, California: RAND Corporation.

Clevenger, C. M., Ozbek, M. E., & Simpson, S. (2013). *Review of sustainability rating systems used for infrastructure projects.* Paper presented at the 49th ASC Annual International Conference.

Clyne, T. (2010). *Warm mix asphalt*. Paper presented at the North Dakota Asphalt Conference, Bismark, North Dakota. www.ndltap.org/events/asphalt/downloads/2010warmMix.pdf.

Economist Technology Quarterly: Q3. (2012). Inside story: Look, no hands. *The Economist,* pp. 17-19. Retrieved (25/08/2019) from www.economist.com/node/21560989.

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice, 77*, 167-181. DOI: 10.1016/j.tra.2015.04.003.

Fagnant, D. J., & Kockelman, K. M. (2014). The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation Research Part C: Emerging Technologies, 40*, 1-13. DOI: 10.1016/j.trc.2013.12.001.

Ford, H. J. (2012). *Shared autonomous taxis: Implementing an efficient alternative to automobile dependency.* (BSc Science and Engineering). Princeton University, Princeton, New Jersey.

Green Highways Partnership. (2007). Retrieved (25/08/2019) from www.greenhighwayspartnership.org/index.php

Greenblatt, J. B., & Shaheen, S. (2015). Automated vehicles, on-demand mobility, and environmental impacts. *Current Sustainable/Renewable Energy Reports, 2*(3), 74-81. DOI: 10.1007/s40518-015-0038-5.

Gupta, S., Kalmanje, S., & Kockelman, K. M. (2006). Road pricing simulations: Traffic, land use and welfare impacts for Austin, Texas. *Transportation Planning and Technology, 29*(1), 1-23.

Holmes, J. (2015). *Zipcar - The promise of automated vehicles*. Paper presented at the 4th Automated Vehicle Symposium, Ann Arbor, Michigan.

Huang, Y., Bird, R., & Bell, M. (2009). A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation. *Transportation Research Part D: Transport and Environment, 14*(3), 197-204.

IHS Automotive. (2014). *Emerging technologies: Autonomous cars - not if, but when*. Retrieved (25/08/2019) from www.press.ihs.com/press-release/automotive/self-driving-cars-movingindustrys-drivers-seat.

Kawakami, A., Nitta, H., Kanou, T., & Kubo, K. (n.d.). Study on CO_2 emissions of pavement recycling methods. Ibaraki, Japan: Public Works Research Institute.

Kornhauser, A. (2013). *Uncongested mobility for all: New Jersey's area-wide aTaxi system. Princeton University*. Retrieved (25/08/2019) from www.orfe.princeton.edu/~alaink/NJ_aTaxiOrf467F12/ORF467F12aTaxiFinalReport.pdf.

KPMG, & Centre for Automotive Research. (2012). Self-driving cars: The next revolution. KPMG and CAR, Ann Arbor, Michigan. pp. 36.

Kuwata, Y., Teo, J., Fiore, G., Karaman, S., Frazzoli, E., & How, J. P. (2009). Real-time motion planning with applications to autonomous urban driving. *IEEE Transactions on Control Systems Technology, 17*(5), 1105-1118.

Leonard, J., How, J., Teller, S., Berger, M., Campbell, S., Fiore, G., Karaman, S. (2008). A perception-driven autonomous urban vehicle. *Journal of Field Robotics, 25*(10), 727-774.

Lesh, M. (2015). *Multimodal ITS transit research direction - integrated, connected, on-demand shared use mobility*. Paper presented at the 4th Automated Vehicle Symposium, Ann Arbor, Michigan.

Litman, T. (2013). Online transportation demand management encyclopaedia. Retrieved (25/08/2019) from www.vtpi.org/tdm/index.php. Victoria Transportation Policy Institute.

Liu, R. R. (2011). Spectrum of automated guideway transit (AGT) technology and its applications. In M. Kutz (Ed.), *Handbook of Transportation Engineering, Volume II: Applications and Technologies* (2nd Ed.). New York, NY: McGraw-Hill Education.

Liu, R. R. (2016). *Automated transit: Planning, operation, and applications*. Hoboken, New Jersey: John Wiley & Sons.

Liu, R. R., Fagnant, D. J., & Zhang, W.-B. (2016). Beyond single occupancy vehicles: Automated transit and shared mobility. In G. Meyer & S. Beiker (Eds.), *Road Vehicle Automation 3* (1st ed., pp. 259-275). Switzerland: Springer International Publishing.

Lopes, J. G., Duarte, J. P. (2013). Tools for evaluating the sustainabikkity of urban design: A review. *Proceedings of the ICE-Urban Design Plan, 166*, 311-325.

López-Lambas, M.E., Alonso, A. (2019). The driverless bus: An analysis of public perceptions and acceptability. *Sustainability, 11*(18), 4986.

Luers, A. L., Mastrandrea, M. D., Hayhoe, K., & Frumhoff, P. C. (2007). *How to avoid dangerous climate change: A target for US emissions reductions*. Retrieved (25/08/2019) from www.gci.org.uk/Documents/UCS_Report.pdf. Cambridge, MA.

Massey, R. (2012, December 05). Volvo develops the 'no death' car: Vehicles which drive themselves and are totally crushproof could be on British roads in eight years. *Daily Mail*. Retrieved (25/08/2019) from www.dailymail.co.uk/sciencetech/article-2242930/The-crashproof-car-Volvo-say-British-roads-years.html?ITO=1490&ns_mchannel=rss&ns_campaign=1490.

Muench, S. T., Anderson, J. L., Hatfield, J. P., Koester, J. R., & Söderlund, M. e. a. (2011). *Greenroads manual V1.5*. Seattle, Washington: University of Washington.

National Highway Traffic Safety Administration – NHTSA. (2013). *Preliminary statement of policy concerning automated vehicles*. National Highway Traffic Safety Administration (NHTSA), Washington, DC.

Nissan Motor Company. (2013). Nissan announces unprecedented autonomous drive benchmarks [Press release]. Retrieved (25/08/2019) from www.nissannews.com/en-US/nissan/usa/releases/nissan-announces-unprecedented-autonomous-drive-benchmarks.

O'Brien, C. (2012, September 25). Sergey Brin hopes people will be driving Google robot cars in "several years". *Silicon Beat*. Retrieved (25/08/2019) from http://www.siliconbeat.com/2012/09/25/sergey-brin-hopes-people-will-be-driving-google-robot-cars-in-several-years.

Polzin, S. E. (2016). How new technologies and autonomous vehicles may change public transportation. PSTA Board Workshop, Centre for Urban Transportation Research, University of South Florida.

Raney, S., & Young, S. E. (2004). *Morgantown people mover–updated description.* Paper presented at the Transportation Research Board Annual Meeting 2005, Washington, DC.

Rigole, P.-J. (2014). *Study of a shared autonomous vehicles based mobility solution in Stockholm.* (Master of Science). Retrieved (25/08/2019) from www.diva-portal.org/smash/get/diva2:746893/FULLTEXT01.pdf. Royal Institute of Technology (KTH), Stockholm.

Rister, B., & Graves, C. (2002). *The cost of construction delays and traffic control for life-cycle cost analysis of pavements* (KTC-02-07/SPR197-99 & SPR218-00-1F). Lexington, Kentucky.

Santos, A., McGuckin, N., Nakamoto, H. Y., Gray, D., & Liss, S. (2011). *Summary of travel trends: 2009 national household travel survey* (FHWA-PL-ll-022). Retrieved (25/08/2019) from www.nhts.ornl.gov/2009/pub/stt.pdf. Washington, DC.

Santos, J., Ferreira, A., Flintsch, G. (2015). A life cycle assessment model for pavement management: Road pavement construction and management in Portugal. *International Journal of Pavement Engineering, 16*(4), 315-336.

Schrank, D., Eisele, B., & Lomax, T. (2012). *TTI's 2012 urban mobility report*. Texas.

Shaheen, S., & Cohen, A. (2016). Worldwide carsharing growth continues. In *Innovative Mobility Carsharing Outlook: Carsharing Market Overview, Analysis, and Trends* (pp. 1-6). Berkeley, California: University of Berkeley.

Shaheen, S., & Cohen, A. (Summer 2013). North American carsharing market trends. *Innovative Mobility Carsharing Outlook: Carsharing Market Overview, Analysis, and Trends, 2*(1), 1-6. Retrieved (25/08/2019) from www.tsrc.berkeley.edu/sites/default/files/Innovative%20Mobility%20Industry%20Outlook_Carsharing_Spring%202013%20FINAL_0.pdf.

Shaheen, S. A., & Lipman, T. E. (2007). Reducing greenhouse emissions and fuel consumption: Sustainable approaches for surface transportation. *IATSS Research, 31*(1), 6-20. DOI: 10.1016/S0386-1112(14)60179-5.

Shladover, S., Su, D., & Lu, X.-Y. (2012). Impacts of cooperative adaptive cruise control on freeway traffic flow. *Transportation Research Record: Journal of the Transportation Research Board, 2324*, 63-70. DOI: 10.3141/2324-08.

Srinivasan, S., Smith, S., & Milakis, D. (2016). Implications of vehicle automation for planning. In G. Meyer & S. Beiker (Eds.), *Road Vehicle Automation 3* (1 ed., pp. 287-295). Switzerland: Springer International Publishing.

Tang, S., Wang, F.-Y., & Miao, Q. (2006). ITSC 05: Current issues and research trends. *IEEE Intelligent Systems, 21*(2), 96-102.

Tientrakool, P., Ho, Y. C., & Maxemchuk, N. F. (2011). *Highway capacity benefits from using vehicle-to-vehicle communication and sensors for collision avoidance.* Paper presented at the 2011 IEEE Vehicular Technology Conference (VTC Fall), San Francisco, CA, USA.

Tupper, L. L., Chowdhury, M. A., Klotz, L., & Fries, R. N. (2012). Measuring sustainability: How traffic incident management through intelligent transportation systems has greater energy and environmental benefits than common construction-phase strategies for "green" roadways. *International Journal of Sustainable Transportation, 6*(5), 282-297.

U.S. Department of Transportation. (2015). *Beyond traffic: 2045 final report*. Retrieved (25/08/2019) from www.transportation.gov/sites/dot.gov/files/docs/BeyondTraffic_tagged_508_final.pdf. Washington, DC.

United States Government Publishing Office. (2011). Part 393 – Parts and accessories necessary for safe operation. *Code of Federal Regulations: Title 49 - Transportation.* Retrieved (25/08/2019) from www.gpo.gov/fdsys/pkg/CFR-2011-title49-vol5/xml/CFR-2011-title49-vol5-part393.xml.

Walker, D. (2009). Gaining experience with warm mix asphalt. *Asphalt: The Online Magazine of the Asphalt Institute, 24(3)*. Retrieved (25/08/2019) from www.asphaltmagazine.com/gaining-experience-with-warm-mix-asphalt.

Wang, F.-Y. (2005). Agent-based control for networked traffic management systems. *IEEE Intelligent Systems, 20*(5), 92-96.

Wang, F.-Y. (2006). Driving into the future with ITS. *IEEE Intelligent Systems, 21*(3), 94-95.

Wang, F.-Y., & Tang, S. (2004). Artificial societies for integrated and sustainable development of metropolitan systems. *IEEE Intelligent Systems, 19*(4), 82-87.

Wang, F.-Y., Zeng, D., & Yang, L. (2006). Smart cars on smart roads: An IEEE intelligent transportation systems society update. *IEEE Pervasive Computing, 5*(4), 68-69.

Whyte, A. (2012). *Life-cycle assessment of built asset waste materials-sustainable disposal options* (1st Ed.). Saarbrücken, Germany: Lambert Academic Publishing (LAP).

Zhou, Y., Tupper, L., Chowdhury, M., & Klotz, L. (2010). Green credits versus environmentally sustainable traffic operations: Comparison of contributions to energy and emissions reductions. *Transportation Research Record: Journal of the Transportation Research Board* (2163), 103-111.

Zielinski, S. (2015). *Whole system connectivity: Focus on user*. Paper presented at the 4th Automated Vehicle Symposium, Ann Arbor, Michigan.

CHAPTER 4

FRAMEWORK DEVELOPMENT AND METHODOLOGY

4.1 INTEGRATED AND SYSTEMIC PERSPECTIVE TO ROAD TRANSPORT

The review of the existing issues in road and transport service studies regarding triple-bottom-line sustainability: cost, environment and social (stakeholders) performed in Chapters 2–3 identified the potential applicability of autonomous vehicle technologies and recycled material usage as a mitigation strategy. Government agencies, private organisations, and analysts are now interested in forecast of cost and environmental fluxes as a function of construction investment endeavours and government policies, on the tenet that a product eventually ends as waste. However, the same analogy may not apply to roads as they are seldom retired and the policy decisions of government agencies continue to carry cost, environmental and social implications long after the road construction. For example, the recent deduction that a road's usage stage is the most significant contributor to the lifecycle cost and environmental burdens, as well as road user cost (Lee, Thomas, & Alleman, 2018), had been somewhat absent from the earlier works. In newer urban developments, consideration must also be given to the different lane configurations, public transit services as load reduction options and recycled material usage over the entire lifecycle in terms of the three sustainability parameters of economics, environment and safeguard of everyone, i.e., the social factor (Hasan, Whyte, & Al Jassmi, 2019).

4.2 DEVELOPMENT OF THE MCDM FRAMEWORK

Road transport investment strategies thus involve complex managerial decisions where the decision-makers have to consider several critical factors while working within the confines of a limited budget and social expectations. Production and marketing strategists have long been relying on MCDM to aid in such decisions, e.g., Dempster-Shafer theory (Dempster, 1968), multi-attribute utility theory (Wu & Flintsch, 2009) and AHP from Saaty (1990) which proposes a pairwise weighting comparison. AHP has been used in road transport literature to represent the comparative benefits/costs of project alternatives (e.g. prioritisation of Brazilian infrastructure investments by Quadros and Nassi (2015) and integration of sustainability in planning and investments on transport systems in Denmark by Pryn, Cornet, and Salling (2015)). The threshold of profit accumulation and benefit harvesting as MCDM objectives had been extended to sustainable transport systems by some researchers (Awasthi, Chauhan, and Omrani, 2011). However, integration of stakeholder participation models, traffic flow models, environmental impact assessment, energy/resource consumption and cost performance throughout the lifecycle of a road transport system to rank and identify the optimum alternatives is still lacking for applicability to actual projects. This thesis thus proposes a robust multi-criteria optimisation model to evaluate the trade-offs based on empirical relations (quantitative data) and stakeholder judgment (qualitative data).

4.2.1 Selection of the MCDM framework assessment criteria to evaluate project proposals for road transport systems

The useable life of any product, such as a road transport system, developed to satisfy a real or perceived function starts from the planning and design in the conceptual phase to extraction of raw material, manufacturing or construction, use and the final end-of-life stage that itself may be composed of cataloguing, recycling and disposal (Norman, MacLean, & Kennedy, 2006). Since every stage during the life of a product involves energy input/outputs (I/Os) and resource consumption, any comprehensive study aiming to optimise the impacts from the product must acknowledge the process flow over the entire cycle of the supply chain (Reap, Roman, Duncan, & Bras, 2008), thereby reducing a "shifting of issues" from one phase or ecosystem to another, given the phases in a product's life-cycle consist of several intermingled loops. This is where the sustainability triple-bottom-line sustainability concept of social, cost and environmental performance (impact reduction/benefit) is the necessary tool for optimising the entire lifecycle (IPCC, 2008). Table 4.1 covers five recent studies on road transport systems addressing the prevalent assessment criteria for evaluating the sustainability performance of road transport projects. Additionally, it also shows the assessment criteria that have been integrated in the framework proposed in the current study for evaluating alternate project proposals for constructing, maintaining or upgrading the sustainability performance of any road transport system from a holistic lifecycle perspective.

Table 4.1 Assessment criteria for evaluating road transport project proposals

Assessment criteria	**Sustainability dimension**	**Onat et al. (2016)**	**Trigaux et al. (2016)**	**Tong et al. (2017)**	**Xie et al. (2018)**	**Goh et al. (2019)**	**Integrated in proposed framework**
Life expectancy and human health		●	●	● (partially)	●	●	●
Public welfare		●		● (partially)		●	●
Employment impacts	Social	●					
Travel demand and mode choices		●					●
Traffic management and public transport uptake							●
Vehicle operation and maintenance cost		●		●			●
Annual vehicle depreciation cost							●
Vehicle fuel costs		●		●			●
User time-delay costs							●
Initial road construction costs	Cost/Economic		●		●	●	●
Roadworks routine maintenance and periodic rehabilitation costs			●		●	●	●
Roadways operation, traffic signs lighting and electricity costs			● (partially)		● (partially)		●
Roadways EOL recycling and disposal costs			●		●		●

Emissions from extraction, transport and in-plant processing of raw materials for roadworks	Environmental		●		●	●
Emissions from initial roadway construction			●		●	●
Emissions from roadway operation, routine maintenance and lighting			●			●
Emissions from fuel consumption of on-road vehicles		●		● (partially)		●
Emissions from roadway periodic rehabilitation works			●		●	●
Emissions from disposal and recycling of roads			●		●	●

The studied covered in the Table 4.1 above covered some of the recent significant studies in transport literature that relied on sustainability parameters (social, cost, environmental impacts) as the assessment criteria for evaluating project proposals. The following sections further provide a detailed analysis of each of these assessment criteria and justifications on their selection as the performance indicators for evaluating road transport project proposals, based on the existing literature.

4.2.1.1 *Social criteria: Sustainability path dependency of transit mode trends*

Cities around the world and specifically in developing countries rely heavily on public bus services to decrease private automobile usage. Abenoza, Cats, and Susilo (2017) suggested that identifying the motivations of an individual traveller is valuable for the transport experts in channelling transit loads towards public transport and service design optimisation. Early transportation research (Chikaraishi et al., 2010; Kitamura et al., 2006) focused on investigating temporal patterns and travel activities, with less emphasis on studying the contributing factors (of perceived service quality and satisfaction from service accessibility level) behind mode choice. However, recent studies have assessed these relations in the limited location-specific context of the United States (Buehler & Hamre, 2016) and Europe (Heinen & Chatterjee, 2015).

***Quality attributes of the provided public transit service*:** Past studies (Abenoza et al., 2017; Ahrholdt, Gudergan, & Ringle, 2017) implied the importance of service quality attributes of journey time, distribution of service nodes (rail and bus stations) across travel routes, and on-board journey experience towards public transport as the preferred user mode choice. Similarly, two studies in Spain found that passengers were more inclined towards public transport if they were less crowded (dell'Olio, Ibeas, & Cecin, 2011) and frequent (de Oña et al., 2014). Grdzelishvili and Sathre (2011) investigated the travel behaviour of Georgian Tbilisi residents and found out that location, comfort, frequency and journey time are the most important attributes. While a study on Bangladeshi passengers in Dhaka by Samir (2001) found service comfort, regularity, transit load, bus waiting time and travel time on buses as instruments of perceived quality attributes.

***User expectation and satisfaction from level of service*:** Passenger satisfaction from service level has been analysed in relation to mode choice in several travel behaviour studies (Abenoza et al., 2017). In line with consumer behaviour research, user satisfaction from bus service is a two-part problem: expectation and satisfaction (i.e., the degree to which expectations are met by public transport). This concept has found proponents in literature, e.g., Kamaruddin, Osman, and Pei (2017) analysed consumer expectation-satisfaction dynamics in a study on Klang Valley public transport users in Malaysia. They used structural equation model (SEM) and descriptive statistics to show passenger expectations strongly influence their level of satisfaction. The study also determined environmental factors and quality attributes that cause users to prefer a particular transport mode. Studies (e.g., Batarce, Muñoz, and Ortúzar (2016)) noted that passengers tend to favour private automobiles over public transport if they perceive the latter fails to meet their expectations in terms of accessibility, reliability, service frequency and network coverage.

4.2.1.2 Cost assessment criteria: Economic feasibility of road transport system

The costs associated with road networks, including extension proposals to support mass-transit services, vary across regions. Cost optimisation needs to acknowledge all up and downstream cash-flows and costs to stakeholders: users (passengers) and service providers (transport agencies and transit service providers). Traditionally, an LCCA methodology approach is applied to compare the cost benefits of any optimising alternative against the baseline (do nothing) case. An underestimation of costs to any stakeholder in any of the lifecycle stages of a road transport system can influence the overall cost optimisation results of the applied cost analysis framework as, instead of reduction, the cost may actually be shifted from one stage to another. Wennström and Karlsson (2016) propose that construction costs only form a small portion of the overall system-wide costs and most of the costs are endured by road users and should also be “optimised”, presumable by local authorities in some fashion.

Future-proofing and optimising lifecycle cost of any project on one of the primary road network elements requires the prior establishment of needs and issues, cost parameters, LCCA time horizon, design parameters, and constraints. Lack of a systematic approach to LCCA acceptable by decision-makers was recognised by Safi, Sundquist, and Karoumi (2014) in their study on bridge procurement in Sweden. As contractors in a traditional design-bid-build process are extended the freedom to exploit the most cost-efficient designs, the authors proposed an embedment of LCC-efficient benchmarks as primary specifications within tender documents. In line with a potential reduction of overall system-wide loads to all stakeholders, efficient public transit services may reduce indirect user costs (fuel consumption, vehicle operation, and maintenance costs) as well road maintenance costs to management agencies – as the deteriorating effects of extensive private vehicular traffic can be potentially reduced.

Qiao et al. (2015) in their study on the maintenance of roads in the United States found that timely maintenance of roads may reduce costs occurred by the users as well as increase the road assets' service life. Interestingly, climate change from emissions was found to likely increase the agency costs by ~2% net present value and also increase vehicle operating costs to the users. Indirect benefits such as personnel employed for operating public transport (even as autonomous transit service technicians) and accessibility to business centres also occur. Nelson et al. (2007) explored this as a "cancellation of bus and rail transport" case-study scenario, which was subsequently estimated to result in a loss of 736 million USD in annual public benefits.

4.2.1.3 Environmental assessment criteria: Emissions and energy feedbacks

Road transport systems largely rely on fossil fuels (~94%) to support passenger and freight transport, causing the generation of environmental, and by extension cost, burdens (IPCC, 2008). Road transport emissions, due to road construction and maintenance and more so, heavy dependence on fossil fuel-powered private vehicles, have long-term effects on public health, resource conservation, and climate. Long queue formations on peak hours and the ensuing traffic congestion also carry indirect costs. For example, in early 2004 United Kingdom estimates, time lost in traffic accounted for a loss of 1.2% of GDP (IPCC, 2008). At the localised scale, respiratory diseases due to local air pollution feedbacks may be mitigated by using recycled road construction materials, alternative fuel technology, and mode shift to faster, reliable and interconnected public transit service. Expert appraisal of these feedbacks can be argued to be performed through a lifecycle analysis decision-making framework.

According to Bicalho et al. (2017), an LCA study on any asset must acknowledge: site- and project-specific constraints including spatial variations, material procurement and transport to/from construction and demolition sites; dynamics of the local temporal patterns; local environmental sensitivity to resource extraction, land use, and urbanisation; and local road typology, vehicular distribution, and emissions from the asphalt or concrete processing plants. Safe and legal disposal of waste from industries and construction projects is also a major global concern. It has instigated research initiatives to aid the reuse of recycled and waste materials for reducing the negative imprint of virgin materials and waste disposal (Hasan et al., 2016). Road projects dominate civil engineering projects and therefore, demand a high magnitude of raw materials. Notably, Singhvi, Ozer, and Al-Qadi (2016) found hot in-place recycling to exhibit a 1.3-19.2% GHG and 3.9-17.6% energy consumption difference.

To practice LCA as a comprehensive decision-making framework for multi-criteria analysis of the several environmental impact categories (e.g., human toxicity, ozone depletion, eco-toxicity, eutrophication, acidification and climate change) generated across the different stages of an alternative, such LCA results must be presented in a comprehensible form that can be easily compared. In order to tackle this aspect, ISO 14044 (2006) provides an optional step of normalisation and weighting of the results obtained after the lifecycle assessment stage. The aim is to identify the optimum alternative out of the available option after assessing their sustainability performance over a group of selected and weighted indicators (Stranddorf, Hoffmann, and Schmidt, 2005). In order to bridge the gap between theoretical research and real world application, this study proposes an expert-oriented weighting and multi-criteria ranking approach using analytic hierarchy process that reflects the opinion of a group of selected industry experts and government officials that are normally involved with the decision-making procedure, towards increasing practitioner confidence.

4.2.1.4 Integrating the assessment criteria: Social, cost and environment

The studies discussed above highlight that construction, operation, and maintenance of road transport and mobility assets are not isolated activities and depend on social acceptance and carry environmental loads along with monetary implications. The literature covered in Chapter 2-3 and Table 4.1 recommends that all project proposals must be optimised across all dimensions of these three criteria in order to achieve true sustainability and system-wide benefit throughout the lifecycle of any road transport system. The most cost-effective alternate for example – road expansion may not be selected as there may be other criteria such as ease of access to the targeted population, political promises or presence of heavy traffic congestion pockets within the zone, affecting the final decision. The evolution of technology has brought in new prospects of intelligent transportation systems and AVs. At network-level, decision-makers have to practice consistency in investment decisions while evaluating interdependent and often conflicting ideals of economic, environmental and social performance of a road transport project.

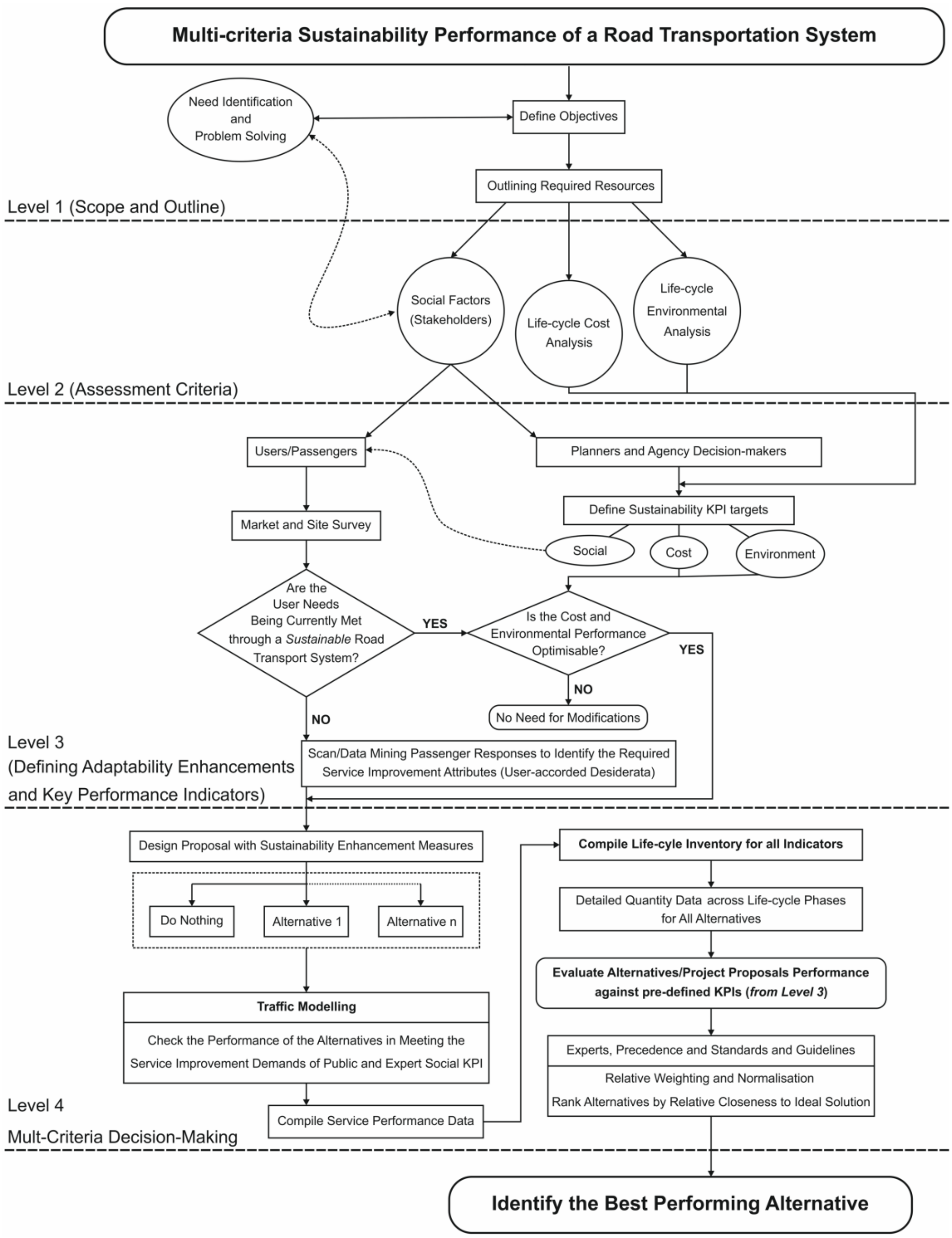


Figure 4.1 Proposed MCDM framework for multi-criteria sustainability performance evaluation of road transport systems

IPCC (2008) postulates that the different decarbonisation strategies rely on understanding the trade-offs between cost, adoption rate and environmental savings from advanced technologies of alternate fuel like natural gas, electric, hybrid-fuel (and autonomous) vehicles and continuous maintaining/upgrading of infrastructures. Furthermore, decision-making frameworks must be capable of handling: passenger biases; expectations and satisfaction from service leading to mode use, preferably public transport; and, business models for lifecycle environmental and cost performance evaluation of road transport project proposals. The results obtained from the different frameworks are often on different scales and complex to interpret. It is essential to provide a performance assessment framework that is practical and accommodates stakeholder confidence along with environmental and cost considerations. Based on these arguments, the decision-making framework in Figure 4.1 is proposed to analyse the sustainability performance and specifically identify the local need for AV-based mass mobility and alternate-fuel solutions within the frame of an overall *road transportation system*.

4.3 THESIS METHODOLOGY: FRAMEWORK APPLICATION

The proposed framework in Figure 4.1 is expected to answer the primary research aim of this thesis (Section 1.2), thus acting as a transparent decision-making tool for sustainability optimisation of a road transport system. Furthermore, the following tasks described in Table 4.2 are expected to be taken to meet the specific research objectives.

Table 4.2 Work breakdown structure (WBS) of the research methodology

WBS ID	Task description	Targeted objective	Achievement status[5]	Targeted chapters
WBS task 1	- Conduct a literature review. - Identify the methodological issues in decision-making tools to mitigate lifecycle impacts from the different components of road transport system.	Objective 1	Completed	Chapter 2 (2.3, 2.3.7, 2.4, 2.4.6, and 2.5).
WBS task 2	Literature review on identifying the applicability of advances in vehicle technology and alternate fuels.	Objective 2	Completed	Chapter 3 (3.4 and 3.6)
WBS task 3	Identify the KPIs for sustainability optimisation.	Objective 3	Incomplete	Chapter 4 (4.2.1.1, 4.2.1.2, 4.2.1.3 and 4.2.1.4) and Chapter 9
WBS task 4	- Gathering of input information required for the regression sub-model required to compute the user travel choice preferences. - Identifying influence of public transport through surveys and information existing in the local government databases.	Objective 4	Incomplete	Chapter 5
WBS task 5	Perform data mining of travel surveys to establish user preferences for improving the existing road transport system.	Objective 4	Incomplete	Chapter 6

[5] The achievement status of each WBS is as of the current page of the thesis. Refer to Table 10.1, for an updated list of achievement status for each WBS after the completion of this research work.

WBS task 6	- Development of data inventory after information collection from local agencies, suppliers and contractors regarding the unit energy consumption and emission data for the materials required. - Compute the total energy consumption and emissions for the required quantity of materials in complete roadworks using a case study road transport system.	Objective 5	Incomplete	Chapter 7
WBS task 7	Using existing lifecycle assessment databases (e.g., Ecoinvent), local resources and any reported peer-reviewed studies, calculate the energy consumption and pollutant emission reduction potential of recycled materials across the lifecycle stages of roadworks.	Objective 6	Incomplete	Chapter 7
WBS task 8	- Coordinate with the relevant local government agencies to determine the initial agency costs for both approaches (virgin and recycled materials) including the cost of initial designs, rental of equipment and vehicles for site work and labour costs. - Calculate lifecycle agency costs of electricity for traffic lighting and signals, M&R and other operational costs	Objectives 7 and 8	Incomplete	Chapter 9
WBS task 9	Analyse and use micro-simulation models (e.g., Vissim) to calculate the additional fuel consumption, user time and vehicle operation costs, and pollutant emissions during the usage stage after establishing local vehicle inventory through a market survey	Objectives 9 – 11	Incomplete	Chapter 8
WBS task 10	- Calculation of quantitative performance of alternatives across all KPIs. - Using AHP-TOPSIS, couple quantitative data and qualitative weightage for sustainability KPIs from local decision-makers using surveys	Objectives 12 and 13	Incomplete	Chapter 9
WBS task 11	Validate the proposed framework by determining performance of greener alternatives and find the alternative with optimum performance across all KPIs for a case study road transport system	Objective 14	Incomplete	Chapter 9

4.3.1 Data collection methodology

The MCDM framework proposed in this study relies on extensive collection of critical data inventory on stakeholder objectives, public/user opinion, material cost and quantity data for roadworks and inventory data on the vehicle fleet for any case study region. Thus, both quantitative and qualitative data collection methods are required for the completion of this study. As the selection of a case study transport system plays and important role for the execution as well as research and practical (industrial) applicability of this study, a suitable case study location in Abu Dhabi city was selected due to the following reasons.

Firstly, Abu Dhabi provides a unique opportunity to study the travel behaviour of urban residents in a municipal setting where the public transit service is still under development (despite a considerable economic and industrial growth), and can thus the government investments can be considerably directed towards intiatives to improve public transit service uptake (Maraqa et al., 2018). Secondly, the environmental emissions from the road transport sector in the region are considerably high due to use of virgin materials (Alzard et al., 2019) and over-reliance on private cars for passenger transit (ADDoT, 2009), which provides another opportunity for system-wide optimisation by evaluating the lifecycle performance of alternate and recycled approaches for the road component and public transport-based traffic management strategies for the traffic commponet of a metropolitan road transport system. Multiple types of data including travel and expert surveys, material and vehicle inventory, fuel, bus fare and user time costs were collected. A summary of the data collection process is provided in Table 4.3 below.

Table 4.3 Summary of the data collection process adopted in this thesis

Data classification	Data type	Collection process	Sample description	Technique	Detailed methodology
Qualitative	User opinion	On-board travel survey	Passengers	Puposive sampling of daily travellers on study route.	Sections 5.4.1 and 6.4.1.
Qualitative	Expert opinion	Consultation with local experts	Experts and decision-makers	Purposive sampling of local experts	Section 9.4.2
Quantitative	Roadworks material quantity	Original drawings, specifications and material quantity sheets	Material quantities and local construction and M&R processing technique	Document analysis and bill of quantities (BoQ)	Sections 7.4 and 9.4.4
Quantitative	Cost of roadworks	Original material and process cost data	Material, resources and works cost for construction and M&R	Document analysis, BoQ and tender analysis	Section 9.4.4
Quantitative	Roadworks emissions	Original quantity sheets and consultation with local vendors.	Unit emission and energy use data for materials, construction and M&R process	Document and literature analysis, BoQ, Ecoinvent v3.3 database analysis	Sections 7.4 and 9.4.4
Quantitative	Daily traffic emissions	Traffic counts and local market survey	Volume, age, emission standards and type of vehichles	Traffic data from local agencies and inventory data collection	Sections 8.3 and 9.4.8
Quantitative	Vehicle, user time and PT costs	Traffic counts, local market survey and vehicle inventory data	Fuel, vehicle cleaning, maintenance and depreciation costs, user time, public transit operation and fare costs	Analysis of traffic, local market, passenger demographic and vehicle inventory data	Section 9.4.8
Qualitative	Expert opinion	Survey of local experts	Experts and decision-makers	Purposive sampling of local experts	Sections 4.2.1.4 & 9.3.6

4.4 References

Abenoza, R. F., Cats, O., & Susilo, Y. O. (2017). Travel satisfaction with public transport: Determinants, user classes, regional disparities and their evolution. *Transportation Research Part A: Policy and Practice, 95*, 64-84. DOI: 10.1016/j.tra.2016.11.011.

ADDoT. (2009). *Surface transport master plan - A vision for connecting Abu Dhabi*. Abu Dhabi Department of Transport. Abu Dhabi, United Arab Emirates.

Ahrholdt, D. C., Gudergan, S. P., & Ringle, C. M. (2017). Enhancing service loyalty: The roles of delight, satisfaction, and service quality. *Journal of Travel Research, 56*(4), 436-450.

Alzard, M. H., Maraqa, M. A., Chowdhury, R., Khan, Q., Albuquerque, F. D. B., Mauga, T. I., & Aljunadi, K. N. (2019). Estimation of greenhouse gas emissions produced by road projects in Abu Dhabi, United Arab Emirates. *Sustainability, 11*(8), 2367. DOI: 10.3390/su11082367.

Awasthi, A., Chauhan, S. S., & Omrani, H. (2011). Application of fuzzy TOPSIS in evaluating sustainable transportation systems. *Expert Systems with Applications, 38*(10), 12270-12280. DOI: 10.1016/j.eswa.2011.04.005.

Batarce, M., Muñoz, J. C., & Ortúzar, J. d. D. (2016). Valuing crowding in public transport: Implications for cost-benefit analysis. *Transportation Research Part A: Policy and Practice, 91*(Supplement C), 358-378. DOI: 10.1016/j.tra.2016.06.025.

Bicalho, T., Sauer, I., Rambaud, A., & Altukhova, Y. (2017). A management science perspective. *Journal of Cleaner Production, 156*, 888-898. DOI: 10.1016/ j.jclepro.2017.03.229.

Buehler, R., & Hamre, A. (2016). An examination of recent trends in multimodal travel behavior among American motorists. *International Journal of Sustainable Transportation, 10*(4), 354-364. DOI: 10.1080/15568318.2014.945672.

Chikaraishi, M., Zhang, J., Fujiwara, A., & Axhausen, K. (2010). Exploring variation properties of time use behavior on the basis of a multilevel multiple discrete-continuous extreme value model. *Transportation Research Record: Journal of the Transportation Research Board, 2156*, 101-110. DOI: 10.3141/2156-12.

de Oña, R., López, G., Rios, F. J. D. d. l., & de Oña, J. (2014). Cluster analysis for diminishing heterogeneous opinions of service quality public transport passengers. *Procedia - Social and Behavioral Sciences, 162*, 459-466. DOI: 10.1016/j.sbspro.2014.12.227.

dell'Olio, L., Ibeas, A., & Cecin, P. (2011). The quality of service desired by public transport users. *Transport Policy, 18*(1), 217-227. DOI: 10.1016/j.tranpol.2010.08.005.

Dempster, A. P. (1968). A generalization of Bayesian inference. *Journal of the Royal Statistical Society. Series B (Methodological)*, 205-247.

Grdzelishvili, I., & Sathre, R. (2011). Understanding the urban travel attitudes and behavior of Tbilisi residents. *Transport Policy, 18*(1), 38-45.

Goh, K. C., Goh, H. H., & Chong, H.-Y. (2019). Integration model of fuzzy AHP and life-cycle cost analysis for evaluating highway infrastructure investments. *Journal* *of Infrastructure Systems, 25*(1), 04018045. DOI: 10.1061/(ASCE)IS.1943-555X.0000473

Hasan, U., Whyte, A., & Al Jassmi, H. (2019). Critical review and methodological issues in integrated life-cycle analysis on road networks. *Journal of Cleaner Production, 206*, 541-558. DOI: 10.1016/j.jclepro.2018.09.148.

Hasan, U., Chegenizadeh, A., Budihardjo, M. A., & Nikraz, H. (2016a). Experimental evaluation of construction waste and ground granulated blast furnace slag as alternative soil stabilisers. *Geotechnical and Geological Engineering, 34*(6), 1707-1722. DOI: 10.1007/s10706-016-9983-z.

Heinen, E., & Chatterjee, K. (2015). The same mode again? An exploration of mode choice variability in Great Britain using the National Travel Survey. *Transportation Research Part A: Policy and Practice, 78*, 266-282. DOI: 10.1016/j.tra.2015.05.015.

IPCC. (2008). *Climate change 2007: The physical science basis. Contribution of working group I, II and III to the fourth assessment report of the IPCC* (Core Writing Team, R. K. Pachauri, & A. Reisinger Eds.). Geneva, Switzerland: Intergovernmental Panel on Climate Change.

ISO 14044. (2006). Environmental management – Life cycle assessment – Requirements and guidelines. Vol. 14044:2006, pp. 46. Geneva, Switzerland: International Organization for Standardization.

Kamaruddin, R., Osman, I., & Pei, C. A. C. (2017). Customer expectations and its relationship towards public transport in Klang Valley. *Journal of ASIAN Behavioural Studies, 2*(4), 29-39.

Kitamura, R., Yamamoto, T., Susilo, Y. O., & Axhausen, K. W. (2006). How routine is a routine? An analysis of the day-to-day variability in prism vertex location. *Transportation Research Part A: Policy and Practice, 40*(3), 259-279. DOI: 10.1016/j.tra.2005.07.002.

Lee, E.-B., Thomas, D., & Alleman, D. (2018). Incorporating road user costs into integrated life-cycle cost analyses for infrastructure sustainability: A case study on Sr-91 corridor improvement project (Ca). *Sustainability, 10*(1), 179. DOI: 10.3390/su10010179.

Maraqa, M., Chowdhury, R., Mauga, T., Albuquerque, D., Alzard, M., Khan, Q., Sherif, M. (2018). *Assessing the carbon footprint of road projects and related sustainability initiatives in Abu Dhabi*. Abu Dhabi, UAE.

Nelson, P., Baglino, A., Harrington, W., Safirova, E., & Lipman, A. (2007). Transit in Washington, DC: Current benefits and optimal level of provision. *Journal of Urban Economics, 62*(2), 231-251. DOI: 10.1016/j.jue.2007.02.001.

Onat, N. C., Kucukvar, M., Tatari, O., & Egilmez, G. (2016). Integration of system dynamics approach toward deepening and broadening the life cycle sustainability assessment framework: a case for electric vehicles. *The International Journal of Life Cycle Assessment, 21*(7), 1009-1034. DOI: 10.1007/s11367-016-1070-4.

Pryn, M. R., Cornet, Y., & Salling, K. B. (2015). Applying sustainability theory to transport infrastructure assessment using a multiplicative AHP decision support model. *Transport, 30*(3), 330-341. DOI: 10.3846/16484142.2015.1081281.

Qiao, Y., Dawson, A. R., Parry, T., & Flintsch, G. W. (2015). Evaluating the effects of climate change on road maintenance intervention strategies and life-cycle costs. *Transportation Research Part D: Transport and Environment, 41*, 492-503. DOI: 10.1016/j.trd.2015.09.019.

Quadros, R., Germano, S., & Nassi, C. D. (2015). An evaluation on the criteria to prioritize transportation infrastructure investments in Brazil. *Transport Policy, 40*, 8-16. DOI: 10.1016/j.tranpol.2015.02.002.

Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research, 48*(1), 9-26.

Safi, M., Sundquist, H., & Karoumi, R. (2014). Cost-efficient procurement of bridge infrastructures by incorporating life-cycle cost analysis with bridge management systems. *Journal of Bridge Engineering, 20*(6), 04014083.

Samir, K. D. (2001). LOS evaluation of improved bus services in Dhaka city. *Journal of the Eastern Asia Society for Transportation Studies, 4*(1), 235-250.

Singhvi, P., Ozer, H., & Al-Qadi, I. L. (2016). *Environmental and functional benefits and trade-offs of hot in-place recycling treatment techniques* (UILU-ENG-2017-2001). Retrieved (11/08/2017) from www.chpp.egr.msu.edu/wp-content/uploads/2014/04/CHPP-Report-UIUC1-2016.pdf. Washington, DC United States.

Stranddorf, H. K., Hoffmann, L., & Schmidt, A. (2005). *Impact categories, normalisation and weighting in LCA* (Vol. 78). Luxembourg: Danish Ministry of the Environment - Environmental Protection Agency.

Wennström, J., & Karlsson, R. (2016). Possibilities to reduce pavement rehabilitation cost of a collision-free road investment using an LCCA design procedure. *International Journal of Pavement Engineering, 17*(4), 331-342.

Tong, F., Hendrickson, C., Biehler, A., Jaramillo, P., & Seki, S. (2017). Life cycle ownership cost and environmental externality of alternative fuel options for transit buses. *Transportation Research Part D: Transport and Environment, 57*, 287-302. DOI: 10.1016/j.trd.2017.09.023.

Trigaux, D., Wijnants, L., De Troyer, F., & Allacker, K. (2017). Life cycle assessment and life cycle costing of road infrastructure in residential neighbourhoods. *The International Journal of Life Cycle Assessment*, *22*(6), 938-951. DOI: 10.1007/s11367-016-1190-x.

Wu, Z., & Flintsch, G. (2009). Pavement preservation optimization considering multiple objectives and budget variability. *Journal of Transportation Engineering, 135*(5), 305-315. DOI: 10.1061/(ASCE)TE.1943-5436.0000006.

Xie, H.-B., Wu, W.-J., & Wang, Y.-F. (2018). Life-time reliability based optimization of bridge maintenance strategy considering LCA and LCC. *Journal of Cleaner Production, 176*, 36-45. DOI: 10.1016/j.jclepro.2017.12.123.

CHAPTER 5

PUBLIC BUS TRANSPORT SERVICE SATISFACTION: UNDERSTANDING ITS VALUE TO URBAN PASSENGERS TOWARDS IMPROVED UPTAKE

5.1 ABSTRACT

Recent years have seen a considerable shift in the focus of government agencies from extensive road networks to a more planned and *sustainable transport* approach. In order to accurately direct the investment capital towards sustainable development, current transport status and factors driving passengers towards private cars instead of sustainable public transport should be identified first. Past research advocated improvements in public transport to shift mode-usage *but* has yet to model the different causal effects that direct bus users to cars in rapidly developing yet congested urban areas. On-board questionnaire survey data from intra-city Abu Dhabi bus passengers ($n = 1520$, $variables = 31$) over a month were gathered in this study during both weekends and weekdays. The study modelled existing bias of travellers *and* quality attributes as antecedents of bus service's perceived *value for money* and *satisfaction from the level of service* and mode choice (car vs. bus) as the ultimate consequence. Findings revealed that any previous biased opinions of travellers adversely affected satisfaction and perceived value, while quality attributes had a positive effect. Mode use was influenced by satisfaction from service level (frequency of buses and network coverage), which was a positive consequence of perceived value for money (quality of ride and level of fare trade-off). Journey time and bus-stop waiting area quality also positively influenced satisfaction from fare level while passenger socio-demographic distribution showed that most respondents travelled more than five times a week by bus and were full-time workers and transport agencies may target service improvements around office-hours.

5.2 INTRODUCTION

Increased dependence on private vehicle use produces congestion on roads. Adverse effects are amplified by tailpipe emissions, noise pollution, and road rehabilitation costs, more-so as road deteriorations are catalysed by constantly increasing traffic. In essence, individual travel *mode use over time* not only affects general standards of living, personal wellbeing and productivity of travellers but also influences the sustainability performance of road assets (Hasan, Whyte, & Al Jassmi, 2018). Transportation management agencies constantly develop public transit strategies to maintain public bus service as a more financially and environmentally sustainable (Kwan, Sutan, & Hashim, 2018) transport service for passengers. These strategies are aimed to provide increased bus service frequency and accessibility (Renne, Hamidi, & Ewing, 2016), reduced journey time on buses and priority lanes (Wu & Pojani, 2016), discounting bus fares (Eboli & Mazzulla, 2008), improving bus-stop quality (Redman et al., 2013). This chapter provides a model for analysing the mode use data, collected for indicating the underlying roles played by these factors towards mode use.

However, user attitude towards transport systems is becoming more complex as user understanding of ride quality, network coverage, fare level, travel duration, and service frequency is changing. These factors constrain passenger willingness to choose public transport over private vehicles as it increases traveller likeness (dell'Olio, Ibeas, & Cecin, 2011) towards private cars and prejudice against public transit (hereby referred to as *travel bias*). The trend of private cars as preferred mode choice is also emerging in developing countries (Ma et al., 2013), making mode choice towards public transport an issue.

Batarce et al. (2016) noted that passengers tend to favour private cars over public transport if they perceive the latter fails to meet their expectations and as such, satisfaction from the level of service is conceptualised as a composite variable inclusive of both factors. Similarly, the concept of transit service's value to the passengers has been profusely studied in travel behaviour research (Gallarza & Saura, 2006; Chen, 2008; Chen & Chen, 2010). Yet, there is little empirical research as to what consumers actually perceive as "value" in a transit system and how it may influence their overall satisfaction from the offered level of service. Interestingly, despite there being evidence of the perceived quality and its value for the passengers' money (affordability) affecting passenger satisfaction, the exact effect leading to mode use is still not established. This chapter provides a model for analysing the mode use data of passengers that are largely public bus service users. These users, already familiar with the existing public transport service, may provide more informed responses towards the critical attributes that may need improvement or that may have attracted them towards public transport.

If passengers are treated as consumers and public transit system (e.g., a bus service) as a marketable product, understanding their motivations may help increase "sale" of the supplied "product". To that end, user satisfaction from public transport *level of service* (LoS) and its status as a *product* that provides some *value* for passenger *money* (VfM), are modelled as antecedents of car vs. bus mode use in this study. Previous studies (Hoorens, 2012; Shen et al., 2016; Kamaruddin et al., 2017) analysed satisfaction from service level as a function of quality perceived by the passengers and their expectations and travel biases towards different travel modes. However, the exact effects of transport consumer satisfaction from service level and delivering value for money to consumers on the overall consumption (i.e., mode use) have *not* been measured. Moreover, the manifest variables of the exogenous latent variables "value for money" and "level of service" should be established. This research specifically focuses on this issue by analysing bus transport service data towards improving overall ridership within a representative setting of Abu Dhabi bus passengers and exploring some rudimentary relations between variables related to mode use and transit behaviour.

The three modelled antecedents of customer satisfaction are: perceived value for money; travel bias; and, the perceived ranking of quality attributes. Value for money itself is a consequence of the last two factors, whereas mode use (bus vs. car) is the ultimate consequence of the model. Drawing upon this, appropriate hypotheses are developed in the following section and validated thereafter.

5.3 DEVELOPMENT OF RESEARCH HYPOTHESES

5.3.1 Satisfaction from level of service (LoS) and travel bias relationship

A majority of the studies on passenger behaviour primarily focused on cluster analysis of passengers based upon their mode choice with less emphasis on the motivations behind individual travel choices. A recent shift in research directions (Heinen & Chatterjee, 2015) proposed that age, social status, access to car and public transport, and employment status somewhat limits mode choice by influencing their satisfaction from the service. To build upon the underlying finding of these studies, it can be summarised that the perceived opinions of passengers towards travel mode due to the background, social status or experience, etc., influences mode use habits. This travel bias is essentially a three-dimensional problem; spatial (e.g., journey purpose and accessibility), structural (e.g., financial and work commitments) and socio-demographic constraints (e.g., age, gender, and social status). Drawing upon these researches, the following hypothesis for public bus service passengers is analysed to identify the significance of travel constraints in influencing passenger satisfaction.

H_1: Passenger satisfaction from level of service is influenced by travel bias of passengers.

5.3.2 Correlation between travel bias, quality attributes and value for money

Research into travel bias of passengers showed that the ranking of quality attributes such as journey and waiting time, bus-stop waiting area, distance to bus-stop and travel comfort significantly influence the perception of the bus service. Past research (Guirao et al., 2016) proposed that the socio-demographic constraints of travellers also significantly affect their respective rankings of quality attributes. Young student travellers listed accessibility to bus tickets (Eboli & Mazzulla, 2009), while retiree highlighted comfort (dell'Olio et al., 2011) as a significant quality attribute influencing their service quality perception. Lavery et al. (2013) found that respondents expressed public transport of higher value provided the journey time is optimised. Shen et al. (2016) found that the passengers' perceived value for money of service is positively affected by their ranking of the service quality attributes. These studies imply that the bias held by passengers affects their ranking of quality attributes while both factors influence the perceived value for money of the service, therefore, this study explores:

H_2: Passengers' perceived value for money of bus service is related to their travel bias.

H_3: Travel bias of passengers affects their ranking of quality attributes.

H_4: Passengers' ranking of quality attributes positively affects perceived value for money of service.

5.3.3 Relationship between satisfaction from LoS and quality attributes ranking

Consumer ranking of service quality attributes is an important driver of customer satisfaction from the LoS. A SEM proposed by Lai and Chen (2011) found that the perceived quality and value were strongly correlated with passenger satisfaction. They also identified that a more accurate bus service analysis should explore marketing strategies towards improved uptake of public transport by existing users. The satisfaction of passengers driving to work in a small urban English area was investigated by Gardner and Abraham (2007) in 19 semi-structured interviews. They found that the decision may indirectly stem from their satisfaction from the level of service of public transport. A majority of the passengers perceived public transport to be comparatively slower. The quality attribute of journey time was thus a significant indicator of satisfaction from LoS followed by cost, effort minimisation, and location. In line with this, the current research explores the following empirical relationship.

H_5: Relative ranking of quality attributes is indicative of passenger satisfaction from the level of service.

5.3.4 Relationship between perceived value for money and satisfaction from LoS

Creating value for consumers is not a novel concept and is often stated within a company's mission statement. Lovelock and Wirtz (2016) describe the perceived value for money as some sort of a middle-ground between perceived cost and benefits. Interestingly, few studies in transportation literature (e.g., Shen et al. (2016)) empirically investigated this relationship. A recent study by Kamaruddin et al. (2017) found passenger satisfaction as an antecedent of mode use choices. They further suggested the importance of improved ride quality, low level of fares and better service towards improved public transport uptake. It should be noted that improving ride quality does not necessarily imply an oversupply of service (Friman & Fellesson, 2009), rather implies that travellers are perhaps seeking value for money in the service. For example, Hensher, Stopher, and Bullock (2003) found customers perceiving service quality to be lower than the charged fares, i.e., failing passenger ride quality expectations. The current study modelled value for money as a trade-off between *ride quality* satisfaction and *level of fare* to study effect on the service level satisfaction.

H_6: Passenger perceived value for money has a positive effect on their satisfaction from the level of service.

5.3.5 Relationship between satisfaction from LoS and mode use

Passenger satisfaction from various travel modes is considered one of the primary determinants of mode use and has been widely discussed in the literature. A qualitative study to identify the mode choice attitude of car and public transport users was conducted by Beirão and Cabral (2007). They found that mode choice is affected by exogenous variables of latent "satisfaction from LoS" variable: *quality attributes*, *traveller bias,* and user characteristics. They proposed that the policy-making process should accommodate customer expectations and satisfaction so that public transport usage can be increased. Gardner and Abraham (2007) found that time delays in the public transport system and lack of reliance on its schedule significantly affect passengers' satisfaction which subsequently affects mode choice. Research into infrequent bus users (e.g., Thompson and Schofield (2007) in United Kingdom and by dell'Olio et al. (2011) in Spain) found customer satisfaction from LoS (quality of ride) as a determinant of future mode use. This further implies the role of affective elements (Abenoza, Cats, & Susilo, 2017; Guirao et al., 2016) such as level of fare, ride quality, journey time and purpose, origin-destination matrices, bus-stations, network coverage, and service frequency. The following relation is studied to explore mode use choices.

H_7: Passengers' satisfaction from the level of service positively affects their choice to travel by bus and negatively influences their car usage.

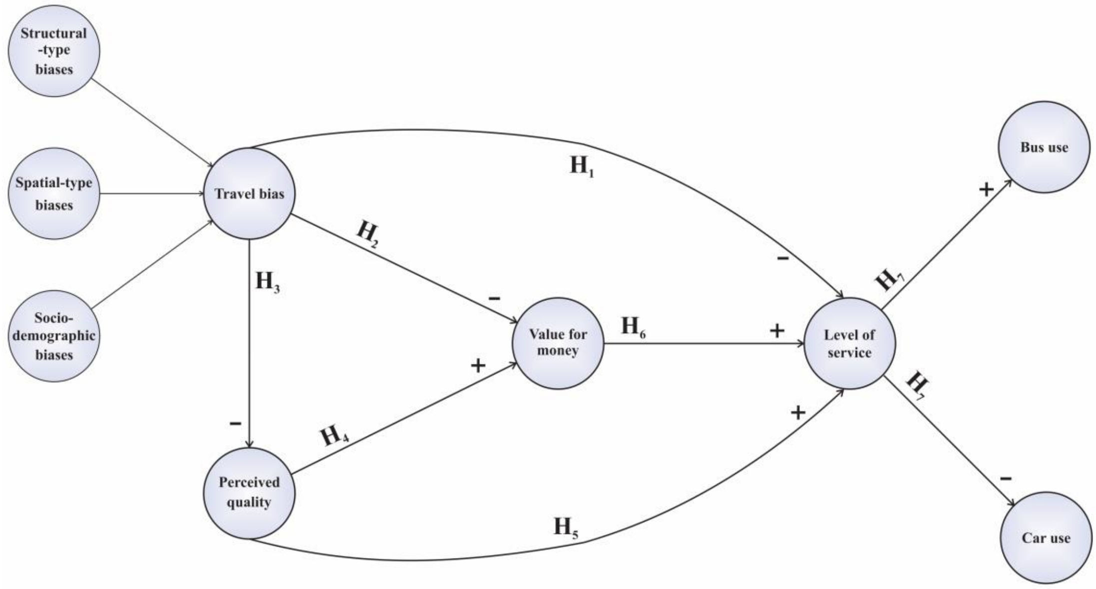


Figure 5.1 Proposed structural equation model based on the studied hypotheses

Drawing upon these seven hypotheses, the research model proposed by this study is displayed in Figure 5.1 above. Case study (public bus user survey data) of intra-city passengers in Abu Dhabi is used for studying mode choice and its antecedent latent variable constructs and sub-constructs. The City of Abu Dhabi has witnessed an increase in population which is accompanied by increasing dependence of passengers on private vehicle use, resulting in traffic congestion and emissions in many Abu Dhabi localities. The current study is aimed at providing the local DoT planners with the contributing effect of each factor to develop effective remedial strategies instead of *arbitrarily* adding bus lines or bus-stations on existing routes and reducing fares etc.

5.4 METHOD

5.4.1 Travel survey procedure and sampling

Data regarding travel patterns is collected through travel surveys (Guirao et al., 2016) or mining the transit data (Chen et al., 2012). The current analysis is based upon travel data of intra-city bus passengers in Abu Dhabi (Figure 5.2) collected through on-board surveys as the study focuses on identifying factors that may discourage their bus travel patterns. The surveyed routes consisted of both outer urban and downtown city routes.

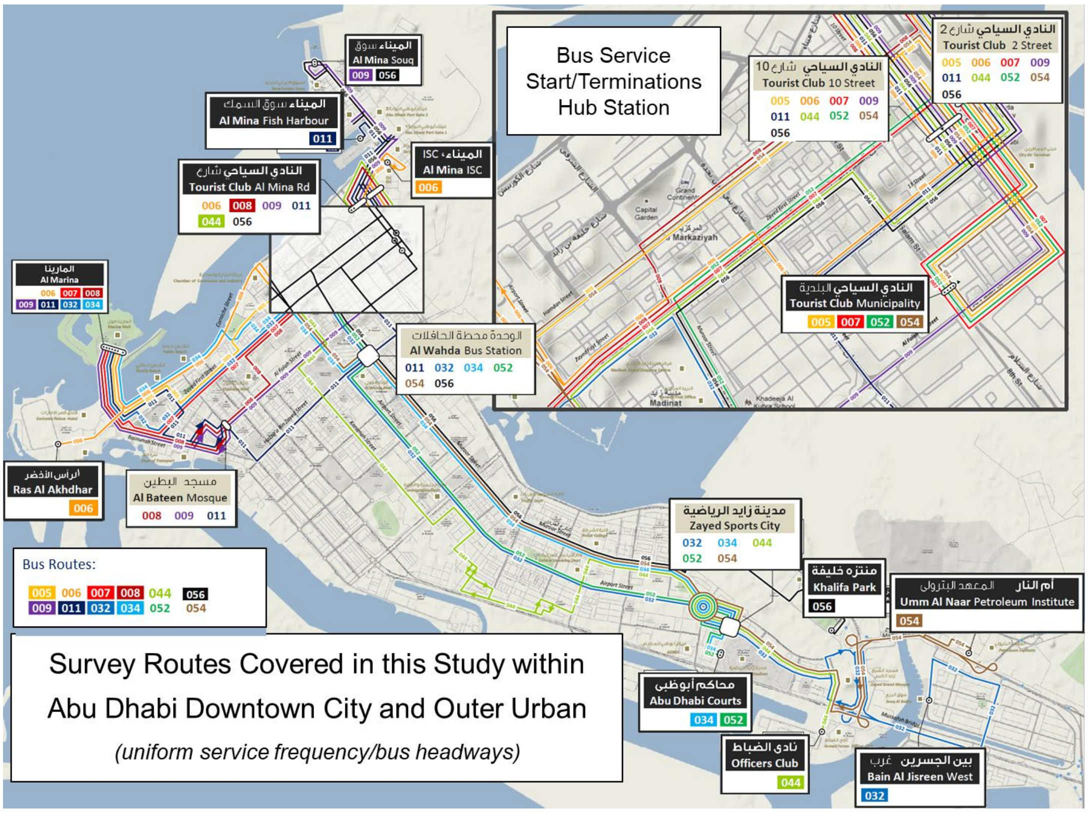


Figure 5.2 Surveyed outer urban and downtown bus routes (based on plans from Abu Dhabi DoT)

A survey questionnaire was designed for soliciting travel information of existing bus users and their perception of the existing bus network, demographic profile of the service users and their respective attitude towards travelling attributes: network coverage, quality, and satisfaction, level of fare and potential improvement strategies that may improve their bus ridership. A representative questionnaire sample is provided in Table A.1. The questionnaire was limited to 11 multiple-choice questions and 31 variables and teams designated by the Abu Dhabi Department of Transport were used to gather the passenger travel behaviour and psychometric data for the passengers that travel along the pre-existing bus travel routes illustrated by coloured lines in Figure 5.2. The mode use and travel bias (structural-type, spatial-type and socio-demographic) questions were coded for categorical responses and perceived quality attributes were based on a Likert-type scale ranging from "*1 = strongly disagree*" to "*5 = strongly agree*" and the level of service and value for money were measured on a Likert-type satisfaction scale.

5.5 DATA ANALYSIS

In the current study, *mode use* is conceptualised as a function of latent variable *satisfaction with LoS*, itself a consequence of latent variable *perceived VfM* of existing bus service. SEM is frequently used to calculate the latent variables in a collected data set that may be otherwise unobservable in the direct estimations. For example, de Oña et al. (2013) used SEM analysis to estimate the latent "passenger satisfaction" variable from the manifest "bus service quality" variables. Traditionally a multivariate normal distribution is assumed in the collected manifest variables and linear structural relationship is used to develop the relationship model. This practice has been debated by other researchers (Lin, Liu, & Han, 2005; Shen et al., 2016). They have argued that the data collected through passenger satisfaction surveys rarely follow this distribution and the observed variables are usually dependent on each other.

Partial Least Squares (PLS) method has little reliance on normal distribution assumptions and can be used for research in passenger satisfaction to explicitly estimate the latent variables. It is also more suitable for the work presented here due to its ability to handle complicated models with both formative (i.e., indicators *cause* latent variable) and reflective (i.e., latent variable *cause* indicators) constructs (Gefen et al., 2000; Hair et al., 2012). SmartPLS 3.2.6 (Ringle et al., 2015) was used in this work to validate the hypotheses by explaining the presence of a causal relationship between the variable constructs. Following the above literature review, this work modelled "*Travel Bias*" as a second-order formative construct (where indicators are also latent variables) with endogenous variable constructs of spatial, structural and socio-demographic constraints. Latent variable "*Perceived Quality*" constituted the second formative construct with some of the most commonly used quality attributes as exogenous variables. Value for money, satisfaction from level of service and frequency of bus and car travel were modelled here as reflective constructs. All the exogenous variables remained independent throughout the model. Framework is shown in Figure 5.1 and the model is composed of two components, both used to confirm the validity of our hypotheses. First, the measurement model describing the relationship between latent variable and manifest variables of a formative construct, defined as:

$$x = \Lambda_x \xi + \delta \qquad \text{Equation (5.1)}$$

For exogenous variables with structural coefficient matrix $q \times n$ by Λ_x

$$y = \Lambda_y \eta + \varepsilon \qquad \text{Equation (5.2)}$$

For endogenous variables with structural coefficient matrix $p \times m$ by Λ_y with a second, structural model describing the relationship between the different constructs themselves, defined as:

$$\eta = \beta\eta + \Gamma\xi + \zeta \qquad \text{Equation (5.3)}$$

Where, endogenous latent variable vector $m \times 1$ is defined by η, path coefficient $m \times m$ matrix by β, residual $m \times 1$ vector by ζ with $m \times n$ path coefficient matrix Γ and, the exogenous latent variable $n \times 1$ vector by ξ. The number of SEM equations depend upon the number of endogenous latent variables. Equations (5.1) – (5.3) are a simplified version of the PLS equations modelled by the researchers in behavioural data sciences and statistical analyses, such as Tenenhaus et al. (2005), and Henseler et al. (2016) to define the relationship between the variables modelled through a PLS algorithm.

5.6 RESULTS AND DISCUSSION

5.6.1 Socio-demographic distribution of passengers

A total of 769 interviews for the weekend and 751 interviews for weekdays were completed. Initial descriptive statistical analysis suggests that traveller distribution was skewed towards males (86%-weekdays and 89%-weekends) of South-Asian descent (57%, 57%). Table 5.2 shows the detailed passenger distribution.

Table 5.1 Statistical descriptive distribution of the collected variables

No.	Variables	Valid cases	Mean	Standard deviation	Variance
MU1	Frequency of bus travel	1517	5.20	1.149	1.321
MU2	Frequency of car travel	1305	2.94	1.414	2.000
LoS1	Satisfaction with frequency of buses	1512	3.70	0.899	0.809
LoS2	Satisfaction with network coverage	1494	3.74	0.890	0.793
VfM1	Satisfaction with quality of ride	1501	3.98	0.976	0.953
VfM2	Satisfaction with level of fare	1505	3.37	1.351	1.824
ST1	Your accommodation type?	1509	2.52	1.390	1.933
ST2	What is your employment status?	1505	5.55	1.103	1.216
ST3	What is your annual rent? (AED)	1384	2.09	1.252	1.566
SP1	Where do you live?	1519	3.76	1.814	3.291
SP2	Where did you start this journey?	1518	3.35	1.845	3.405
SP3	Where are you travelling to?	1515	3.38	1.823	3.323
SP4	Purpose of your journey today?	1514	3.25	2.130	4.539
SP5	Type of ticket you purchased today?	1516	1.32	0.732	0.536
SD1	Age (years)	1507	3.21	0.923	0.851
SD2	Number of cars in household	1440	0.17	0.392	0.153
SD3	Do you hold a UAE driving license?	1503	1.79	0.411	0.169
SD4	Ethnicity/Nationality	1507	5.02	1.070	1.145
SD5	Gender	1509	1.13	0.333	0.111
SD6	Your gross monthly income in AED	1385	2.47	1.048	1.099
SQ1	I am satisfied with journey time	1508	3.95	0.826	0.682
SQ2	The buses are too crowded	1519	0.60	0.489	0.240
SQ3	Bus travel is the easiest way for me	1519	0.66	0.475	0.226
SQ4	I am satisfied with the bus-stops	1496	3.38	1.125	1.265
SQ5	Travel by car or taxi is expensive	1519	0.45	0.497	0.247
SQ6	Traffic congestion delays journey	1519	0.35	0.478	0.228
SQ7	I chose to live further from work	1519	0.66	0.472	0.223
SQ8	I chose to live closer to work	1319	4.70	2.70	7.301
SQ9	Willing to pay more for bus seat	1519	0.36	0.479	0.229
SQ10	Satisfied with existing bus-stop distribution	1519	2.10	0.676	0.457

The passengers predominantly fall into the fulltime workforce category (82.5%) and the travel mode frequency (bus and cars) is shown in Figure 5.3 below.

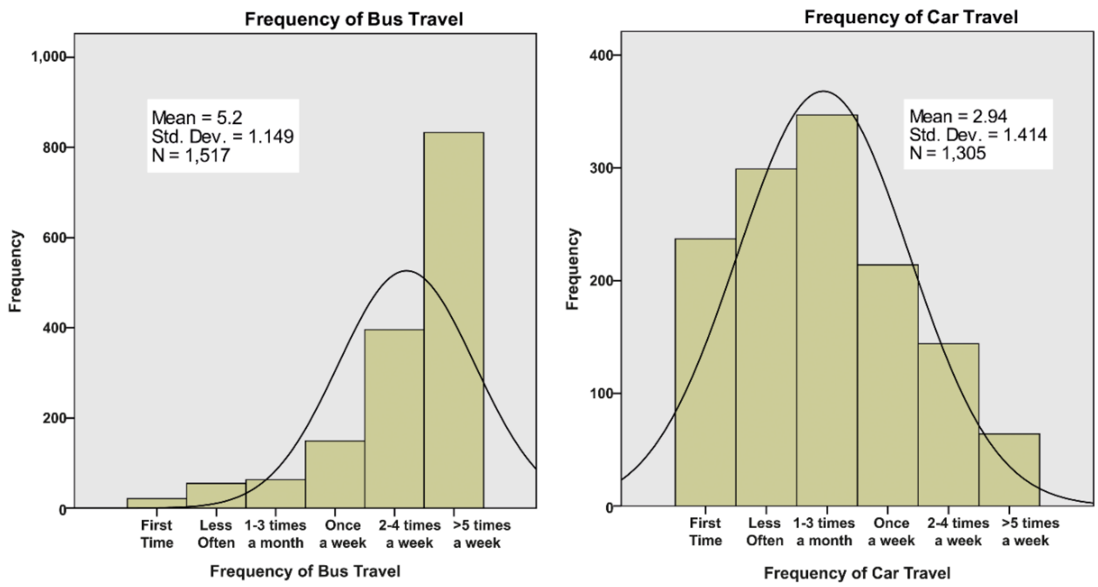


Figure 5.3 Distribution of bus and car travel frequencies among surveyed passengers

5.6.2 Evaluation of measurement model

Measurement models are analysed using construct reliability, convergent validity, and discriminant validity tests. Since this study recognises both formative and reflective constructs, only measures related to the specific constructs were used. In contrast to reflective constructs, very few guidelines exist for validating formative constructs. *Travel bias* was a second-order formative construct, with formative sub-constructs of *spatial*, *structural* and *socio-demographics*, its validity was checked by following the guidelines from Benbasat and Wang (2005) these were replaced by their respective latent variable scores from SmartPLS. In order to check the construct reliability, bootstrapping (random sampling with replacements) was performed with SmartPLS to check the absence of multi-collinearity and validity of the indicators, following the guidelines by Andreev et al. (2009). Indicator validity was tested using t-statistics values of path coefficients as shown in Figure 5.4. Only the origin and residential areas, employment status and possession of driving license were noted as somewhat insignificant indicators.

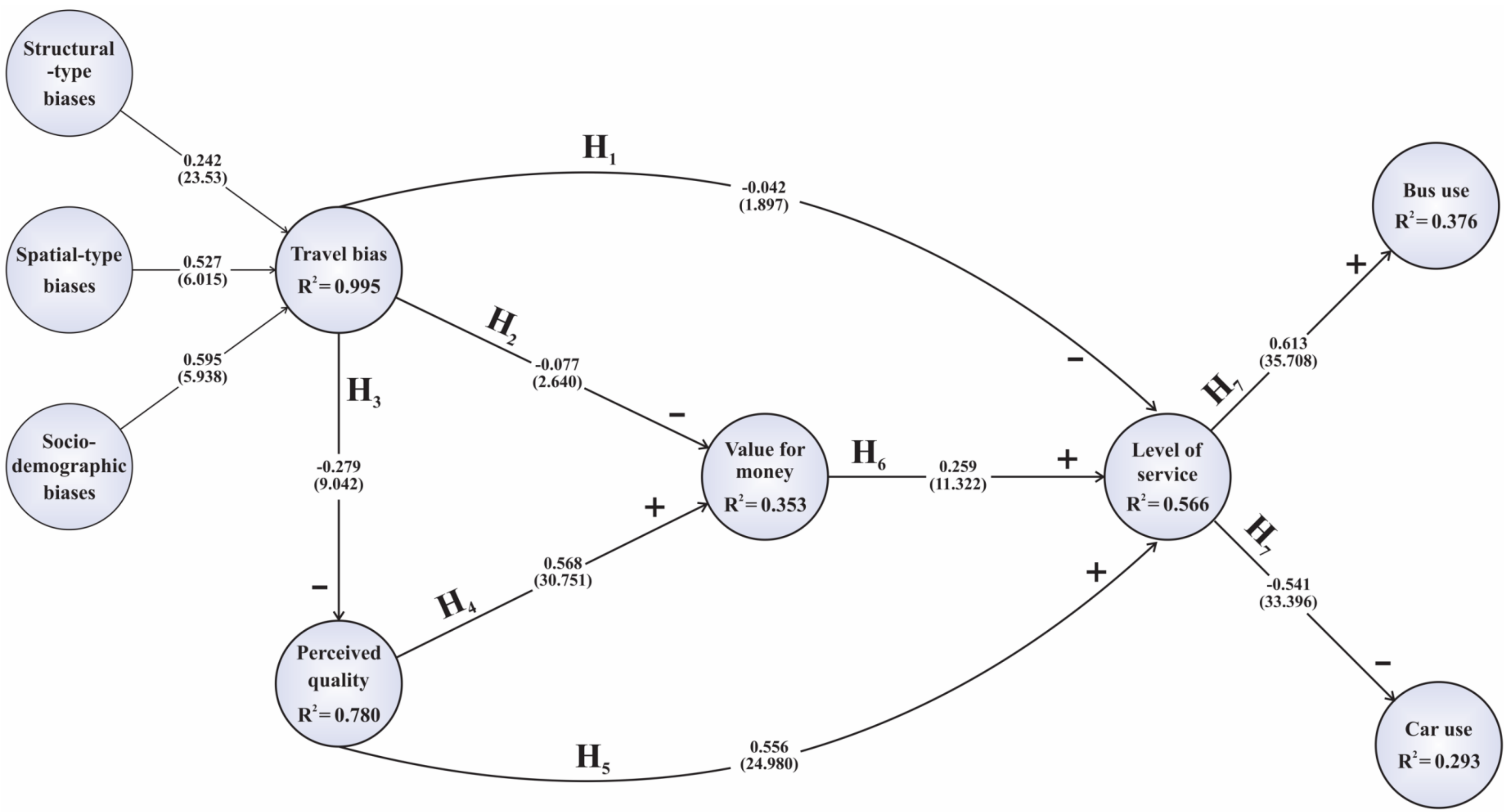


Figure 5.4 PLS analysis results for the proposed structural equation model

Variance inflation factors (VIF) scores were used to test for multi-collinearity. The VIF values ranged from 1.017 to 1.796 (Table 5.2), which confirms that all the formative latent variables met the required thresholds of VIF<10 (Henseler et al., 2016) with no multi-collinearity present. The convergent and discriminant validity of the formative constructs was assessed using the multitrait-multimethod matrix approach (Andreev et al., 2009) in a two-step process. First, SPSS 13 was used to obtain the standardised scores of all manifest variables and the standardised weights of the first- and second-order formative constructs were extracted from SmartPLS. These two values were then multiplied to obtain the weighted manifest variables and then summed up to obtain the respective composite construct scores.

Table 5.2 Path analysis and multi-collinearity results

1st order constructs	2nd order formative sub-constructs	Path coefficient	Sample mean	Standard deviation	t-statistics	VIF
Travel bias	***Structural-type bias***					
	Accommodation type?	0.349	0.336	0.138	2.527**	1.792
	Employment status?	0.193	0.202	0.132	1.467	1.796
	Annual rent? (in AED)	0.805	0.795	0.073	11.024***	1.017
	Spatial-type bias					
	Where do you live?	0.200	0.188	0.11	1.818	1.075
	Where did you start this journey?	0.145	0.136	0.103	1.401	1.061
	Where are you travelling to?	0.402	0.396	0.087	4.593***	1.024
	Purpose of your journey today?	0.698	0.686	0.07	9.953***	1.045
	Type of ticket you purchased today?	0.304	0.305	0.083	3.646***	1.023
	Socio-demographic					
	Age (years)	0.171	-0.164	0.071	2.401*	1.039
	No. of cars in household	0.277	0.272	0.088	31.16**	1.287
	Do you hold a UAE driving license?	0.031	0.028	0.091	0.347	1.343
	Ethnicity/Nationality	0.626	0.616	0.068	9.196***	1.085
	Gender	0.405	-0.411	0.08	5.042***	1.019
	Gross monthly income?	0.309	0.29	0.104	2.964**	1.155

Perceived quality	I am satisfied with journey time?	0.649	0.648	0.028	22.841***	1.23
	The buses are too crowded	-0.015	-0.104	0.027	3.864***	1.226
	Bus travel is the easiest way for me	0.068	0.069	0.026	2.64**	1.105
	I am satisfied with the bus-stops	0.504	0.501	0.029	17.57***	1.24
	Travel by car or taxi is expensive	-0.014	-0.013	0.028	2.489**	1.204
	I chose to live further from work	0.026	0.027	0.027	1.975**	1.243
	I chose to live close to work	0.048	0.048	0.027	1.966***	1.169
	Pay more to travel by bus for a seat	-0.015	-0.016	0.026	2.571*	1.283
	Satisfied with bus-stops' distribution	0.070	0.069	0.024	2.974**	1.019
	Traffic congestion delays my journey	0.026	0.026	0.025	3.029**	1.114

Listed values are for second-order formative constructs. $***p < 0.001$, $**0.001 \le p < 0.01$, $*p < 0.05$.

Campbell and Fiske (1959) postulated that the manifest variables belonging to the same construct should be significantly correlated with each other, rather than the indicators of other constructs. Generally, the indicators of travel bias exhibited a high correlation with inter-measure indicators rather than the perceived quality construct, thus confirming the convergent validity of the instrument. However, due to the presence of some correlations between different indicators of the three sub-constructs (structural, spatial and socio-demographic), some of the indicators of sub-constructs displayed stronger correlations with those belonging to the other sub-construct. For example, respondents from high-income groups also occupied high rental properties, yet were not necessarily fulltime employed. Another example is that the respondents with high rental properties were also more likely to have higher household car possession. Findings such as these, although technically violate the threshold, can, however, be easily explained by the factors unique to the emirate of Abu Dhabi such as having more business owners and a majority of the population living in high rental apartments than traditional villa-style houses. Previous studies employing the same methodology (e.g., Loch, Straub, and Kamel (2003)) have proposed similar arguments for identifying false red flags in the analysis results.

Table 5.3 Composite reliability, convergent and discriminant validity results

Constructs	**Composite reliability**	**Cronbach's alpha**	**AVE**	**Correlations**			
				LoS	VfM	Car	Bus
Level of service (LoS)	0.891	0.757	0.804	**0.896**			
Value for money (VfM)	0.781	0.745	0.647	0.597	**0.804**		
Car use (Car)	0.712	0.726	0.616	-0.553	-0.311	**0.785**	
Bus use (Bus)	0.773	0.849	0.724	-0.613	-0.434	0.669	**0.851**

Reflective constructs of *value for money*, *satisfaction from the level of service*, *frequency of bus travel* and *frequency of car travel* were examined for composite reliability and internal consistency through Cronbach's alpha. Convergent and discriminant validity were also examined by average variance extracted (AVE). The results shown in Table 5.3 exhibit that all composite reliability and Cronbach's alpha scores were above the recommended minimum threshold of 0.7 (Hair et al., 2012), indicating that internal consistency and reliability were confirmed. As all AVE values were above the 0.5 cut-off (Hair et al., 2012), the convergent validity of the constructs was also established. The bolded values along the diagonals in Table 5.3 show the square-roots of AVE for each construct (e.g., 0.896 for LoS). In order for the discriminant validity to be true, these values should exceed the inter-construct correlations (Kim, Lee, & Bonn, 2017), which was also confirmed. Overall, even though there were some violations in the measurement models, the constructs had appropriate validity and the majority of the indicators passed the required reliability and validity tests. Furthermore, the violations were explainable due to the nature of the data. This exhibits an ability to significantly define the respective latent variable constructs and as such the current study was then able to proceed to test the research hypotheses by evaluating the structural model.

5.6.3 Evaluation of structural model: Hypotheses testing

The results of the PLS structural model are shown in Figure 5.4. According to the guidelines by Henseler et al. (2016), the primary criterion for assessing the validity of a structural model is the explained variance level based on R^2 values of the endogenous latent variable constructs. The non-parametric method of bootstrapping was conducted, which performs re-sampling to evaluate the significance and conformance of the model (Kim et al., 2017). The R^2 values of the endogenous latent variables are illustrated in Figure 5.4 and a majority of the values were in the 0.376 – 0.995 range, showing a substantial degree of overall goodness-of-fit. The criteria specified by Chin (1998) proposes that an R^2 value between 0.33 – 0.66 indicated a moderate estimation while lower and higher values respectively describe a weak and substantial estimation.

Table 5.4 Hypotheses testing results

Hypotheses		β	**t-statistic**	**Outcome**
H_1: Passenger satisfaction from the level of service is influenced by travel bias of passengers.		0.259^{***}	11.322	Validated
H_2: Passengers' perceived value for money of the bus service is related to their travel bias.		$-.042^{*}$	1.897	Invalid
H_3: Travel bias of passengers affects their ranking of quality attributes.		0.556^{***}	24.980	Validated
H_4: Passengers' ranking of quality attributes positively affects the perceived value for money of the service.		$-.279^{***}$	9.042	Validated
H_5: Relative ranking of quality attributes is indicative of passenger satisfaction from the level of service.		$-.077^{**}$	2.640	Validated
H_6: Passenger perceived value for money has a positive effect on their satisfaction from the level of service.		0.568^{***}	30.751	Validated
H_7: Passengers' satisfaction from the level of service positively affects their choice to travel by bus and negatively influences their car usage.	**Bus**	0.613^{***}	35.708	Validated
	Car	$-.541^{***}$	33.396	Validated

$***p < 0.001$, $**0.001 \le p < 0.01$, $*p > 0.05$

Even though the manifest variables from the "car use" latent variable passed the significance criteria, the latent variable itself had a low R^2 value, probably due to the comparatively lower response rate in the collected sample. The hypotheses testing results in Table 5.4 show that all of the study's proposed hypotheses were supported except hypothesis H_2, which failed both t-statistics and p-value tests. Even though the travel bias of passengers negatively influenced their perceived value for money (H_2: path coefficient = – 0.077, $p < 0.01$), its influence on passenger satisfaction from LoS was not supported (path coefficient = – 0.042, *p-value* 0.06), which invalidated H_2. However, as the hypothesis marginally failed the pass criteria, a further in-depth investigation may be needed.

Positing in H_3 that travel bias affects the respective rankings survey respondents assign to each quality attribute, PLS results show that the travel biases of passengers reduced their perception of quality attributes. It leads to the argument that passengers on a bus service were less likely to positively appraise the service quality depending upon their individual characteristics and any policy strategies should also consider these variables to attract the itinerant market. Also, the quality attributes affected the value for money of the bus service as perceived by the passengers, validating H_4.

The satisfaction of passengers from the level of service of public bus transport was found to be substantially affected by the ranking assigned to the quality attributes of the service (H_5: path coefficient = 0.556, $p < 0.001$). The perceived value for money had a strong influence on satisfaction from the level of service (H_6: path coefficient = 0.259, $p < 0.001$) which subsequently affected the mode use. The role of passenger satisfaction from the level of service in defining the mode choice of passengers was investigated by H_7. Overall, the frequency of bus use increased as the LoS satisfaction also increased whereas the tendency of respondents to opt for private automobile travel reduced with the escalating satisfaction levels. In addition, all the manifest variables of the latent variables *perceived value for money* and *LoS satisfaction* were also significant. This study's results propose that both latent variable constructs influenced mode use and were respectively described by the manifest variable groups of "*ride quality* and *level of fare*" and "*frequency of buses* and *network coverage*".

Drawing upon these findings, it may be postulated that any future analysis aimed at analysing passenger surveys to discover critical factors that can attract existing passengers more towards sustainable bus transport mode to reduce the environmental burdens related with private vehicle use, may study the market based upon their current mode use and its relation with these variables, as they were significant in defining the passenger perceptions.

5.7 CONCLUSION AND FUTURE RESEARCH DIRECTION

Although the negative traits of car usage and environmental benefits of public transport have been documented (Mahesh, Ramadurai, & Nagendra, 2018), understanding passenger attraction towards the latter is important if adequate policy decisions are to be made. Consequently, assessing the current perception of public transport users from the offered services is critical for transport management agencies. In the first stage of this current work, a detailed literature review was conducted and findings were provided as to the factors that constitute the passenger behaviour.

The current study then utilised a survey questionnaire to capture intra-city Abu Dhabi passenger responses on mode use, passenger characteristics, perception of existing bus service and its quality attributes. This work built upon prior research on consumer psychometrics and review of transport literature to represent passenger satisfaction as a function of perceived value, service quality attributes, and passenger travel bias. The bus or car frequencies of passengers were established as the two model consequences. The validity of these hypotheses between the various endogenous latent variables (mode choice, level of service, value for money, quality attributes and travel bias) and their manifest variables was then tested.

Some caveats from this study are recognised. Firstly, the survey was conducted in an intra-city setting and as such may not be indicative of intercity and extremely short distance passengers. Secondly, the responses of passengers are in context of the populace in Abu Dhabi and may be bound by the cultural, climatic and behavioural constraints of the region. Notably the hot climate, where walking and bicycling over long distances are deemed untenable.

The results show strong effects of quality attributes of the bus service, most notably journey time and bus-stop waiting area quality as a reinforcing factor for perceived value and satisfaction. On the other hand, some study factors such as overcapacity vehicles inhibit public transport as a viable mode choice. Travel bias held by passengers based on individual characteristics influenced the perceived quality and its consequences (perceived value for money and satisfaction from service level). Overall, this study contributes to a theoretical understanding of passenger behaviour. It provides an opportunity for policymakers to create homogenous passenger segments based on each latent variable which can then be further studied to identify the indirect association between variables in each segment.

5.8 References

Abenoza, R. F., Cats, O., & Susilo, Y. O. (2017). Travel satisfaction with public transport: Determinants, user classes, regional disparities and their evolution. *Transportation Research Part A: Policy and Practice, 95*, 64-84. DOI: 10.1016/j.tra.2016.11.011.

Andreev, P., Heart, T., Maoz, H., & Pliskin, N. (2009). *Validating formative partial least squares (PLS) models: Methodological review and empirical illustration.* Paper presented at the 13th International Conference on Information Systems, Phoenix, Arizona.

Batarce, M., Muñoz, J. C., & Ortúzar, J. d. D. (2016). Valuing crowding in public transport: Implications for cost-benefit analysis. *Transportation Research Part A: Policy and Practice, 91*(Supplement C), 358-378. DOI: 10.1016/j.tra.2016.06.025.

Beirão, G., & Cabral, J. S. (2007). Understanding attitudes towards public transport and private car: A qualitative study. *Transport Policy, 14*(6), 478-489.

Benbasat, I., & Wang, W. (2005). Trust in and adoption of online recommendation agents. *Journal of the association for information systems, 6*(3), 4.

Campbell, D. T., & Fiske, D. W. (1959). Convergent and discriminant validation by the multitrait-multimethod matrix. *Psychological bulletin, 56*(2), 81-105.

Chen, C.-F. (2008). Investigating structural relationships between service quality, perceived value, satisfaction, and behavioral intentions for air passengers: Evidence from Taiwan. *Transportation Research Part A: Policy and Practice, 42*(4), 709-717.

Chen, C.-F., & Chen, F.-S. (2010). Experience quality, perceived value, satisfaction and behavioral intentions for heritage tourists. *Tourism management, 31*(1), 29-35.

Chen, R., Fung, B. C. M., Desai, B. C., & Sossou, N. M. (2012). *Differentially private transit data publication: A case study on the Montréal transportation system*. Paper presented at the Proceedings of the 18th ACM SIGKDD international conference on Knowledge discovery and data mining, Beijing, China.

Chin, W. W. (1998). The partial least squares approach to structural equation modeling. In G. A. Marcoulides (Ed.), *Modern methods for business research* (Vol. 295, pp. 295-336). London, U.K.: Lawrence Erlbaum Associates.

de Oña, J., de Oña, R., Eboli, L., & Mazzulla, G. (2013). Perceived service quality in bus transit service: A structural equation approach. *Transport Policy, 29*, 219-226.

dell'Olio, L., Ibeas, A., & Cecin, P. (2011). The quality of service desired by public transport users. *Transport Policy, 18*(1), 217-227. DOI: 10.1016/j.tranpol.2010.08.005.

Eboli, L., & Mazzulla, G. (2008). A stated preference experiment for measuring service quality in public transport. *Transportation Planning and Technology, 31*(5), 509-523. DOI: 10.1080/03081060802364471.

Eboli, L., & Mazzulla, G. (2009). A new customer satisfaction index for evaluating transit service quality. *Journal of Public transportation, 12*(3), 21-37. DOI: 10.5038/2375-0901.12.3.2.

Friman, M., & Fellesson, M. (2009). Service supply and customer satisfaction in public transportation: The quality paradox. *Journal of Public transportation, 12*(4), 57-69. DOI: 10.5038/2375-0901.12.4.4.

Gallarza, M. G., & Saura, I. G. (2006). Value dimensions, perceived value, satisfaction and loyalty: An investigation of university students' travel behaviour. *Tourism management, 27*(3), 437-452.

Gardner, B., & Abraham, C. (2007). What drives car use? A grounded theory analysis of commuters' reasons for driving. *Transportation Research Part F: Traffic Psychology and Behaviour, 10*(3), 187-200.

Gefen, D., Straub, D., & Boudreau, M.-C. (2000). Structural equation modeling and regression: Guidelines for research practice. *Communications of the association for information systems, 4*(7), 1-78.

Guirao, B., García-Pastor, A., & López-Lambas, M. E. (2016). The importance of service quality attributes in public transportation: Narrowing the gap between scientific research and practitioners' needs. *Transport Policy, 49*, 68-77. DOI: 10.1016/j.tranpol.2016.04.003.

Hair, J. F., Sarstedt, M., Ringle, C. M., & Mena, J. A. (2012). An assessment of the use of partial least squares structural equation modeling in marketing research. *Journal of the Academy of Marketing Science, 40*(3), 414-433.

Hasan, U., Whyte, A., & Al Jassmi, H. (2018). Life-cycle asset management in residential developments building on transport system critical attributes via a data-mining algorithm. *Buildings, 9*(1). DOI: 10.3390/buildings9010001.

Heinen, E., & Chatterjee, K. (2015). The same mode again? An exploration of mode choice variability in Great Britain using the National Travel Survey. *Transportation Research Part A: Policy and Practice, 78*, 266-282. DOI: 10.1016/j.tra.2015.05.015.

Henseler, J., Hubona, G., & Ray, P. A. (2016). Using PLS path modeling in new technology research: Updated guidelines. *Industrial Management and Data Systems, 116*(1), 2-20. DOI: 10.1108/IMDS-09-2015-0382.

Hensher, D. A., Stopher, P., & Bullock, P. (2003). Service quality – Developing a service quality index in the provision of commercial bus contracts. *Transportation Research Part A: Policy and Practice, 37*(6), 499-517. DOI: 10.1016/S0965-8564(02)00075-7.

Hoorens, V. (2012). Expectation. In V. S. Ramachandran (Ed.), *Encyclopaedia of Human Behavior* (2nd Ed., pp. 142-149). San Diego: Academic Press.

Kamaruddin, R., Osman, I., & Pei, C. A. C. (2017). Customer expectations and its relationship towards public transport in Klang Valley. *Journal of ASIAN Behavioural Studies, 2*(4), 29-39.

Kim, M. J., Lee, C.-K., & Bonn, M. (2017). Obtaining a better understanding about travel-related purchase intentions among senior users of mobile social network sites. *International Journal of Information Management, 37*(5), 484-496.

Kwan, S. C., Sutan, R., & Hashim, J. H. (2018). Trip characteristics as the determinants of intention to shift to rail transport among private motor vehicle users in Kuala Lumpur, Malaysia. *Sustainable Cities and Society, 36*, 319-326. DOI: 10.1016/j.scs.2017.10.030.

Lai, W.-T., & Chen, C.-F. (2011). Behavioral intentions of public transit passengers – The roles of service quality, perceived value, satisfaction and involvement. *Transport Policy, 18*(2), 318-325. DOI: 10.1016/j.tranpol.2010.09.003.

Lavery, T. A., Páez, A., & Kanaroglou, P. S. (2013). Driving out of choices: An investigation of transport modality in a university sample. *Transportation Research Part A: Policy and Practice, 57*, 37-46. DOI: 10.1016/j.tra.2013.09.010.

Lin, S., Liu, J.-l., & Han, W.-x. (2005). Method on customer satisfaction assessment based on the partial least square for structural equation. *Journal of System Engineering, 20*(6), 653-659.

Loch, K. D., Straub, D. W., & Kamel, S. (2003). Diffusing the internet in the Arab world: The role of social norms and technological culturation. *IEEE Transactions on Engineering Management, 50*(1), 45-63.

Lovelock, C., & Wirtz, J. (2016). *Services marketing: People, technology, strategy* (Samsudin Ed.). Singapore: World Scientific.

Ma, X., Wu, Y.-J., Wang, Y., Chen, F., & Liu, J. (2013). Mining smart card data for transit riders' travel patterns. *Transportation Research Part C: Emerging Technologies, 36*, 1-12. DOI: 10.1016/j.trc.2013.07.010.

Mahesh, S., Ramadurai, G., & Shiva Nagendra, S. M. (2018). Real-world emissions of gaseous pollutants from diesel passenger cars using portable emission measurement systems. *Sustainable Cities and Society, 41*, 104-113. DOI: 10.1016/j.scs.2018.05.025.

Norman, J., MacLean, H. L., & Kennedy, C. A. (2006). Comparing high and low residential density: Life-cycle analysis of energy use and greenhouse gas emissions. *Journal of Urban Planning and Development, 132*(1), 10-21. DOI: 10.1061/(ASCE)0733-9488(2006)132:1(10).

Redman, L., Friman, M., Gärling, T., & Hartig, T. (2013). Quality attributes of public transport that attract car users: A research review. *Transport Policy, 25*(Supplement C), 119-127. DOI: 10.1016/j.tranpol.2012.11.005.

Reap, J., Roman, F., Duncan, S., & Bras, B. (2008). A survey of unresolved problems in life cycle assessment. *The International Journal of Life Cycle Assessment, 13*(5), 374-388. DOI: 10.1007/s11367-008-0009-9.

Renne, J. L., Hamidi, S., & Ewing, R. (2016). Transit commuting, the network accessibility effect, and the built environment in station areas across the United States. *Research in Transportation Economics, 60*(Supplement C), 35-43. DOI: 10.1016/j.retrec.2017.02.003.

Ringle, C. M., Wende, S., & Becker, J.-M. (2015). SmartPLS 3. Bönningstedt: SmartPLS.

Shen, W., Xiao, W., & Wang, X. (2016). Passenger satisfaction evaluation model for urban rail transit: A structural equation modeling based on partial least squares. *Transport Policy, 46*(Supplement C), 20-31. DOI: 10.1016/j.tranpol.2015.10.006.

Tenenhaus, M., Vinzi, V. E., Chatelin, Y.-M., & Lauro, C. (2005). PLS path modeling. *Computational Statistics & Data Analysis, 48*(1), 159-205. DOI: 10.1016/j.csda.2004.03.005.

Thompson, K., & Schofield, P. (2007). An investigation of the relationship between public transport performance and destination satisfaction. *Journal of Transport Geography, 15*(2), 136-144. DOI: 10.1016/j.jtrangeo.2006.11.004.

Wu, I., & Pojani, D. (2016). Obstacles to the creation of successful bus rapid transit systems: The case of Bangkok. *Research in Transportation Economics, 60*(Supplement C), 44-53. DOI: 10.1016/j.retrec.2016.05.001.

CHAPTER 6

TRAVEL PATTERN BEHAVIOUR IN INTRA-CITY TRANSPORTATION SYSTEMS: A MARKET-BASED ASSOCIATION ALGORITHM FOR DATA MINING

6.1 ABSTRACT

Public transport can discourage individual car usage as a lifecycle asset management strategy towards carbon neutrality. An effective public transport system contributes greatly to the wider goal of a sustainable built environment; provided the critical transit system attributes are measured and addressed to improve passenger uptake of public systems by residents living and working in local communities. Travel data from intra-city travellers can advise discrete policy recommendations based on public transport demand. Passenger segments related to travelling frequency, satisfaction from the service level and its value for money are evaluated to extract econometric models/association rules. A data mining algorithm with minimum confidence, support, interest, syntactic constraints and meaningfulness measure as inputs is designed to exploit a large set of 31 variables collected for 1,520 respondents, generating 72 models. This methodology presents an alternative to multivariate analyses, to find correlations in bigger databases of categorical variables. Results here augment literature by highlighting traveller perceptions related to frequency of buses, journey time and capacity, as a net positive effect of frequent buses operating on rapid transit routes. Policymakers can address public transport uptake through service frequency variation during peak-hours with resultant reduced car dependence apt to reduce induced lifecycle environmental burdens.

6.2 INTRODUCTION

Regional constraints notwithstanding, mass-transit system plans are generally developed by municipal and transportation agencies to reduce ever-increasing traffic congestion on road networks by affecting mode choices of building residents (Dodd et al., 2015). These plans are simultaneously targeted as being environmentally conservative for the cities. The implication of adequate public transport accessibility and reduced reliance on private automobile usage towards sustainable residential areas; e.g., compact neighbourhoods, walking habits of residents, urbanisation and shared-space designs, is abundant in literature (Badland & Schofield, 2005; Yigitcanlar, Kamruzzaman, & Teriman, 2015). Other researchers, such as Zimring et al. (2005) and Cervero (2009) propose that sustainable transport systems and urban forms should be designed so as to promote sustainable modes of transport, e.g., public transport, and devise policies to discourage individual car usage, among residents.

On the other hand, transportation researchers such as de Luca (2014) and Leyden et al. (2017) argue that planning and provision of any (public) transport system is largely “flawed” as alternatives and policies are prioritised subjectively by decision-makers alone, with very little public engagement from local building occupants or consultation at the initial stages. Often public feedback generated is neglected or only marginally used to improve the existing system, which is argued by these studies to significantly increase the risk of implementing a public transport service and an overall transportation system incoherent with public expectations. This may lead to higher private automobile dependence. For example in case of high traffic volume roads, around 95% emissions are traffic-related (Hasan, Whyte, & Al Jassmi, 2019).

Diana (2012a) and de Vos et al. (2016) suggest that traveller expectations influence passenger satisfaction, which ultimately influences the variation in their ridership preference over time (public vs. private transit), hereby referred to as modal variability. Establishing the satisfaction of an individual traveller may be difficult, aligning satisfaction with travel patterns of daily passengers is important for policymakers aiming to influence mode choice and travel survey datasets are used for this purpose by transport researchers (Batarce et al., 2015). However, the presence of large quantities of variables in the travel dataset complicates the pattern discovery process of deducing the potential for passenger mode choice diversion in favour of public transport (Stathopoulos et al., 2017) and optimising the *consumer mode choice – satisfaction* dynamics. Golob and Hensher (2007) and Diana and Pronello (2010) maintain that although the patterns in large categorical variable sets may be discovered to some extent through multiple correspondence analysis, scatter plots and cross-tabulation techniques, such methods are fairly limited when many variables are to be jointly considered. Limitations of frameworks only applying these statistical analysis to study travel survey datasets can thus be avoided by data mining (Elder, 2009; Tan, Steinbach, & Kumar, 2005) through its potential to handle a large number of interrelated variables (Al-Hussaeni et al., 2018).

In Chapter 5, a multipartite model was developed by the authors to establish passenger satisfaction from the level of service (measured on network coverage and frequency) as the antecedent of building residents' mode choice. The explicit objectives of the research presented in this chapter are described below:

1. Examine the travel patterns in a representative intra-city (Abu Dhabi) dataset.
2. Present a systematic way of assessing critical factors eliciting mode choice in passenger market segments towards optimising the social, i.e., stakeholder demands, aspect of the overall LCA of transportation systems and in the process, reduce the user-transport lifecycle energy and environmental load.
3. Determine bus service desiderata for policymakers to develop an ameliorated bus service in the future, which may divert more passengers to the improved bus service.

In order to meet the study objectives, a custom travel data processing algorithm unifying association rules mining, and statistical analysis techniques is developed to identify two classes of variable combinations; statistically-significant and validated association-only. The two different groups aim to provide policymakers with the maximum information about the travel habits of passengers in the city. Whilst statistical analysis is informative and interesting, it may fail to uncover the underlying modal variability patterns and passenger behaviour which may be visualised through association rules (Chu & Chapleau, 2010; Diana, 2012b; Gürbüz & Turna, 2018). For this purpose, validation of filtered out association rules against an internal validation set was conducted to further generate a set of association rules (Ordonez, 2006; Shaharanee et al., 2011) followed by data reduction (similar to Gürbüz & Turna (2018) and Lazcorreta et al. (2008)) to remove redundant rules.

6.3 THEORETICAL BACKGROUND

6.3.1 Factors affecting travel perception and mode choice

Researchers studying factors affecting mode choice behaviour, such as Dell'Olio et al. (2010) and de Oña et al. (2012) proposed that generally any bias possessed by passengers, as *for or against* a particular travel mode (referred to as travel bias, henceforth) depending upon their unique characteristics, influences their perception of the quality attributes offered by a particular mode and may translate to a subsequent mode choice. The factors behind mode choices and variation of travel behaviour were also focused in a study conducted by Schmid, Schmutz, and Axhausen (2016). They performed a hypothetical study of a low carbon post-private car world and found public transport to be the most popular mode amongst survey respondents, followed by bikes and car-sharing. Stradling (2007) found that the modal variability of residents in a case-study Scottish housing area is temporally constrained, with 20% of private automobile users actually acting as multimodal, i.e., using several transport modes, when the analysis period is stretched over a week. Building upon this, the present study gathered passenger behavioural responses and travel pattern data over a month to investigate the sensitivity of modal shifts in long-term mobility patterns.

Friman and Fellesson (2009) and Diana (2012a) found modal variability and level of passenger satisfaction from public transport as highly dependent upon the zonal characteristics (urban vs suburban) of the study area. They noted that the travellers near the city centres tended to sway towards higher public transport usage compared to their urban/suburban counterparts. The current study addresses this issue by surveying passengers on the intra-city travel routes across all zones of a metropolitan city (Abu Dhabi) to capture the maximum variability of responses. The City of Abu Dhabi has witnessed an increase in population accompanied by an increasing passenger dependence on private vehicles (Menichetti & Vuren, 2011), resulting in traffic congestion and as such, is a suitable case study area for the purpose of this research. Furthermore, the excessive private vehicle ridership is responsible for high greenhouse gas emissions, for example in the United Arab Emirates alone, it annually exceeds 11735.6 Gg CO_2 equivalent (Environment Agency - Abu Dhabi, 2012) from road transport. The research presented in this chapter and its accompanying works (Hasan et al., 2018a, 2019) may aid in reducing the environmental burden from daily transit dimensions towards an overall sustainable future city development.

6.3.2 Data mining for analysing travel datasets

Limitations of frameworks applying only statistical analysis to study travel survey datasets can be avoided by data mining (Tan et al., 2005; Elder, 2009) through its potential to handle a large amount of interrelated variables. Provided the competitive benefit of outlining passenger expectations, perceptions and rankings of existing service level to create pro-public transport policies, a large database of underlying variables (journey time, ride quality, transit fare, accessibility, socio-demographics of passengers, etc.) are generally collected from representative population samples. The presence of large quantities of variables in the travel dataset complicates the situation of pattern discovery to deduce the potential for modal diversion and optimising consumer mode choice-satisfaction dynamics. Golob and Hensher (2007) and Diana and Pronello (2010) maintain that although the patterns in large categorical variable sets may be discovered to some extent through multiple correspondence analysis, scatter plots and cross-tabulation techniques, such methods are fairly limited when many variables are to be jointly considered.

A recent study by Liu et al. (2018) on improving the public mass-transit service quality in China acknowledges that an efficient data mining framework is capable of extracting useful information from transit data and representing it into clear and succinct policy-related recommendations. Liu et al. (2018) developed a data mining algorithm with data cleaning and filtration options. However, their proposed algorithm focused only on the time parameters and the pre-journey (accessibility, location, train/bus-station) and on-board (crowding, seating arrangements, fare and ride quality) parameters were not involved in the algorithm design.

Similarly, a Weka classifying algorithm-based data mining study on the occurrence of faults on tram lines, local atmospheric conditions and safety was performed by Gürbüz and Turna (2018). The study noted the ability of data mining algorithms to filter through large mobility datasets and association rules to visualise the interrelation between various variables in the collected dataset. Building upon these studies, the work presented in this chapter contends that many of the variables collected through travel surveys or response diaries are interdependent or associated to varying degrees. Studying them in isolation may be inadequate to study the complex relationship of categorical and nonmetric variables and recommend apposite policies to promote PT. Current literature has no such framework that can help policymakers to segregate the most desired transit service attributes from the several underlying variables affecting passenger psychometrics. This aspect is of particular importance for deducing marketing tactics aimed at attracting users that have somewhat of a neutral perception of either travel mode (bus or car) as well as retaining the loyal public transport users.

Inspired by Ponte et al. (2018), who used the Gini coefficient primarily used in economics, for measuring the public bus-transit travel time heterogeneity in municipal areas and Diana (2012b) who used association rules for studying travel pattern, this study explores the applicability of data mining techniques used in economics and marketing research. Apriori association rules data mining is used here for identifying the motivations behind passenger mode choices. Introduced by Agrawal, Imieliński, and Swami (1993) and Agrawal and Srikant (1994) for mining frequent item-sets in transaction data without using any underlying relative and distributional assumptions, it has now developed into a robust market analysis technique. Association rules identify the frequency of different variables appearing together in an observation (data) set. An association analysis reads every single row of variables on the travel datasets to produce association rules, which are of the implication form given in Equation (6.1).

$$x_i, x_j, \ldots, x_n \Rightarrow y \qquad \text{Equation (6.1)}$$

Where the left-hand side is the antecedent (a set of predictor variables) and the right-hand side is the consequent (and represents the response variable). Periodically used for frequent pattern mining in fields besides management sciences, e.g., health (Nahar et al., 2013) and weather forecasting (Hu, Zhuo, & Qiu, 2009), its application in transportation research is relatively new. Nonetheless, researchers (Diana, 2012b; Pande & Abdel-Aty, 2008) have explored the efficacy of association rules for handing large and complex travel datasets. A primary advantage of using Apriori over traditional multivariate analyses is its ability to rapidly find an association between large sets of metric and non-metric variables. Once association is established, traffic flow patterns and individual transport service attributes behind passengers' observable modal variability can be extrapolated for policy recommendations.

Conversely, one of the main drawbacks of Apriori algorithm is its tendency to produce a large number of rules, rendering the technique to be an ineffective process if no other controls are provided. Pruning the rules is the next step (Tan et al., 2004) to filter out meaningless rules that may be misleading for policymakers. Association rules are constrained by the number of times a certain rule is *supported* by the dataset and the strength of rule (i.e., *confidence*) which is the fraction of dataset rows that contain both consequent and antecedent of the rule. However, confidence is an asymmetric measure that may provide erroneous results if the consequent has a large probability (Nosratabadi et al., 2011). Moreover, if the antecedent and consequent variables are independent of each other, the generated rules may be unsuitable, irrespective of high confidence (Ma, Wang, & Liu, 2011), for establishing inference relations for policy development. Wu, Zhang, and Zhang (2004) have introduced an additional measure called "*interestingness*" to discard unsuitable association rules (Equation (6.2)).

$$Interest(X,Y) = \left| Support(X \cup Y) - Support(X) \bullet Support(Y) \right| \quad \text{Equation (6.2)}$$

6.4 MATERIALS AND METHOD

6.4.1 Survey design and analysis

A questionnaire was designed to gather data on the factors that affect user perception of the existing bus network. A total of 11 questions were developed for the survey, aimed at capturing passenger responses on the different variables according to Likert-type scales, dichotomous and multiple-choice options. This study targets the passengers in all zonal distributions (urban and suburban) of Abu Dhabi city. The survey questionnaire used for this study and the different zonal distributions are shown in Table 5.1 and Figure A.1, respectively. The eight arterial and medium to high traffic routes were selected for data collection (Table 6.1) to capture an optimally representative data of the city's usual passengers and weekly data over six weeks was collected to improve the number of observations.

Table 6.1 Bus routes selected for the purpose of the study

Outer-urban or suburban routes	**Route number**
Al Mina Souq ↔ Khalifa Park	056
Petroleum Institute ↔ Tourist Club Municipality	054
Abu Dhabi Courts ↔ Al Marina	034
Downtown city and urban routes	**Route number**
Al Mina Fish Harbour ↔ Al Marina Mall	011
Al Mina Souq ↔ Al Marina Mall	009
Al Mina Road Tourist Club ↔ Al Marina	008
Tourist Club Municipality ↔ Al Marina	007
Al Mina ISC and Tourist Club ↔ Ras Al Akhdhar	006

The survey design procedure, method and population selection followed the guidelines by the Travel Survey Manual (Tierney et al., 1996). The survey population thus included all on-board, peak/off-peak passengers on the selected routes, carrying significant proportion (~90%) of the total transport system's ridership. The completed questionnaires collected by the Department of Transport survey teams (AECOM,

2015) were then analysed. Logic checking of data consistency was performed by the authors to address data sparseness, outliers and missing data based upon the guidelines by Osborne (2014). This resulted in a useful sample of 1520 (~30% response rate) completed individual questionnaires (inclusive of weekdays and weekends surveys) of the 1.45 million population of Abu Dhabi city at the time of the survey (corresponding to a sample size margin of error of 2.51% at 95% confidence level). The collected data sample represents 0.1% of the overall population of Abu Dhabi, which are all assumed to be potential bus users. The survey also identified ten passenger segments, namely:

1. Modal variability: distribution of generated trips for each mode (i.e., bus and car travel). Five segments as *pro-sustainability* (PS) passengers (i.e., regular bus travellers and non-users of cars), *occasional multimodal* (OMD) travellers, *frequent car/taxi travellers* (FrCT) and *environmentally insensitive* (EI) passengers (i.e., non-users of public bus service).
2. Perception of bus service as value for money (VfM): trade-off between quality of ride and level of fare. Three segments of *good value for money*, *borderline value for money* and *bad value for money*.
3. Passenger satisfaction from level of service (LoS): ranked based on perception of the current level of network coverage and frequency of buses. Three segments of *good level of service*, *borderline level of service* and *bad level of service*.

The statistical distribution of the collected passenger responses is shown in Table 5.2. The study objective is finding service desiderata critical for policymakers to deter private car use and increase uptake of bus usage by developing an improved public transit service. A data mining algorithm is thus proposed below which is used to analyse the above case study passenger segments to generate variable associations for explaining the daily travel behaviour of the local passengers.

6.4.2 Conceptual framework: Overall proposed modelling approach

Current research suggests a market-based analysis that unifies "statistical measurement" and "associate data mining". The combination has been used to some extent in marketing literature (e.g., Shaharanee et al. (2011)) for filtering out redundant rules. Work here contributes by building a multi-tier modelling approach for travel survey dataset that filters "interesting rules" to split them into two distinct categories: associated rules; and, statistically-significant models. Initially, the generated rules are filtered using an "interestingness measure" from Equation (6.2). The filtered rules are then used to build ordinal regression models, followed by (only) selecting meaningful rules at the filtration stage 2. "Meaningful rules" are defined as those that provide association between the variables that have not been already construed by the other rules passing the minimum thresholds, thereby rejecting the repetitive or redundant sets of rules. The problem is further explained in Figure 6.1.

Definition 1: Let $V = \{x_1, x_2, \dots, x_m; y_1, y_2, \dots, y_n\}$ be the set of variables, where x_m and y_n are respectively the antecedent and consequent variables. Apriori algorithm predicts sets of association rules R_1, R_2, R_3 as $R = \{R_1, R_2, R_3, \dots, R_{xy}\}$ or $R = \{(x_1, x_2 \Rightarrow y_1); (x_1, x_2, x_3 \Rightarrow y_2); \dots; (x_1, \dots, x_m \Rightarrow y_n)\}$. Note: there may be some rules in set R whose variables imply the same relation or association. Towards a simplified form of the classic set cover problem to provide an approximation solution with M as a set of meaningful rules, defined by the following relation:

$$\text{M} \subseteq \text{R} \ \exists \forall \text{ rule in R} \in \text{rules in M}$$

Figure 6.1 Definition of "meaningfulness measure" to filter repetitive rules

This twofold technique proposed in this study filters out redundant rules and provides final sets of statistically significant rules. The rejected rules are then analysed in the second phase by a validation technique using a validation set. It is argued here that this technique will remove any misleading rules while still retaining a significant number of rules for policymaking without compromising the analysis accuracy. The proposed conceptual framework is presented in Figure 6.2. It should be noted that there are several off-the-shelf packages available for performing the Apriori association mining (Diana, 2012b). However as this chapter proposes a unified framework, a tailored JavaScript was used for data mining due to its compatibility with SPSS 23.0 regression functions, which can then be used to perform ordinal regression on the observed rules.

The initial travel dataset "ζ" was cleaned to ensure a high quality of the dataset is fed into the analysis algorithm. Data cleaning is an important step in the knowledge discovery process from analysis of predictor and response variables as it removes missing or anomalous values (Osborne, 2014). Numerical values of household car-ownership and time to reach bus stations were also transformed into nominal variables using equally distributed classes to maintain uniformity in the data variable classes and ease the analysis procedure.

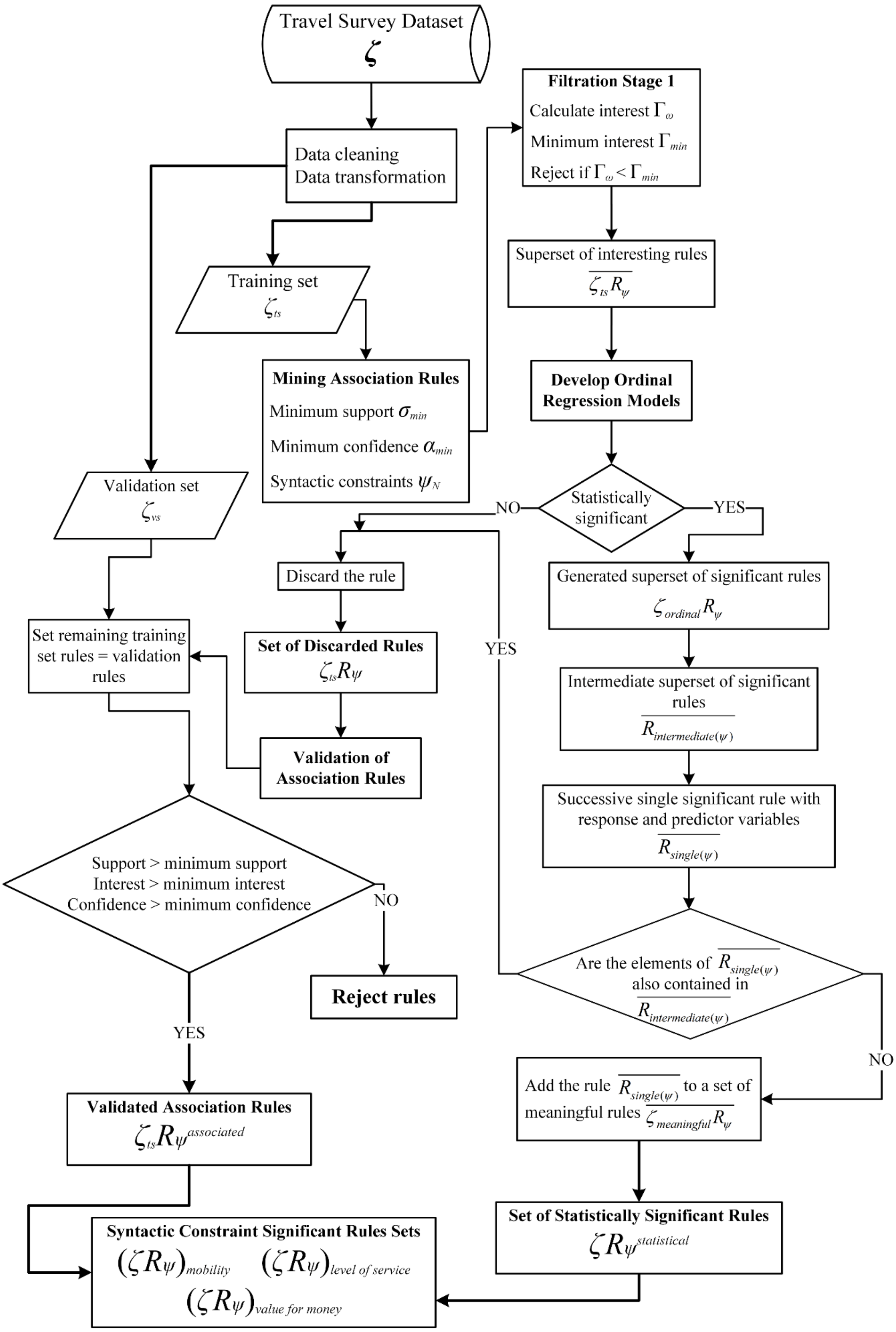


Figure 6.2 Conceptual framework of the proposed data mining algorithm

The resulting dataset was then randomly split into a training dataset (ζ_{ts}, containing ≈ 70% data) and, a validation dataset (ζ_{vs}). The training dataset was then used for generating an initial set of association rules: frequency of bus travel (FBT); frequency of car/taxi travel (FCT); satisfaction with network coverage (NetCov); quality of ride (QoR); level of fare (LvlFare); and, frequency of buses (FreqBus) which were used interchangeably as response variables based upon the desired output.

In order for the algorithm to generate association rules, there should be at least one tuple in the dataset for each observation. Given our target of finding policy-related hotspots towards PT uptake, syntactic constraints were put towards the consequent-side based upon the market segments. According to the principles of Apriori data mining, only one response variable can be set as a consequent. Therefore, response variables were interchangeably used as consequent for obtaining association rules for the respective category and obtain sets of rules specific to each segment, e.g., frequent car travellers, travellers ranking bus service as good value for money, and so on.

Past literature has suggested that higher support and confidence relate to a better category of rules but that lower values of support and confidence are still recommended. Therefore, to capture the most "interesting" rules, minimum support and confidence were respectively set here at 0.1 and 65% (Chu & Chapleau, 2010; Diana, 2012b). After appropriate data transformation and setting syntactic, support and confidence constraints, a number of frequent item rules were obtained for each category. The "interestingness measure" was used in the first filtration stage by setting a minimum interest value "Γ_{min}". The association rules mining through the Apriori algorithm permits the analysts to set the minimum threshold for selecting useful models from a large set of created rules. Large numbers of association rules are initially generated which are then pruned by the analysts to reject falsely produced rules from the ruleset that fail to qualify the established minimum threshold.

Evaluating the minimum threshold in the analysis may be guided through past experience or research literature. Therefore, in the present analysis, a minimum interest value of 0.05 was selected (de Luca, 2014; Shaheen & Shahbaz, 2017) with any future application of the proposed algorithm able to use a higher or lower value depending upon the study objectives. The retained rules were then used for ordinal regression analysis. The ordinal regression analysis calculated *log-likelihood* and *p-values* for the models (the models were based on the association rules). Models that showed considerable change in *log-likelihood* compared to null model and p*–values* < 0.05 were retained. The repetitive rules were then rejected using the theory defined in Figure 6.1 and the retained rules were used to represent the statistically-significant rules. The remaining rules were then used in phase II of the analysis to validate against the validation set while controlling for the minimum support, interest, confidence and non-repetitive criteria as discussed earlier. The algorithm proposed in this study is illustrated in Figure 6.3.

Input: Dataset ζ consisting of 31 travel attributes, minimum confidence, minimum support, minimum interest and number of rules across 1,520 questionnaires.

Syntactic Constraint Parameters: *FBT*, *FCT*, *NetCov*, *FreqBus*, *QoR*, *LvlFare* (**interchangeable**).

Output: $(\zeta R_{\psi}^{statistical})_t, (\zeta R_{\psi}^{associated})_t$;

As significant rules $| \; t \in \{\text{mode use, level of service, value for money}\}$.

1. Data transformation: transform numeric attributes into nominal variables.
2. Dataset partition: split dataset into training dataset ζ_{ts} and validation dataset ζ_{vs}
3. **<u>Phase I</u>:** Generation of rules using ζ_{ts} based on syntactic constraints.

a. Using minimum support σ_{min}, minimum confidence α_{min} and syntactic constraints ψ_N for $N \in \{\text{FBT, FCT, NetCov, FreqBus, QoR, LvlFare}\}$; **return** $\overline{R_{initial\ set(\psi)}}$ as a superset of association rules.

b. **Filtration stage 1**, rejecting uninteresting rules based on minimum interest Γ_{min}

- **For any association rule** $\overline{R_{\psi}}$ contained in superset $\overline{R_{initial\ set(\psi)}}$ as a subset, $\overline{R_{\psi}}$ describes the association between predictor variable(s) "X" and response variable "Y", **calculate** interestingness as per Equation (6.2).
- **If** interest Γ_{ω} of rule $\overline{R_{\psi}}$ is less than Γ_{min}; **reject rule** $\overline{R_{\psi}}$ as uninteresting
- **Return** remaining interesting rules as subsets in the superset $\overline{\zeta_{ts} R_{\psi}}$.

c. **Develop** ordinal regression models $\overline{\ln(\psi_k)}$ for each response variable ψ in $\overline{\zeta_{ts} R_{\psi}}$

Compute; log-likelihoods *LL*,

Coefficients β_i of predictor variables x_i and *p–values*.

d. **Filter** rules in superset $\overline{\zeta_{ts} R_{\psi}}$ based on computed $\overline{\ln(\psi_k)}$ models.

For all $\overline{\ln(\psi_k)} \in \overline{\zeta_{ts} R_{\psi}}$

- **If** $\beta_i x_i$ insignificant; **reject** the model $\overline{\ln(\psi_k)}$

Return retained rules passing statistical significance test in superset $\zeta_{ordinal} R_{\psi}$

e. Filtration stage 2, rejecting redundant rules postulating similar results

- **For** the superset $\zeta_{ordinal} R_{\psi}$, **construct** an intermediate superset $\overline{R_{intermediate(\psi)}}$ containing all rules in $\zeta_{ordinal} R_{\psi}$, **while** $\overline{R_{single(\psi)}}$ is any single association rule from $\zeta_{ts} R_{\psi}$ containing response and predictor variables
- **Select** $\overline{R_{single(\psi)}} \in \zeta_{ts} R_{\psi}$ by maximising $\left| \overline{R_{single(\psi)}} \cap \overline{R_{intermediate(\psi)}} \right|$
- **At each stage** $\overline{R_{intermediate(\psi)}} \leftarrow \overline{R_{intermediate(\psi)}} - \overline{R_{single(\psi)}}$
- **And** $\overline{\zeta_{meaningful} R_{\psi}} \leftarrow \overline{R_{intermediate(\psi)}}$, as sets of meaningful rules

f. Denote retained rules as $\zeta R_{\psi}^{statistical}$;

g. Set rejected rules from both **Stages d and e** as $\zeta_{ts} R_{\psi}$

4. **<u>Phase II</u>:** Validate rules $\zeta_{ts} R_{\psi}$ on ζ_{vs}.

Set $\zeta_{vs} R_{\psi} = \zeta_{ts} R_{\psi}$. **Compute** support σ & confidence α for each rule (X⟹Y) on ζ_{vs}

Reject rules with $\sigma < \sigma_{min}$, and $\alpha < \alpha_{min}$

Only repeat Step 3b (Filtration Stage 1) and **Step 3e (Filtration Stage 2)** to further cleanout uninteresting rules as retain only non-repetitive rules.

Label retained rules as $\zeta R_{\psi}^{associated}$; $\exists \zeta R_{\psi}^{associated} \in \overline{\zeta_{ts} R_{\psi}}$ and $\zeta R_{\psi}^{associated} \notin \zeta R_{\psi}^{statistical}$

5. **<u>Phase III</u>: Group** remaining rules into syntactic constraint significant rules sets as: $(\zeta R_{\psi})_{\text{mode use}}$, $(\zeta R_{\psi})_{level\ of\ service}$, $(\zeta R_{\psi})_{value\ for\ money} \subset (\zeta R_{\psi}^{statistical} \cup \zeta R_{\psi}^{associated})$

Figure 6.3 Proposed data mining algorithm for the studied travel dataset

6.5 RESULTS

6.5.1 Performance of the proposed algorithm

The initial application of the proposed algorithm produced a large set (~1559) of association rules between the collected variables in the travel dataset that passed the minimum support (σ_{min} = 0.1) and minimum confidence (α_{min} = 65%) thresholds set in Step 3a of the algorithm proposed in this study (Figure 6.3). Filtration stage 1 (Step 3b) was then applied to remove uninteresting rules based on Equation (6.2) with the minimum interest threshold (Γ_{min} = 0.05). This way only 351 or 22.5% of the association rules were retained in the so-called intermediate superset as interesting rules. These 22.5% remaining association rules were then subjected to the algorithm stages in Step 3c and Step 3d and ordinal regression models were developed for each rule. All the association rules with insignificant p-values for coefficients were filtered out as a separate superset. Approximately 231 or ~65.8% of the remaining association rules passed the ordinal regression performance tests and were collected in a superset of ordinal rules. Although all of these 231 association rules may be useful for developing some pro-public transit policies, the large number of rules may be impractical for policy analysis and may also have some redundant or reoccurring relations (Gürbüz and Turna, 2018). The algorithm steps of feature selection and Filtration Stage 2 were thus used for data-reduction to filter out redundant rules using the superset of the 231 ordinal regression rules, as explained below.

First, an intermediate superset was created as an exact copy of ordinal rules superset and using variable selection, any smaller association rule subset (e.g., {FBT 5 or more times a week, Weekday ⟹ Very satisfied with level of fare}) implying an association or interrelation already present in a larger subset association rule (e.g., {FBT 5 or more times a week, Employed full-time, Weekday ⟹ Very satisfied with level of fare}) already present in the intermediate superset was removed. The steps were automatically repeated for all the remaining association rules subsets as rules describing an existing or reoccurring association were redundant since they were already contained in the larger subset in the intermediate superset. This way only 25 or ~11% of the 231 ordinal regression rules were retained in the so-called intermediate superset as statistically-significant rules in Step 3f, while the filtered out rules (total of 326 rules) from both Step 3d and Step 3e were collected in a separate superset.

Using the validation travel dataset, 213 rules or approximately 65% of these discarded rules were found to be validated in Phase II, where again filtration approach based on interestingness measure (Step 3b) and meaningfulness (Step 3e) resulted in retainment of 22% or 47 rules in the superset of association-only rules. Finally, both supersets were grouped to give three association rules sets for 1) mode use, 2) level of service, and 3) value for money. Figure 6.4 presents the results of applying various filtration techniques in the developed algorithm where Phase III results present the grouping of phase I and II association rules. The overall algorithm application managed to filter out a total of 95% (~1487 rules) of initially obtained association rules (total rules: ~1559) as redundant or insignificant to the total travel dataset, generating a total of ~5% or 72 rules for policy-making purposes.

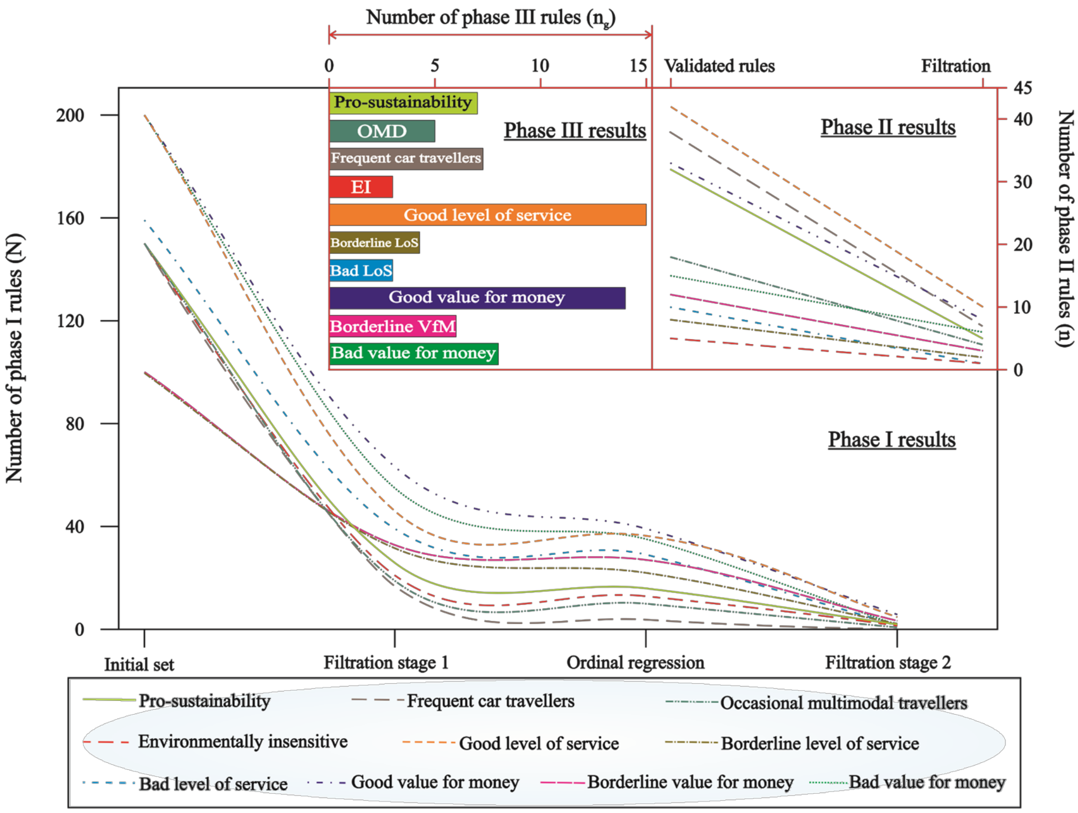


Figure 6.4 Filtration results of different phases in the developed algorithm

The results from each phase are separately presented below to elucidate the respective findings. An importance index is also introduced to summarise public perception of the existing service. Policy recommendations are also given related to improving public (bus) transport ridership among the local passengers.

6.5.2 Phase I results: Public responses from statistically significant rules

Ordinal regression showed that a majority of the passengers reported bus travel to be easy and that 36% were willing to pay more for a seat. Full-time workers were more flexible towards bus use than the younger respondents. Furthermore, as the collected data was skewed towards male passengers, some of the association rules were found to be affected by the gender of the respondents. On the other hand, only a few of the quality attributes of the bus service were found to be statistically significant. In addition, the statistically significant models also failed to produce inference between the purpose of the passengers' journey and their mode choice, thereby requiring further analysis in phase II. The ordinal regression performance results of the meaningful association rules, retained after the second filtration stage, are presented in Table 6.2.

6.5.2.1 Affordability and constrained users

In the first block of mode use results, the odds of a full-time employed passenger to choose public transport was 6-7 times that of their unemployed counterparts (*PS rule 1*: $\chi^2 = 72.68, p < .001$)). The passengers admitting affordability of private automobiles were 1.3 ($p < .05, \chi^2 = 140.07$: *OMD rule 1*) times more likely to be multimodal and 0.85 ($p < .05, \chi^2 = 39.96$: *EI rule 1*) as likely to be first time travelling by bus compared to others. Further exploring the affordability of the bus service exhibited that the passengers with a "very satisfied" perception of level of fare, also had 6.72 times likelihood of travelling 5 or more times/week by bus transport (*Good VfM rule 2*). The passenger satisfaction of public transport service level exhibited a slight decline relative to passenger travel time to the nearest bus-stop (see *rule 2* of *borderline level of service* and *rule 1* of *bad value for money*). Similarly, modal variability was affected when analysed against the same attribute as both *rule 2* of *pro-sustainability* and *rule 2* of *environmentally insensitive* market segments. Moreover, the passengers reporting buses to be crowded, were also twice as likely to belong to the environmentally insensitive group, indicating its significance in defining this market segment.

6.5.2.2 Crowded buses

Rules pertaining to crowded buses were found in both less frequent bus users (*EI rule 2*) and bad service level (*Bad LoS rule 1*) groups. The passenger market segment willing to pay more for a seat in the bus, were also 1.16 times more likely to hold a neutral perception of the level of fare (*Borderline VfM rule 3*: $p < 0.05$, $\chi^2 = 62.22$) and 0.71 times more likely to be very dissatisfied ($p < 0.01, \chi^2 = 632.49$: *Bad VfM rule 2*). This implies that merely increasing the number of seats may at first persuade borderline users, but may not affect dissatisfied travellers to the same extent. Interestingly, travellers labelling buses as crowded were 1.62 times as likely to be "dissatisfied" by the frequency of buses (*Bad LoS rule 2*). Even though a direct relationship between the variables may have been unperceived, a deeper correlation may be present as less frequent buses on the travel routes serving the commute demands of these passengers may impose a higher load on the existing buses. This finding indicates the presence of a potential target market (of borderline and dissatisfied passengers) for PT uptake by implementing a more frequent service.

Table 6.2 Predictors of modal variability and service perception from association rules passing ordinal regression performance test

Rules	Predictor variables	Odds ratio	Response variable category	Model χ2 ***	– 2LL†	Group
1	Employed full-time Willingness to pay more for seat	6.71*** 0.47***	Bus travel > 2 times a week	72.68	72.68	PS
2	5 – 15 min to bus stop No cars	2.22** 1.86*	Bus travel > 2 times a week	67.18	67.18	PS
1	Car/taxi is inexpensive Weekday	1.30* 0.27***	Once a week by car	140.07	1.54	OMD
1	Living near friends & family is important Car/taxi is inexpensive	0.47*** 0.85*	First time by bus	39.96	46.46	EI
2	Buses are crowded 5 – 15 min to bus stop	2.04*** 2.21**	First time by bus	57.41	41.62	EI
1	Male Bus travel is easy	14.1*** 1.27*	Very satisfied with frequency of bus	42.48	57.41	Good LoS
2	Very satisfied with network coverage Very Satisfied with ride quality	2.88* 2.67**	Very satisfied with frequency of bus	352.27	167.16	Good LoS
3	Very satisfied with frequency of buses	7.49***	Very satisfied with network coverage	354.67	140.07	Good LoS
4	Male Employed full-time Bus travel is easy	6.06** 5.61** 1.30*	Satisfied with network coverage	39.23	139.62	Good LoS
5	Satisfied with journey time	13.22***	Satisfied with network coverage	214.14	42.48	Good LoS
1	Neutral on network coverage	7.08***	Neutral on frequency of buses	348.09	140.74	Borderline LoS
2	Willingness to pay more for seat 5 – 15 min to bus stop	1.87*** 0.56*	Neutral on network coverage	47.70	352.27	Borderline LoS

1	Car/taxi is inexpensive Buses are crowded	0.53*** 1.62***	Dissatisfied with frequency of bus	38.145	155.53	Bad LoS
2	Dissatisfied with frequency of buses	10.45***	Dissatisfied with network coverage	354.67	385.31	Bad LoS
1	Satisfied with frequency of buses	9.65***	Satisfied with ride quality	164.79	38.15	Good VfM
2	FBT 5 or more times a week Employed full-time Weekday	6.72*** 3.66*** 3.69***	Very satisfied with fare level	671.05	214.14	Good VfM
3	Very Satisfied with ride quality	2.86***	Very satisfied with fare level	97.02	47.71	Good VfM
4	Employed full-time Car/taxi is inexpensive	3.48*** 1.24*	Very satisfied with fare level	54.11	354.67	Good VfM
5	Satisfied with journey time Employed full-time	3.68** 6.36***	Satisfied with fare level	66.09	26.66	Good VfM
1	Neutral on network coverage	3.89***	Neutral on ride quality	210.79	354.67	Borderline VfM
2	Neutral on frequency of buses	8.48***	Neutral on ride quality	164.79	39.23	Borderline VfM
3	Employed full-time Willingness to pay more for seat	4.95** 1.16*	Neutral on fare level	62.22	7.68	Borderline VfM
1	Dissatisfied with bus-station 5 – 15 min to bus stop	14.3*** 2.68***	Dissatisfied with ride quality	288.16	21.18	Bad VfM
2	Willingness to pay more for seat Delayed by traffic congestion Weekend	0.71** 0.75* 0.04***	Very dissatisfied with fare level	632.49	164.80	Bad VfM

PS = pro-sustainability, OMD = occasional multimodal travellers, FrCT = frequent car travellers, EI = environmentally insensitive, LoS = level of service, VfM = value for money.

$*p < 0.05$, $**0.001 \le p < 0.01$, $***p < 0.001$. † *Difference in -2 log likelihood of final model and null model.*

Proposing investment in the number of units of supply (buses) to meet this local need can then be countered by slightly higher fares and it may optimise the financial elasticity of the publicly-owned transport agencies. It is reiterated by the observance of travellers "satisfied" with journey time, as 13.22 times likely to be also satisfied with the network coverage (*Good LoS rule 5*: $p < 0.001$, $\chi^2 = 214.14$). It should also be noted that the two indicators of level of service, namely *network coverage* and *frequency of buses* were found to be highly correlated as the travellers who were "very satisfied" with the coverage were 2.88 times more likely to have the same perception of the frequency (*Good LoS rule 2*: $p < 0.05$, $\chi^2 = 352.27$). Passengers were also around 7 times more likely (*Borderline LoS rule 1*: $p < 0.001$, $\chi^2 = 348.09$) to hold a neutral perception of network coverage, causing a neutral opinion of the bus frequency, and 10.45 times more likely to be dissatisfied with both; thereby exhibiting a strong correlation between the two attributes. A follow-up lifecycle study on the cost of running this more frequent (shorter headways) PT service is conducted in Chapter 8.

6.5.2.3 Dynamics of bus fare, quality and frequency

Exploring the reciprocity between fare and quality added to this recommendation of a more frequent bus service supported by higher fares. The passengers unequivocally associated "levels of fare" with "quality of ride" (*rule 3* of *good VfM; OR =2.86,* $p < 0.001$, $\chi^2 = 97.02$), so the bus transit was regarded as a value worthy of riders' money. Statistically, quality of ride was also found to be constrained by the frequency of buses as passengers satisfied with frequency were 9.65 times more likely to be also satisfied by the quality of ride (*rule 1 of good VfM;* $p < 0.001$, $\chi^2 = 164.79$) and similar trends of interdependency were observed for the neutral perception of these three variables. This study implies that unlike findings of previous studies (Bachman and Katzev (1982) and Savage (2010)[7]), and fortifying the observations by Tirachini (2013) and Tirachini et al. (2014), decreasing levels of fare may not be solely responsible for influencing the perceptions of passengers regarding existing public transport services.

A slight increase in fares may be justified by more frequent buses or a higher ride quality; even though more frequent bus travellers exhibited an unwillingness to pay more for seats, a sizeable increase in the frequent bus passengers may be achieved by optimising the "fare-frequency-quality" dynamic due to modal diversion, i.e.,

[7] Reduced fare caused by less frequent service or fare subsidies to increase ridership.

occasional multimode (both bus and car) users and frequent car travellers shifting towards higher bus service ridership. Transportation strategists traditionally propose a balance between frequency of buses, journey time and the level of fare (Savage, 2010), but fall somewhat short of indicating how the balance affects passenger behaviour and perception. As the fares were recently increased by the Department of Transport – Abu Dhabi, the observations of the current study may be of significance to the policymakers to understand the straightforward implications of such decisions in the studied traveller market. A benefit of the proposed algorithm is that the endogenous variables determining the perception of these variables among the passenger market segments are analytically filtered across a broad range of travel attributes.

6.5.3 Phase II results: Policy insights from validated association rules

Mode choice dependency trends and bus ridership characteristics were further studied by analysing the association rules filtered out from phase I. Table 6.3 presents the validated association rules, grouped analogous to market segmentation analysis (Hasan et al., 2018b). Some interesting econometric models about the journey purpose and backgrounds of the passengers were found; contrary to past research, this study found that statistical analyses alone may be deficient for capturing detailed characteristics of the traveller market. Inner correspondence of association rules was also partially detected by *rule 1* of PS where first time car travellers at the time of the survey, indicated to be more frequent bus users.

6.5.3.1 Targeting work commutes and full-time workers

Studies on full-time workers have found that a majority of them use private automobiles for work commutes (Stephan & Stephan, 2016; Wang & Chen, 2012), yet research targeting work-related commutes to encourage public transport use is usually neglected. Policymakers may need to further investigate the quality improvements for attracting these consumers as this study found full-time workers commuting to/from work as predominant in both occasional multimodal (*OMD rule 3*) and frequent car travellers (*FrCT rule 1*). These findings are also consistent with the previous findings by Horner and Mefford (2005) where the potential of public transit for work-related commutes was recognised. Furthermore, the need to live close to the place of work and/or friends and family was one of the primary elicited reasons across all segments (e.g., *PS rule 4*, *Good LOS rule 7*, *Borderline LOS rule1* and *Good VfM rule 5*).

6.5.3.2 Budgetary constraints, bus service frequency and network coverage

This work found that the environmentally insensitive passengers, i.e., those who primarily use private automobiles for daily travel (*rule 1* of *EI*), were largely satisfied with the public transport fare level. It can be inferred that the budgetary constraints and pricing of the service may be of little or no concern to such users (high social or financial background, employment status, etc.) and there can be several underlying reasons that may motivate their mode choice shift to public buses, if at all. Frequent car travellers indicated a willingness to pay further after observing a need for seat as a major concern (*rule 5* of *FrCT*) and attributed no delays due to traffic congestion during their daily commute. Phase II results also showed that some passengers may have been compelled to use public transport due to necessity, *rules 1* and *4* of *PS* (no driving license or car-ownership). Investigation of the rules on neutral and dissatisfied consumers of both *LoS* and *VfM* also revealed that financially (or otherwise) obliged travellers might have settled for public transport against a more idealised mode.

Consumer satisfaction from the level of fare was also found to be dependent upon the quality of ride, thereby confirming initial perceptions that passengers perceive fare as a function of ride quality, as presented in *rule 2* of *VfM*. This is also largely consistent with the findings of Hensher et al. (2003) and fare resilience addressed in the literature review by Redman et al. (2013) where fare was largely associated with service quality. It is likely that the solution to motivating transit mode choice shift from private vehicles and/or improving the service perception may not be a reduction in fares but delivering consumer-expected quality for the charged price. One interesting finding of phases I and II was the tendency of a majority of passengers to purchase cash tickets instead of monthly passes regardless of the transit service perception. Marketing policies for monthly fare collection may prove to be significant in this regard. Additionally, follow up analysis attributed to *rules 1* and *2* (*good LoS*) and *rules 1*, *4*, *5*, *6* and *7* (*good VfM*) exemplifies that contrary to past research (see Redman et al. (2013)), economic restraints only partly diminish the passengers' positive cognitive assessment of the public transport. Moreover, perception of the service quality attributes, such as journey time was also found to influence the satisfaction from level of bus service and should also be carefully considered by the policymakers.

Table 6.3 Validated association rules for the interdependency of studied transit-related variables[††]

Rules	Antecedent		Consequent	Group	Support	Confidence	Interest
1	> 5 times/week by bus, Weekday, No cars	⟹	First time by car	PS	0.526	0.837	0.493
2	Work-related commute, Employed full-time	⟹	> 5 times/week by bus	PS	0.389	0.702	0.215
3	Residential apartment, 5 – 15 min to bus stop	⟹	> 5 times/week by bus	PS	0.380	0.705	0.115
4	No driving license, Living near friends & family is important	⟹	2 – 4 times/week by bus	PS	0.206	0.724	0.076
1	Cash ticket, No driving license, Pay seat, Buses are crowded	⟹	1 – 3 times/month by bus	OMD	0.319	0.681	0.295
2	Male, No driving license, No delays by traffic congestion	⟹	1 – 3 times/month by bus	OMD	0.291	0.662	0.264
3	Work commute, Employed full-time, Weekday	⟹	1 – 3 times/month by car	OMD	0.198	0.850	0.160
4	Male, Employed full-time, 5 – 15 min to bus stop, Weekday	⟹	Less often by car	OMD	0.239	0.633	0.113
1	Employed full-time, Buses are crowded, Weekday	⟹	Once a week by car	FrCT	0.441	0.857	0.422
2	25 – 34 years old, Weekday, Employed full-time	⟹	Once a week by car	FrCT	0.310	0.725	0.291
3	Work commute, Employed full-time, Pay for seat	⟹	Once a week by car	FrCT	0.296	0.791	0.282
4	No delays by traffic congestion, Weekday	⟹	Once a week by car	FrCT	0.235	0.884	0.213
5	Male, Willing to pay more for seat	⟹	Less often by bus	FrCT	0.251	0.826	0.201
1	Cash ticket, Satisfied with level of fare, 5 – 15 min to bus stop	⟹	> 5 times/week by car	EI	0.221	0.830	0.214

1	Very satisfied with journey time, Employed full-time	⟹	Very satisfied with frequency of buses	Good LoS	0.467	0.756	0.406
2	Very satisfied with network coverage, No cars	⟹	Very satisfied with frequency of buses	Good LoS	0.432	0.835	0.376
3	Very satisfied with journey time, Male	⟹	Very satisfied with network coverage	Good LoS	0.417	0.883	0.357
4	Very satisfied with quality of ride, Male	⟹	Very satisfied with network coverage	Good LoS	0.394	0.854	0.329
5	Satisfied with quality of ride, Male	⟹	Satisfied with frequency of buses	Good LoS	0.411	0.829	0.217
6	Male, 5 – 15 min to bus stop	⟹	Very satisfied with network coverage	Good LoS	0.342	0.752	0.185
7	Living near friends & family important, Bus travel is easy	⟹	Satisfied with network coverage	Good LoS	0.352	0.773	0.158
8	Male, Cash ticket, No delays by traffic congestion	⟹	Very satisfied with network coverage	Good LoS	0.247	0.730	0.111
9	Rent under 10,000 AED per annum	⟹	Very satisfied with frequency of buses	Good LoS	0.206	0.628	0.094
1	Employed full-time, Living near work important, No cars	⟹	Neutral on frequency of buses	Borderline LoS	0.362	0.660	0.260
2	No driving license, Employed full-time, No cars	⟹	Neutral on frequency of buses	Borderline LoS	0.258	0.607	0.148
1	Work commute, Male, Living near work important, Weekday	⟹	Very dissatisfied with frequency of buses	Bad LoS	0.169	0.715	0.164
1	> 5 times/week by bus, Cash ticket, Employed full-time	⟹	Satisfied with level of fare	Good VfM	0.518	0.937	0.354

2	Very satisfied with quality of ride	⟹	Very satisfied with level of fare	Good VfM	0.400	0.770	0.335
3	Cash ticket, Employed full-time, Weekday	⟹	Very satisfied with level of fare	Good VfM	0.249	0.799	0.165
4	Satisfied with journey time, Male	⟹	Satisfied with quality of ride	Good VfM	0.351	0.881	0.163
5	Living near friends & family is important, No cars	⟹	Satisfied with quality of ride	Good VfM	0.369	0.826	0.105
6	Bus travel is easy, No cars	⟹	Very satisfied with quality of ride	Good VfM	0.270	0.832	0.103
7	South Asian, Weekend, Cash ticket	⟹	Satisfied with level of fare	Good VfM	0.307	0.819	0.091
1	No driving license, 5 – 15 min to bus stop, No cars	⟹	Neutral on quality of ride	Borderline VfM	0.268	0.736	0.188
2	Buses are crowded, Cash ticket	⟹	Neutral on level of fare	Borderline VfM	0.278	0.742	0.159
1	Cash ticket, Employed full-time, Weekend	⟹	Dissatisfied with level of fare	Bad VfM	0.427	0.877	0.403
2	Cash ticket, Dissatisfied with bus-station	⟹	Dissatisfied with quality of ride	Bad VfM	0.266	0.922	0.262
3	Cash ticket, Neutral on journey time, Weekend	⟹	Very dissatisfied with quality of ride	Bad VfM	0.188	0.739	0.186

††*The reported confidence, support and lift are based upon the original observations in the training dataset.*

Some values are rounded-off.

6.5.3.3 Journey time and ride quality

Rule 3 of *bad VfM* suggests that the passengers mentioning a neutral opinion of the journey time were very dissatisfied with the quality of the ride. It implies passenger sensitivity to journey time (Sottile, Cherchi, & Meloni, 2015). In addition to confirming previously noticed significance of journey time on passenger satisfaction (Hensher et al., 2003) and mode choice (Nguyen-Phuoc et al., 2018), phase II of the proposed algorithm was also able to pinpoint the contingent service level factors (namely frequency of buses and crowded buses). Policymakers can then predict the relative influence of changing any of the antecedent variables on passenger satisfaction from remaining variables and the subsequent mode choice. Another implication was the relative nature of ride quality and network coverage (Rule 4 of *good LoS*), also noticed in ordinal regression performance.

6.5.4 Public-accorded desiderata for value-added bus service for local residents

Public demand-based policy implications for the bus service to improve ridership are distributed across the generated "meaningful rules". In order to encapsulate the findings of the proposed algorithm, this work also sought to solve an importance index (I_{in}) to estimate the policy recommendations consistent with the public demands. For a response variable ψ in the phase III results, with categorical values ranging from *1* to *N*, the importance index can be calculated for a predictor variable x_i as shown in Equation (6.3). It should be worth noting, as the predictor variables are also nominal in nature, only one value η is used at a time to determine the index (I_x) for the specific predictor variable. The results of applying Equation (6.3) and (6.4) on the grouped association rules of phase III are illustrated in Figure 6.5 and have been summarised to some degree to eliminate similar findings from any particular passenger market segment. For example, the variable category *Weekday* was kept for only frequency of car travel despite its occurrence in the results for frequency of bus travel models:

$$I_x^\eta = \left[\sum_{\psi=1}^{N} (x_i)_\psi \right]_\eta \qquad \text{Equation (6.3)}$$

$$I_{in} = \frac{I_x^\eta}{\max\left(I_x^\eta\right)} \times 100 \qquad \forall\, I_x \in \textit{phase III rules}, \qquad \text{Equation (6.4)}$$

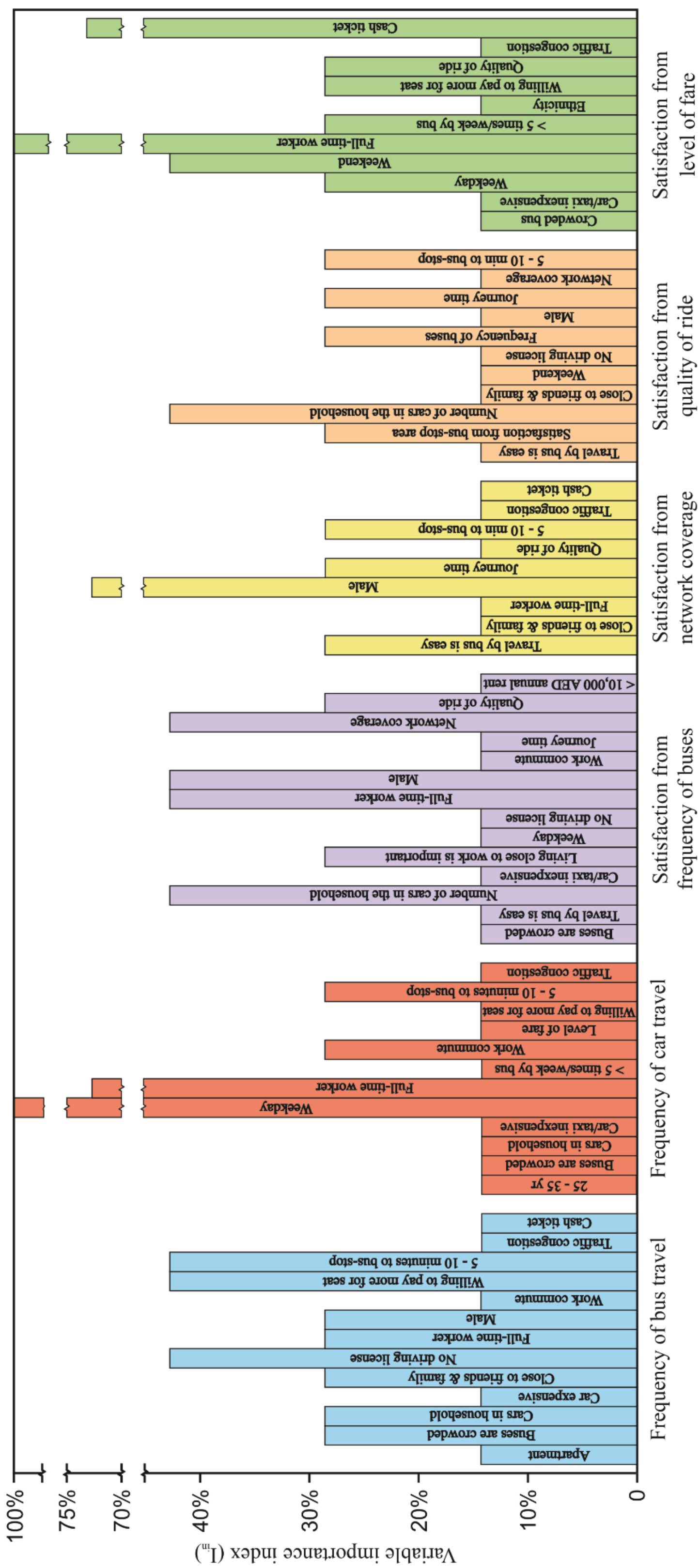


Figure 6.5 Importance index values for the phase III association rules

Findings here suggest that full-time workers formed the major portion of the target market, and frequently commuted on the case study routes during weekdays. These study observations were distinct from some of the past studies that analysed only segregated student and young traveller markets (Nobis, 2007), whereas a majority of the young users studied in this chapter travelled by private automobiles. Further findings are detailed in the text below.

6.5.4.1 Existing nodal (bus-stop) distribution is adequate

The survey respondents generally stated travelling a short distance to reach the nodes (bus-stop) across the studied travel routes and thus the time to reach bus-station only had a nominal effect on the modal variability of their occupants. For example, $I_{in} = 45.57\%$ for the frequency of bus travel and $I_{in} = 28.57\%$ for satisfaction from network coverage and ride quality. This study, therefore proposes that establishing more bus-stations on the studied routes may not necessarily encourage them to shift towards bus transport. This is a policy-sensitive observation and different from some of the past studies (e.g., Chien and Qin (2004)). However, as Heinen and Chatterjee (2015) found in their review on the status of research in transportation literature, few of the studies extensively explored modal variability over long-term and a majority only utilised a limited set of categorical variables to study university students or employees living in near-work communities, which may have also restricted their findings in terms of application to real-world situations.

6.5.4.2 Optimise journey time to impact passenger satisfaction

Intrinsically, importance indices from this study for network coverage and quality of ride show that the passengers assume upper and lower bounds of journey time regardless of mode choice, in line with past works (Milakis, Cervero, & Van Wee, 2015). Any deviation in either direction causes a positive/negative ripple in the passenger predilection of the service depending upon the journey time, confirming findings from previous research (see Hensher et al. (2003)). In general, the passengers satisfied with the journey time on public bus transit were also satisfied with its network coverage ($I_{in} = 28.57\%$) and ride quality ($I_{in} = 42.86\%$). This supports the findings of previous studies (Tirachini, 2013; Yao et al., 2014) where the travellers were found to associate public transport as a slow and inflexible travel mode and the importance of journey time in promoting modal diversion among local passengers towards a more sustainable mode (e.g. buses) was identified. On the other hand, unlike some of the past works (Eriksson, Friman, & Gärling, 2008; Kingham, Dickinson, & Copsey, 2001), results gathered by this work found that the passengers admitting affordability of private automobiles were more likely to be multimodal in their transit behaviour.

6.5.4.3 Bus service frequency, crowded buses, and level of fare

Results here argue that the public ranking of the ride quality was influenced more by the frequency of bus service (I_{in} = *28.57%*) and less by the level of fare. The passengers interviewed were also found to be mainly concerned with the low capacity (crowded) buses, as both frequent bus and car travellers labelled the existing buses to be crowded. Other similar interesting correlations were also found, as the passengers who commented on over-crowded buses were also dissatisfied with the frequency of buses (I_{in} = *14.29%*) and level of fare. It builds upon the deductions from the econometric ordinal models that even though the passengers satisfied with the fare level travelled the most by buses (OR = 6.72); neutral (OR = 1.16) and dissatisfied respondents were more willing to pay extra for seats. Validated association rules further explained these observations by indicating that the level of fare was of little to no concern to non-users of bus services (i.e., the environmentally insensitive passenger segment), unlike past works (Eriksson et al., 2008; Thøgersen & Møller, 2008). Passengers ranking level of fare as satisfactory also indicated a willingness to pay more for a seat (I_{in} = *28.57%*).

Frequent car travellers were also willing to pay more for the bus service if they get a seat (I_{in} = *14.29%*) and face no delays due to traffic congestion (I_{in} = *14.29%*). In addition, the level of fare was mostly perceived by surveyed passengers in terms of ride quality and it is argued here that strong correlations exist between the two variables. These findings support a change in the current perspective of policymakers where agencies generally advocate a reduction in fare level (Trépanier, Habib, & Morency, 2012) to encourage public bus usage instead of private automobiles for the daily commute. This study proposes that instead of implementing a blanket reduction in the fare level, policymakers may be able to achieve better results in terms of user predilection towards bus service and modal use by increasing the frequency of buses, economically supported by a commensurate reasonable increase in the current level of fare. Furthermore, as journey time was of significant concern to the commuting public, travel should also be optimised by route improvements such as establishing a BRT service to facilitate the daily commutes of the current and potential service users in Abu Dhabi. The cost and environmental implication of any improved transit system alternatives for future modifications based on public demand and the resulting journey time savings can then be compared through a detailed LCA study.

6.6 DISCUSSION

There is a lack of research in the behavioural econometric analysis of the social aspect of passenger decision-making regarding transport mode choice, factors and attributes affecting these decision such as biases, service quality and frequency etc. In order to address these issues, the study presented here analyses a survey questionnaire of 1,520 responses gathered to capture the passenger perceptions on mode choice and predilection of an existing intra-city setting bus service towards improving the overall transportation system. Passenger responses can be used to influence their mode choice and reduce overall traffic congestion of the transport system after implementing the prospective changes in the transport service, based upon the public demand.

To identify the motivations behind the public and private transport as the preferred mode choice, this study proposed a data-mining algorithm unifying a modified version of the Apriori algorithm and ordinal regression to highlight policymaking proposals pertinent to the studied Abu Dhabi and Middle Eastern residents. The training portion of the travel dataset was subjected to the modified Apriori algorithm in order to generate the initial set of association rules that were partitioned according to the individual market segment candidates in the consequent of the rules. After initial *interestingness*-based filtration of rules, the results were exported to SPSS for externally executing ordinal regression analyses. Ordinal regression performance results of the obtained association rules, after passing a *meaningfulness* measure, were used to analyse the market segments. Throughout the ordinal regression experiments, a majority of the respondents stated travelling a short distance to reach the bus-stop, and time to bus-station had nominal effect on the modal variability of passengers.

Mode use pattern was found to be only partly related to the socio-demographic characteristics of the surveyed passengers. The gender of these respondents had no statistically significant influence on modal variability but was found to influence their perception of the service as the males generally had a more positive outlook. As such, a majority of similar variables (e.g., building typology, location, age, etc.) failed to pass the ordinal regression tests and the next stage (validation of association rules) was used to capture the influence of these variables. Towards travel constraints limiting mode choice of passengers, this study found that a significant share of frequent bus travellers may have been compelled to uptake of public transport due to socio-demographics (lack of access to cars and lack of driving license). Nonetheless, the economic restraints only partly prejudiced their negative perception of the bus service and a majority of the so-called "compelled" travellers viewed public buses as good value for money.

It is noted here that *occasionally multimodal* and *frequent car travellers* exhibit a substantial willingness to travel by public buses provided the capacity is increased or the buses become less crowded, even at the cost of the higher fare. The results show that passenger satisfaction from the quality of ride and level of fare were highly interrelated. The frequency of the public bus service, as a measure of passenger satisfaction from the level of service, is found to influence the mode choices of local passengers. Given the competitive nature of private automobiles and the tendency of passengers in the studied dataset to use public transport for work-related commute dissimilar to past findings, policymakers may need to optimise quality-frequency-fare dynamics especially targeting peak work hours. One of the common strategies that are often implemented in many countries around the world for this purpose is investing in mass-transit systems. Technical and regulatory aspects of implementing the mass-transit system may include smoother traffic flow due to lesser private vehicles on the road network, reduction in cost and environmental burdens.

6.7 CONCLUSION

Public transport services are generally proposed for alleviating excessive private passenger traffic load on road networks and reduce the overall transport system energy and environmental burdens. Yet, the interrelations of mode choice to underlying social (i.e., stakeholder-related) attributes of journey time, public transit service frequency and characteristics, on-board crowding and ride quality are somewhat unexplored.

To that end, the methodology proposed in this study aids the policymakers in finding the critical attributes for improving the performance of the PT service by engaging users through a social component. It should be noted here that although the transit on-board survey methodology adopted in this study collected adequate sample size data and is considered to provide detailed information on the travel patterns, demographic profile and passenger psychometrics (Tierney et al., 1996), it is still limited by the sampling methodology. For example, the data was collected on intra-city bus routes with mainly high number of daily passenger trips and thus low travel routes may be under-represented. Nonetheless, the findings of the current study demonstrate the application of a data mining algorithm to a real-world case study of Abu Dhabi city passengers, which may be used by future studies to futher investigate such routes.

Based on the results of this study, the proposed algorithm recommends that a BRT service, more frequent at peak office hours, may entice significant car users towards the public bus transport service. Whilst the overall cost and environmental impact of meeting public demands by constructing and managing a proposed practicable BRT system can be explored through subsequent detailed LCA, the work presented here does find that addressing public transportation systems preferences can contribute to congestion reduction and impact positively to sustainable development.

6.8 References

AECOM. (2015). *Working paper No. 1: Task 3 review and recommendations on the proposed travel surveys*. Abu Dhabi, United Arab Emirates.

Agrawal, R., Imieliński, T., & Swami, A. (1993). *Mining association rules between sets of items in large databases.* Paper presented at the ACM SIGMOD International Conference on Management of Data, Washington, D.C.

Agrawal, R., & Srikant, R. (1994). *Fast algorithms for mining association rules.* Paper presented at the Proceedings of the 20th Very Large Data Bases (VLDB) Conference, Santiago de Chile, Chile.

Al-Hussaeni, K., Fung, B. C. M., Iqbal, F., Dagher, G. G., & Park, E. G. (2018). SafePath: Differentially-private publishing of passenger trajectories in transportation systems. *Computer Networks, 143*, 126-139. DOI: 10.1016/j.comnet.2018.07.007

Al Tayer, S. M. (2018). UAE is committed to reducing carbon footprint. *Khaleej Times*. Retrieved (25/08/2019) from www.khaleejtimes.com/editorials-columns/uae-is-committed-to-reducing-carbon-footprint

Arbabi, H., & Mayfield, M. (2016). Urban and rural – Population and energy consumption dynamics in local authorities within England and Wales. *Buildings, 6*(3). DOI: 10.3390/buildings6030034

Bachman, W., & Katzev, R. (1982). The effects of non-contingent free bus tickets and personal commitment on urban bus ridership. *Transportation Research Part A: General, 16*(2), 103-108. DOI: 10.1016/0191-2607(82)90002-4.

Badland, H., & Schofield, G. (2005). Transport, urban design, and physical activity: An evidence-based update. *Transportation Research Part D: Transport and Environment, 10*(3), 177-196. DOI: 10.1016/j.trd.2004.12.001.

Batarce, M., Muñoz, J. C., de Dios Ortúzar, J., Raveau, S., Mojica, C., & Ríos, R. A. (2015). Use of mixed stated and revealed preference data for crowding valuation on public transport in Santiago, Chile. *Transportation Research Record: Journal of the Transportation Research Board, 2535*, 73-78. DOI: 10.3141/2535-08.

Chen, C., Gong, H., & Paaswell, R. (2008). Role of the built environment on mode choice decisions: Additional evidence on the impact of density. *Transportation, 35*(3), 285-299. DOI: 10.1007/s11116-007-9153-5.

Cherchi, E., Cirillo, C., & Ortúzar, J. d. D. (2017). Modelling correlation patterns in mode choice models estimated on multiday travel data. *Transportation Research Part A: Policy and Practice, 96*, 146-153. DOI: 10.1016/j.tra.2016.11.021.

Chien, S. I., & Qin, Z. (2004). Optimization of bus stop locations for improving transit accessibility. *Transportation Planning and Technology, 27*(3), 211-227. DOI: 10.1080/0308106042000226899.

Chu, K., & Chapleau, R. (2010). Augmenting transit trip characterization and travel behavior comprehension. *Transportation Research Record: Journal of the Transportation Research Board, 2183*, 29-40. DOI: 10.3141/2183-04.

de Luca, S. (2014). Public engagement in strategic transportation planning: An analytic hierarchy process based approach. *Transport Policy, 33*, 110-124. DOI: 10.1016/j.tranpol.2014.03.002.

de Oña, J., de Oña, R., & Calvo, F. J. (2012). A classification tree approach to identify key factors of transit service quality. *Expert Systems with Applications, 39*(12), 11164-11171.

De Vos, J., Mokhtarian, P. L., Schwanen, T., Van Acker, V., & Witlox, F. (2016). Travel mode choice and travel satisfaction: Bridging the gap between decision utility and experienced utility. *Transportation, 43*(5), 771-796. DOI: 10.1007/s11116-015-9619-9.

Dell'Olio, L., Ibeas, A., & Cecín, P. (2010). Modelling user perception of bus transit quality. *Transport Policy, 17*(6), 388-397.

Diana, M. (2012a). Measuring the satisfaction of multimodal travelers for local transit services in different urban contexts. *Transportation Research Part A: Policy and Practice, 46*(1), 1-11. DOI: 10.1016/j.tra.2011.09.018.

Diana, M. (2012b). Studying patterns of use of transport modes through data mining: Application to us national household travel survey data set. *Transportation Research Record: Journal of the Transportation Research Board* (2308), 1-9.

Diana, M., & Pronello, C. (2010). Traveler segmentation strategy with nominal variables through correspondence analysis. *Transport Policy, 17*(3), 183-190. DOI: 10.1016/j.tranpol.2010.01.005.

Dodd, N., Donatello, S., Garbarino, E., & Gama-Caldas, M. (2015). Identifying macro-objectives for the life cycle environmental performance and resource efficiency of EU buildings. Luxembourg: JRC EU Commission.

Elder, J. (2009). *Handbook of statistical analysis and data mining applications* (R. Nisbet & G. Miner Eds. 1st Ed.). Boston, Massachusetts: Academic Press.

Environment Agency - Abu Dhabi. (2012). Greenhouse gas inventory for Abu Dhabi Emirate - Inventory results executive summary. Retrieved (25/08/2019) from www.ead.ae/documents/pdf-files/AD-greenhouse-gas-inventory-eng.pdf.

Eriksson, L., Friman, M., & Gärling, T. (2008). Stated reasons for reducing work-commute by car. *Transportation Research Part F: Traffic Psychology and Behaviour, 11*(6), 427-433. DOI: 10.1016/j.trf.2008.04.001.

Friman, M., & Fellesson, M. (2009). Service supply and customer satisfaction in public transportation: The quality paradox. *Journal of Public transportation, 12*(4), 57-69. DOI: 10.5038/2375-0901.12.4.4.

Golob, T. F., & Hensher, D. A. (2007). The trip chaining activity of Sydney residents: A cross-section assessment by age group with a focus on seniors. *Journal of Transport Geography, 15*(4), 298-312. DOI: 10.1016/j.jtrangeo.2006.09.005.

Gürbüz, F., & Turna, F. (2018). Rule extraction for tram faults via data mining for safe transportation. *Transportation Research Part A: Policy and Practice, 116*, 568-579. DOI: 10.1016/j.tra.2018.07.011.

Hasan, U., Whyte, A., & Al Jassmi, H. (2018a). *Framework for delivering an AV-based mass mobility solution: Integrating government-consumer actors and life-cycle analysis of transportation systems.* Paper presented at the 46th European Transport Conference, Dublin, Ireland.

Hasan, U., Whyte, A., & Al Jassmi, H. (2018b). Public-transport system management: Improving service satisfaction and sustainable uptake. *Manuscript submitted*.

Hasan, U., Whyte, A., & Al Jassmi, H. (2019). Critical review and methodological issues in integrated life-cycle analysis on road networks. *Journal of Cleaner Production, 206*, 541-558. DOI: 10.1016/j.jclepro.2018.09.148.

Heinen, E., & Chatterjee, K. (2015). The same mode again? An exploration of mode choice variability in Great Britain using the National Travel Survey. *Transportation Research Part A: Policy and Practice, 78*, 266-282. DOI: 10.1016/j.tra.2015.05.015.

Hensher, D. A., Stopher, P., & Bullock, P. (2003). Service quality – Developing a service quality index in the provision of commercial bus contracts. *Transportation Research Part A: Policy and Practice, 37*(6), 499-517. DOI: 10.1016/S0965-8564(02)00075-7.

Horner, M. W., & Mefford, J. N. (2005). Examining the spatial and social variation in employment accessibility: A case study of bus transit in Austin, Texas. In *Access to Destinations* (pp. 193-214): Emerald Group Publishing Limited.

Hu, L., Zhuo, G., & Qiu, Y. (2009). *Application of Apriori algorithm to the data mining of the wildfire.* Paper presented at the 6th International Conference on Fuzzy Systems and Knowledge Discovery.

Kingham, S., Dickinson, J., & Copsey, S. (2001). Travelling to work: Will people move out of their cars. *Transport Policy, 8*(2), 151-160. DOI: 10.1016/S0967-070X(01)00005-1.

Lazcorreta, E., Botella, F., & Fernández-Caballero, A. (2008). Towards personalized recommendation by two-step modified Apriori data mining algorithm. *Expert Systems with Applications, 35*(3), 1422-1429.

Leyden, K. M., Slevin, A., Grey, T., Hynes, M., Frisbaek, F., & Silke, R. (2017). Public and stakeholder engagement and the built environment: A review. *Current Environmental Health Reports, 4*(3), 267-277.

Liu, F., Xu, R., Fan, W., & Jiang, Z. (2018). Data analytics approach for train timetable performance measures using automatic train supervision data. *IET Intelligent Transport Systems, 12*(7), 568-577. DOI: 10.1049/iet-its.2017.0287.

Ma, W.-M., Wang, K., & Liu, Z.-P. (2011). Mining potentially more interesting association rules with fuzzy interest measure. *Soft Computing, 15*(6), 1173-1182. DOI: 10.1007/s00500-010-0579-x.

Menichetti, D., & Vuren, T. v. (2011). Modelling a low-carbon city. *Proceedings of the Institution of Civil Engineers – Transport, 164*(3), 141-151. DOI: 10.1680/tran.2011.164.3.141.

Milakis, D., Cervero, R., & Van Wee, B. (2015). Stay local or go regional? Urban form effects on vehicle use at different spatial scales: A theoretical concept and its application to the San Francisco Bay Area. *Journal of Transport and Land Use, 8*(2), 59-86. DOI: 10.5198/jtlu.2015.557.

Nahar, J., Imam, T., Tickle, K. S., & Chen, Y.-P. P. (2013). Association rule mining to detect factors which contribute to heart disease in males and females. *Expert Systems with Applications, 40*(4), 1086-1093. DOI: 10.1016/j.eswa.2012.08.028.

Nguyen-Phuoc, D. Q., Currie, G., De Gruyter, C., & Young, W. (2018). How do public transport users adjust their travel behaviour if public transport ceases? A qualitative study. *Transportation Research Part F: Traffic Psychology and Behaviour, 54*, 1-14. DOI: 10.1016/j.trf.2018.01.009.

Nobis, C. (2007). Multimodality: Facets and causes of sustainable mobility behavior. *Transportation Research Record: Journal of the Transportation Research Board, 2010*, 35-44. DOI: 10.3141/2010-05.

Nosratabadi, H. E., Pourdarab, S., Nadali, A., & Khalilinezhad, M. (2011). *Evaluating discovered rules from association rules mining based on interestingness measures using fuzzy expert system.* Paper presented at 4th International Conference on the Applications of Digital Information and Web Technologies, Stevens Point, WI.

Ordonez, C. (2006). Association rule discovery with the train and test approach for heart disease prediction. *IEEE Transactions on Information Technology in Biomedicine, 10*(2), 334-343. DOI: 10.1109/TITB.2006.864475.

Osborne, J. W. (2014). Conceptual and practical introduction to testing assumptions and cleaning data for logistic regression. In *Best Practices in Logistic Regression* (pp. 488): SAGE Publications.

Pande, A., & Abdel-Aty, M. (2008). Discovering indirect associations in crash data through probe attributes. *Transportation Research Record: Journal of the Transportation Research Board* (2083), 170-179.

Ponte, C., Melo, H. P. M., Caminha, C., Andrade Jr, J. S., & Furtado, V. (2018). Traveling heterogeneity in public transportation. *EPJ Data Science, 7*(1), 42. DOI: 10.1140/epjds/s13688-018-0172-6.

Redman, L., Friman, M., Gärling, T., & Hartig, T. (2013). Quality attributes of public transport that attract car users: A research review. *Transport Policy, 25*, 119-127. DOI: 10.1016/j.tranpol.2012.11.005.

Savage, I. (2010). The dynamics of fare and frequency choice in urban transit. *Transportation Research Part A: Policy and Practice, 44*(10), 815-829. DOI: 10.1016/j.tra.2010.08.002.

Schmid, B., Schmutz, S., & Axhausen, K. W. (2016). *Explaining mode choice, taste heterogeneity, and cost sensitivity in a post-car world*. Paper presented at the 95th Annual Meeting of the Transportation Research Board, Washington, DC, USA. https://trid.trb.org/view/1393908.

Shaharanee, I. N. M., Hadzic, F., & Dillon, T. S. (2011). Interestingness measures for association rules based on statistical validity. *Knowledge-Based Systems, 24*(3), 386-392. DOI: 10.1016/j.knosys.2010.11.005.

Shaheen, M., & Shahbaz, M. (2017). An algorithm of association rule mining for microbial energy prospection. *Scientific Reports, 7*, 46108. DOI: 10.1038/srep46108.

Sottile, E., Cherchi, E., & Meloni, I. (2015). Measuring soft measures within a stated preference survey: The effect of pollution and traffic stress on mode choice. *Transportation Research Procedia, 11*, 434-451. DOI: 10.1016/j.trpro.2015.12.036.

Stathopoulos, A., Cirillo, C., Cherchi, E., Ben-Elia, E., Li, Y.-T., & Schmöcker, J.-D. (2017). Innovation adoption modeling in transportation: New models and data. *Journal of Choice Modelling, 25*, 61-68. DOI: 10.1016/j.jocm.2017.02.001.

Stephan, A., & Stephan, L. (2016). Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. *Applied Energy, 161*, 445-464. DOI: 10.1016/j.apenergy.2015.10.023.

Stradling, S. (2007). Determinants of car dependence. In *Threats from Car Traffic to the Quality of Urban Life* (pp. 187-204): Emerald Group Publishing Limited.

Tan, P.-N., Kumar, V., & Srivastava, J. (2004). Selecting the right objective measure for association analysis. *Information Systems, 29*(4), 293-313. DOI: 10.1016/S0306-4379(03)00072-3.

Tan, P.-N., Steinbach, M., & Kumar, V. (2005). *Introduction to data mining* (1st Ed.). Boston, MA: Addison-Wesley Longman Publishing Co., Inc.

Thøgersen, J., & Møller, B. (2008). Breaking car use habits: The effectiveness of a free one-month travelcard. *Transportation, 35*(3), 329-345. DOI: 10.1007/s11116-008-9160-1.

Tierney, K., Decker, S., Proussaloglou, K., Rossi, T., Ruiter, E., McGuckin, N. (1996). *Travel survey manual* (Report No. FHWA-PL-96-029). Cambridge, MA: Federal Highway Administration.

Tirachini, A. (2013). Estimation of travel time and the benefits of upgrading the fare payment technology in urban bus services. *Transportation Research Part C: Emerging Technologies, 30*, 239-256. DOI: 10.1016/j.trc.2011.11.007.

Tirachini, A., Hensher, D. A., & Rose, J. M. (2014). Multimodal pricing and optimal design of urban public transport: The interplay between traffic congestion and bus crowding. *Transportation Research Part B: Methodological, 61*, 33-54. DOI: 10.1016/j.trb.2014.01.003.

Trépanier, M., Habib, K. M. N., & Morency, C. (2012). Are transit users loyal? Revelations from a hazard model based on smart card data. *Canadian Journal of Civil Engineering, 39*(6), 610-618. DOI: 10.1139/l2012-048.

Wang, T., & Chen, C. (2012). Attitudes, mode switching behavior, and the built environment: A longitudinal study in the Puget Sound Region. *Transportation Research Part A: Policy and Practice, 46*(10), 1594-1607. DOI: 10.1016/j.tra.2012.08.001.

Wu, X., Zhang, C., & Zhang, S. (2004). Efficient mining of both positive and negative association rules. *ACM Transactions on Information Systems, 22*(3), 381-405. DOI: 10.1145/1010614.1010616.

Yao, B., Hu, P., Lu, X., Gao, J., & Zhang, M. (2014). Transit network design based on travel time reliability. *Transportation Research Part C: Emerging Technologies, 43, Part 3*, 233-248. DOI: 10.1016/j.trc.2013.12.005.

Yigitcanlar, T., Kamruzzaman, M., & Teriman, S. (2015). Neighbourhood sustainability assessment: Evaluating residential development sustainability in a developing country context. *Sustainability, 7*(3). DOI: 10.3390/su7032570.

Zimring, C., Joseph, A., Nicoll, G. L., & Tsepas, S. (2005). Influences of building design and site design on physical activity: Research and intervention opportunities. *American Journal of Preventive Medicine, 28*(Supplement 2), 186-193. DOI: 10.1016/j.amepre.2004.10.025.

CHAPTER 7

LIFECYCLE ASSESSMENT OF ROADWORKS IN UNITED ARAB EMIRATES: RECYCLED CONSTRUCTION WASTE, RECLAIMED ASPHALT PAVEMENT, WARM-MIX ASPHALT, AND BLAST FURNACE SLAG USE AGAINST TRADITIONAL APPROACH

7.1 ABSTRACT

Lifecycle assessment methodology was applied in this study to calculate environmental impacts of a 3.5km-long dual carriageway asphalt highway section case study in Abu Dhabi across following lifecycle stages: material extraction and production, material and equipment transport, construction, maintenance and rehabilitation; assuming a 30 years lifetime. Environmental impact assessment for air emissions and energy consumption generated by complete roadworks, namely: earthworks; pavement courses; concrete works for traffic barriers, kerbs, parapets, traffic signs, and light systems. A comprehensive analysis of environmental impact reduction was performed using recycled construction waste; reclaimed asphalt pavement; warm-mix asphalt with synthetic zeolite additives; and, slag as alternate material and production options. Actual field data for the road section using virgin materials and traditional asphalt production mix for pavement works and Portland cement concrete for the complete concrete works were used as the baseline case. Routine maintenance and periodic rehabilitation by milling and repaving wearing course (<4.5cm depth) every 5 years was also analysed from an environmental impact reduction perspective. Environmental assessment considered all indicators from ReCiPe midpoint method. Results show that earthworks account for a significant portion (26% of CO_2eq.) of the environmental impacts for complete roadworks. The lifecycle impact results of hot-mix asphalt and warm-mix asphalt were almost equal due to addition of synthetic zeolites. Results showed significant environmental impact reduction across all indicators, after coupling all alternate options as: 34% in CO_2eq.; 48% in energy consumption; 24.4% in NO_xeq.; 21.53% in $PM_{2.5}$eq.; 21.2% in acidification; and, 10.4% in land use. Monte Carlo simulations confirm these results. This study noted higher environmental benefits than reported in roadworks literature due to alternate material and asphalt production options.

7.2 INTRODUCTION

Construction, operation, and maintenance of roads carry a significant environmental impact (Anastasiou, Liapis, & Papayianni, 2015). Road works account for around 28% of global energy consumption and approximately 22% of global CO_2 emissions (Abergel, Dean, & Dulac, 2017). According to 2014 estimates, the road transport sector in the Emirate of Abu Dhabi in the United Arab Emirates generated more than 12 million tonnes CO_2eq. emissions, accounting for approximately 63% of the total transportation sector-related GHG emissions (Hill et al., 2012; SCAD, 2014). Abu Dhabi Transport Master Plan 2009 acknowledges that the UAE has one of the largest per capita emissions globally, i.e., 23.3 tonnes per capita of CO_2 emissions (Bank, 2019; ADDoT, 2009) and needs a low carbon road transport network.

The majority of the 21,673 km paved road in Abu Dhabi is asphalt constructed from virgin materials. Abu Dhabi City Municipality (2010) manual addresses the use of RAPs, in-situ recycling and stabilisation techniques to reduce the environmental impacts. However, there is a considerable lack of research empirically plotting the environmental benefits of using such materials on actual pavement projects from the UAE and the Middle East region overall. Alzard et al. (2019) have explored the CO_2 emissions produced by road projects in Abu Dhabi, but the study was limited in scope.

Lifecycle assessment (LCA) is used to analyse the impact of infrastructure development on the environment (ISO 14040, 2006). Researchers have attempted to address various stages involved in the cradle-to-grave/cradle lifecycle of infrastructure (Batouli et al., 2017; Moretti et al., 2018), yet, construction equipment transport is not modelled in the existing literature. Blengini and Garbarino (2010) explored the environmental benefits of screened and crushed RCW in Italy. They found that RCW used for road base/sub-base construction corresponds to around 14 kg/tonne of avoided GHG emissions. However, regional constraints like transport distance (Turk et al., 2016) may also have some influence on the environmental benefits and the LCA results between studies in different regions may vary.

RAP obtained after milling and screening existing asphalt pavements is also proposed as a viable alternative to mitigate the high GHG burdens of bitumen and aggregates by various researchers (Guo et al., 2018; Praticò et al., 2015) and transport agencies (AASHTO, 2012). Giani et al. (2015) explored the replacement of virgin asphalt by

10% RAP in hot-mix asphalt (HMA) surface course and by 20% RAP in HMA binder course of a 1 km asphalt pavement section in Italy. They found that the HMA RAP alternative exhibited 688 tonnes CO_2eq. (6.8%) GHG emissions reductions.

Warm-mix asphalt (WMA) is another emission and energy impact reduction strategy used by producing asphalt mixtures at lower temperatures (100°C–140°C) compared to the hot-mix asphalt temperature range of 138°C–160°C (Tarefder & Pan, 2014). This reduction in WMA production temperature is traditionally achieved by addition of asphalt additives, such as water-based foaming agents (zeolites), chemical additives (polymers) and organic additives (waxes) which may affect the lifecycle environmental impacts. Regarding performance, Zhao et al. (2012) found that the fatigue resistance, moisture susceptibility and rutting resistance of WMA containing high percentages of RAP was significantly higher than HMA samples. Almeida-Costa and Benta (2016) noted that due to the lower energy requirements for heating aggregates, the total energy consumption reduced by 0.041 GJ (~18.46%) between HMA and WMA production.

AzariJafari et al. (2016) note that since site clearance and earthworks and involve large volumes of material, future pavement LCA studies should include analysis on environmental benefit of recycled alternatives for this component. Additionally, the environmental burden of concrete for kerbs, traffic barriers and parapet walls along the road are usually unacknowledged in pavement LCAs. Concrete is also used for foundation works of traffic signs and streetlight systems, however, it is not studied in the context of the complete pavement lifecycle results. Yang et al. (2015) and Kim, Tae, and Chae (2016) propose that for concrete mix with ground granulated blast furnace slag (GGBFS) replacement in the range of 15%–80%, significant reduction in environmental impacts occur corresponding to insignificant strength loss compared to ordinary Portland cement (OPC) concrete for the 20MPa–170MPa range.

Regional conditions, e.g., transport infrastructure (Hoque et al., 2019) and material recycling/extraction plants, construction machinery and techniques used, road design and cross-sectional characteristics and local material supply chain may also influence the direct interpretation of results (Anastasiou et al., 2015; Yi et al., 2007). Figure 7.1 covers the three most recent state-of-the-art reviews (AzariJafari et al., 2016; Balaguera et al., 2018; Hasan, Whyte, & Al Jassmi, 2019) on the LCAs of pavement sections and associated roadworks. The majority of research was conducted on RAP and RCW usage as environmental impact reducing alternatives for pavement sections in Europe and the Americas.

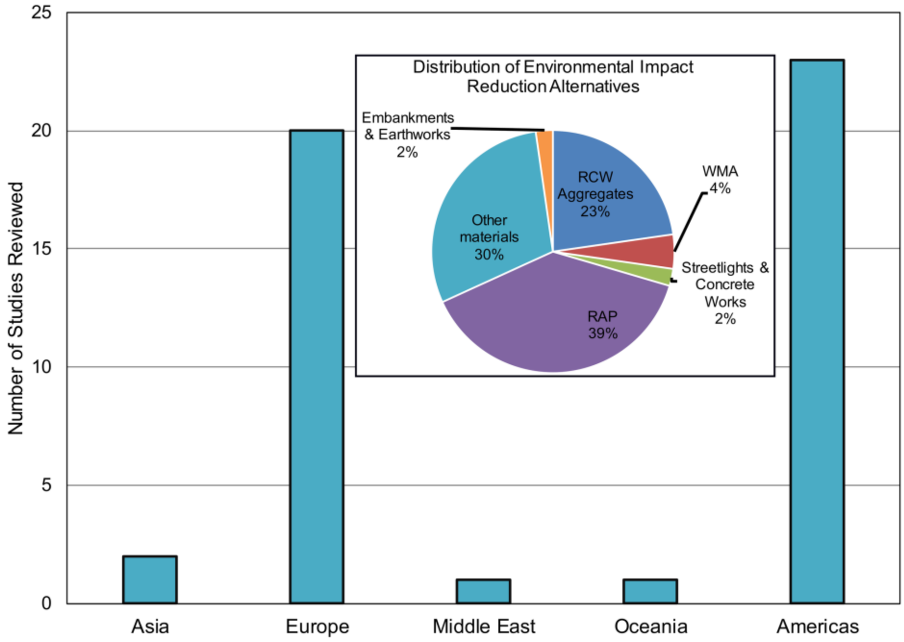


Figure 7.1 Regional and alternative distribution of LCA studies on pavement sections and other roadworks in recent literature

A comprehensive analysis of environmental benefits of RCW as an alternate for natural aggregates, RAP against virgin asphalt and WMA (with synthetic zeolite additives) against HMA is performed here. Different combinations of recycled material alternatives across the pavement cross-section are analysed over the entire lifecycle to calculate the environmental advantages of each alternate option. Additionally, LCA of GGBFS as an alternate option in concrete works is also performed. This comparative environmental benefit assessment for complete roadside works is not only a relatively new and concise study in pavement literature, but it is also the first such study performed in the context of UAE and the Middle East region using different environmental indicators.

7.3 METHODOLOGY

This study uses LCA methodology to calculate and analyse the environmental impacts for roadworks over the entire lifecycle of a highway project in Abu Dhabi city. The lifecycle stages considered are further explained in Section 7.3.2 below. LCA is performed according to the ISO 14040 (2006) guidelines in the following phases: *goal and scope* definition, quantifying and developing *lifecycle inventory* (LCI) and *lifecycle impact assessment* (LCIA) and *interpretation* in terms of results and discussion. The lifecycle assessment software package SimaPro 8.5.2 was used to perform the study (PRé Consultants, 2016; Vidal et al., 2013). ReCiPe (Goedkoop et al., 2009) is the only analysis method available in SimaPro for global LCA studies and is used in this study. Case study data is an extension work on the Sheikh Zayed Bin Sultan Street, originally completed in 2009 by adding one lane (3.65m width) and a shoulder (3m width) each side on the 3.5km dual carriageway asphalt highway section. Missing data, e.g., UAE electricity mix and transport vehicles were developed based on appropriate resources from existing literature and Ecoinvent v3.3 database.

7.3.1 Goal and scope

The goal of the current study is to calculate and compare the environmental emissions and energy consumption between different recycled (RCW and RAP) and producing temperature (WMA vs. HMA) pavement construction alternate options and industrial by-products (GGBFS) as partial replacement of Portland cement for associated roadside works. In this way, the environmental impact reduction performance of different options for complete tender works for constructing an asphalt road can be compared across the roadwork components and the best performing alternative can be identified for real-world applications.

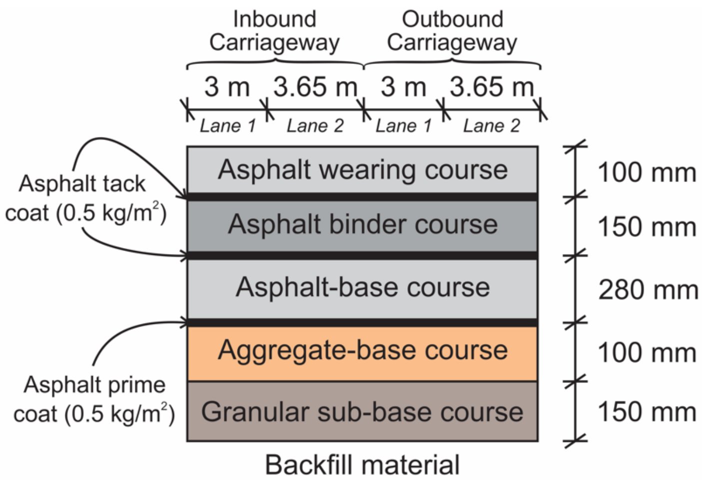


Figure 7.2 Case study pavement cross-section

The functional unit for the LCA methodology used in this study is defined as a 3.5km dual carriageway highway section with two lanes (3.65m + 3m width) in each direction. The two carriageways are separated by concrete barriers. Concrete kerbs are constructed on each side of the carriageways. The pavement cross-section considered in this study is illustrated in Figure 7.2. The average lifetime of asphalt roads varies in the literature, e.g., 100 years (Biswas, 2014), 50 years (Santos, Ferreira, & Flintsch, 2015) and 30 years (Giani et al., 2015; Turk et al., 2016). This study assumed a service life of 30 years based on local government agency guidelines (ADDoT, 2009).

7.3.2 Description of alternatives and system boundaries

The following lifecycle stages of roadworks are considered in this streamlined LCA: raw material extraction, material production/processing, material and equipment transport, construction, M&R and recycling of pavement wearing course. This study is performed as streamlined LCA. The operation and usage stage and end-of-life disposal/landfilling are not considered in this study due to lack of precedence to establish the emissions associated with these stages. A proportion of asphalt from the wearing course is milled up to the depth of 4.5 cm every 5-year as currently practiced in the field (ADM, 1997) during M&R stage.

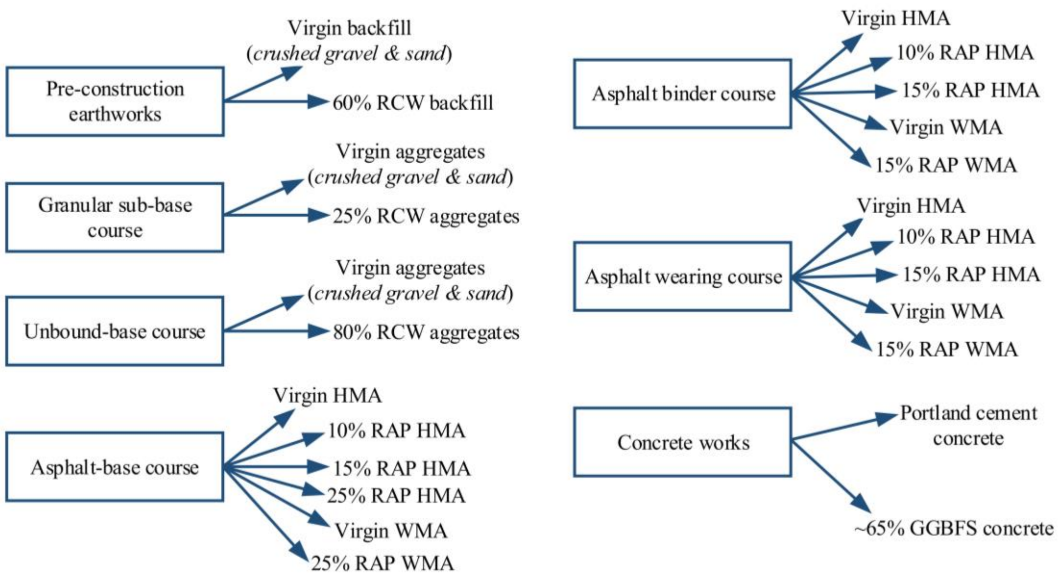


Figure 7.3 Environmental impact reduction alternatives for each component of case study roadworks

The milled asphalt is then transported to an asphalt plant and mixed with virgin bitumen for repaving the wearing course. It is assumed to be a continuous process after the end of the initial 30 years lifetime. Processes post-30 years are not modelled due to unavailability of data on pavement conditions, traffic pattern and historical pavement reuse records. Similar to pavement LCA methodology in literature (Anthonissen et al., 2016; Praticò et al., 2015; Vidal et al., 2013), the burdens from

RAP milling during initial construction process (when it is used as an alternate material) is not included.

However, material transport of milled RAP from recycling facilities (for crushing, screening and quality testing of RAP) to the asphalt plant is included in the analysis. Elchalakani, Aly, and Abu-Aisheh (2014) in an Abu Dhabi region-based study recommend 80% OPC replacement by GGBFS for maintaining optimum durability while reducing the environmental impacts (~107 kg/m of CO_2 emissions). The current study uses a conservative replacement of OPC (~65%) by GGBFS in the concrete used for the case study roadworks. The different environmental impact reduction alternatives (Figure 7.3) and lifecycle stages in the system boundaries (Figure 7.4) are described below.

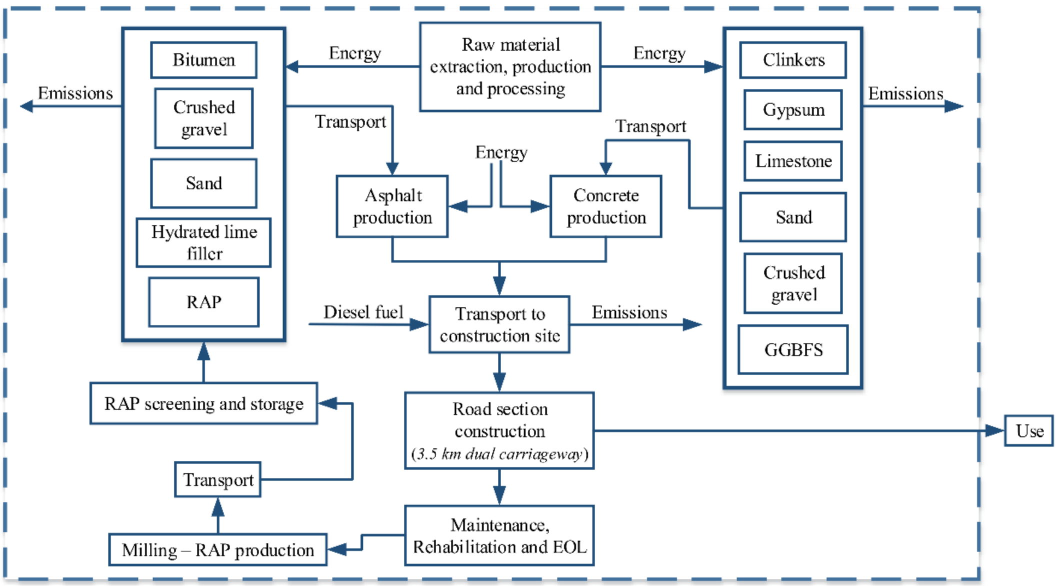


Figure 7.4 System boundaries

a) Material extraction, production, and processing include extraction and plant processing of asphalt, aggregates, cement, and admixtures, etc. required for pavement construction and roadside works. The Abu Dhabi Municipality Road Specifications Manual (ADM, 1997) specifies that crushed gravel with sand should be used as a backfill in pavement construction. Local fine silica sand or *sweet sand* from red dunes in Abu Dhabi is also used as non-load bearing backfill material.

Crushed natural gravel carries a significant environmental impact due to mining, transport and production operations. The current study assesses locally-sourced RCW as an alternative material for crushed natural aggregate in the backfill, sub-base, and unbound granular aggregate-base (u-base) construction. Asphalt production and mixing is a major source of environmental impacts due to fuel consumption, machinery, and supply-chain infrastructure. RAP and WMA are also assessed in this study against virgin HMA to reduce energy-related emissions. Industrial by-product *GGBFS is also used as a partial replacement of Portland cement* for constructing concrete barriers and kerbs and foundations of traffic lighting and signal systems.

b) ***Material transportation to the construction site*** is an important stage in the roadworks lifecycle and as such, data from the local suppliers needs to be collected as environmental impacts depend upon the distance to material production plants and vehicles used for by-road material transportation to the site. Heavy goods vehicles (HGVs) fuel consumption is the main source of emissions in this stage.

c) ***On-site equipment transportation to the construction site*** is also significant for the actual construction process to commence and mostly HGVs are used to transport excavators, milling machines and other roadworks equipment. Similar to the material transport by roads, data from local resources are used to model equipment transport.

d) ***Construction*** environmental impacts are due to the operation of on-site equipment like excavators, pavers, compactors, and wheel-loaders, etc. Constructing traffic and concrete barriers, kerbs, concrete foundations for traffic lights and road markings also constitute a part of the total environmental burdens during road construction. This study considers environmental impacts from all of these road construction processes. The environmental impacts from the vehicles on the work-zone (due to traffic delays in construction and M&R stages) have not been considered in this streamlined LCA as this study focuses on alternate material use for pavements.

e) ***Road use*** environmental impacts are primarily due to emissions from fuel consumption of the vehicles using the road. The surface structure, roughness and other characteristics affect the rolling resistance from pavements to the vehicles which affects the fuel consumption of vehicles. Microscopic vehicle simulation models can measure per-second driving resistance and acceleration-deceleration profile of each vehicle using any case study road. However, Wang (2013) note that microscopic emissions model such as Comprehensive Modal Emission Model, rely on time consuming data input and also neglect the pavement information. Although, other models, e.g., MOVES developed by the United States Environmental Protection Agency can be modified to address dynamic vehicle speeds and rolling resistance induced by pavement surface, such models rely on data from North America and European regions and may not be applicable to the Abu Dhabi carriageway studied here. Past LCA studies have heavily relied on annual average traffic load estimates to calculate the vehicular emissions (Mahesh et al., 2018; Vidal et al., 2013). Abou-Senna et al. (2013) and Quaassdorff et al. (2016), among others, argue that the environmental emission estimates based on average value do not account for dynamic traffic variables and link capacity. This introduces a bias in traffic estimates and an underestimation of emissions. Thus, the road use stage is considered outside the system boundary of this study as it is addressed in Chapter 8 by calculating traffic flow emissions through detailed traffic modelling.

f) ***Routine maintenance and rehabilitation*** environmental burdens are from routine maintenance of the road section during its lifecycle, frequent rehabilitation activities after a specific time period (considered to be repaving of top 4.5 cm of wearing course every five years in this study based on current practice in the case study are) after milling the worn-out wearing course which has reached its end-of-life. This generates another opportunity to reduce environmental impacts. To reduce impacts from this stage, this study compares environmental impact reduction between using virgin HMA materials for asphalt pavement construction and 85% RAP from the milling stage mixed with virgin asphalt through the warm-mix production process in an asphalt plant. Similar to the initial construction stage, GGBFS is used as an alternate option to Portland cement for routine maintenance of concrete roadworks. This study does not consider landfilling/disposal after end-of-life stage as there is no precedence to establish the associated emissions in the region based on consultations with the local experts in the UAE.

7.4 LIFECYCLE INVENTORY (LCI) – ABU DHABI CASE STUDY

7.4.1 Material extraction, production, and processing

The backfill on the case study site as per local municipality guidelines is used as a baseline case (*virgin backfill*). Based on the existing literature (Blankenagel, 2005; Hasan, 2015; Rathje et al., 2002; Vieira & Pereira, 2015), RCW is used as a partial replacement of virgin aggregates in backfill (*60% RCW backfill*). This study also used

RCW as the recycled (25% RCW) *sub-base* and (80% RCW) *u-base*. Sand, crushed gravel and bitumen are used in asphalt plants with hydrated lime as filler to increase asphalt stiffness and rutting resistance (Vidal et al., 2013). As per the Abu Dhabi municipality guidelines (ADM, 1997); HMA with 4% bitumen as binder, 30.2% sand as fine aggregates, 1.5% hydrated lime as filler and 64.3% crushed gravel as coarse aggregates mixed in a batch mixer plant is used for asphalt base course and binder course. The wearing course asphalt uses 4.5% bitumen, 30.1% sand, 1.5% hydrated lime filler and 63.9% crushed gravel as coarse aggregate.

RAP is a traditional alternative material to reduce the bitumen and aggregate content in asphalt. Current Abu Dhabi guidelines mention 15% RAP usage in binder course (Department of Transport Abu Dhabi, 2018). However, researchers investigated different percentages of RAP replacement in pavement construction. Ventura, Monéron, and Jullien (2008) used up to 30% replacement in binder course. Giani et al. (2015) applied up to 30% RAP in the base course, 20% RAP in binder course and 10% RAP in the wearing course. Due to the high strength of asphalt base (Rys et al., 2017) and findings by Zhao et al. (2013) on strength performance of high RAP concrete in asphalt pavements, this study explores the environmental benefit of up to 25% RAP usage in asphalt base course. However, due to limited RAP experimental studies in Abu Dhabi and the Middle East region, an upper limit of 15% RAP in wearing and binder courses is used.

The same upper limits are considered for WMA as Zhao et al. (2013) recommended a maximum 30% RAP content in pavement sections constructed from WMA. The Marini batch-mixer asphalt plants currently operational in the UAE and used as a reference case in this study largely manufacture HMA (RAD International Road Construction L.L.C, 2013). However, the lower energy requirements during WMA manufacturing have been modelled as a theoretical alternative option. To allow for lower asphalt production temperatures, synthetic zeolites are used as an additive to the WMA mixture at the rate of 0.3% by mass, emissions inventory data for WMA additive is adapted from Vidal et al. (2013). This LCI data for HMA and WMA is shown in Table 7.1. The lifecycle inventory for GGBFS production and processing is taken from the Ecoinvent v3.3 database. Inventory for backfill, the pavement courses, and other roadworks materials are taken from the actual material quantity sheet and local UAE material suppliers (Table 7.2).

Table 7.1 LCI of the production of asphalt mixes

Input/output	Hot-mix asphalt (HMA)	Warm-mix asphalt (WMA)
Natural Gas (*MJ/tonne*)	300	240
Electricity (*kWh/tonne*)	6	6
Diesel (*MJ/tonne*)	8.49	8.49
Water (*m^3/tonne*)	0.01003	0.01003
Emissions to air		
CO (*kg/tonne*)	0.16	0.133
CO_2 (*kg/tonne*)	16.8	15.1
NO_x (*kg/tonne*)	0.0125	0.0102
PAH (*kg/tonne*)	3×10^{-6}	1.96×10^{-6}
NMVOC (*kg/tonne*)	0.00441	0.003402
SO_2 (*kg/tonne*)	0.0023	0.00187
$PM_{2.5}$ (*kg/tonne*)	0.00415	0.00338

Table 7.2 Materials inventory for the comparative differences between material alternatives, for each component in roadworks

	Water	Sand	Local silica sand	Geotextile fabric (Polypropylene)	20MPa concrete	Gravel	RCW
Virgin backfill	454.6×10^3 litres	19.8×10^3 m^3	13.10×10^3 m^3	93650 m^2	650 m^3	9100 m^3	
60% RCW backfill	454.6×10^3 litres	19.8×10^3 m^3	13.10×10^3 m^3	93650 m^2	650 m^3	3640 m^3	5460 m^3

Pavement courses varied between alternates (*material unit: tonnes*)	**Crushed gravel**	**Sand**	**Virgin bitumen**	**Hydrated lime**	**RCW**	**RAP**
Granular sub-base course	448	-	-	-	-	-

Baseline case (virgin HMA & aggregates)	Unbound-base course	12600	-	-	-	-	-
	4% bitumen asphalt-base course	6177	2901	384.3	144.1	-	-
	4% bitumen asphalt binder course	5719	2686	355.8	133.4	-	-
	4.5% bitumen asphalt wearing course	9242	4353	650.9	216.9	-	-
80% RCW u-base course	Unbound-base course	10080	-	-	-	2520	-
25% sub-base, 80% RCW u-base course	Granular sub-base course	336	-	-	-	112	-
	Unbound-base course	10080	-	-	-	2520	-
10% RAP a-base, binder & wearing	4% bitumen asphalt-base course	5563	2613	345.9	122.9	-	960.7
	4% bitumen asphalt binder course	5149	2419	321.2	113.8	-	889.5
	4.5% bitumen asphalt wearing course	8331	3920	585.8	183.7	-	1446
15% RAP a-base, binder & wearing	4% bitumen asphalt-base course	5255	2469	326.6	116.3	-	1441
	4% bitumen asphalt binder course	4865	2286	302.4	107.6	-	1334
	4.5% bitumen asphalt wearing course	7868	3703	552.5	173.6	-	2170
25% RAP a-base, 15% RAP binder & wearing	4% bitumen asphalt-base course	4640	2181	288.2	101.8	-	2402
	4% bitumen asphalt binder course	4865	2286	302.4	107.6	-	1334
	4.5% bitumen asphalt wearing course	7868	3703	552.5	173.6	-	2170
25% RCW sub-base, 80% RCW u-base, 25% WMA RAP a-base, 15% WMA RAP binder & wearing	Granular sub-base course	336	-	-	-	112	-
	Unbound-base course	10080	-	-	-	2520	-
	4% bitumen asphalt-base course	4640	2181	288.2	101.8	-	2402
	4% bitumen asphalt binder course	4865	2286	302.4	107.6	-	1334
	4.5% bitumen asphalt wearing course	7868	3703	552.5	173.6	-	2170

	Clinker	**Gypsum**	**Limestone**	**GGBFS**	**Sand**	**Gravel**
Baseline case concrete works (unit: *tonnes*)	416.053	21.897	23.050	-	2090.330	2280.153
Alternate/65% GGBFS case concrete works (unit: *tonnes*)	216.809	11.387	-	232.806	2090.330	2280.153

7.4.2 *Material transportation*

Transportation of produced materials from plants to the construction site is conducted using HGVs delivering on roads. The environmental burdens depend upon the fuel consumption efficiency, exhaust emissions, and age of the transporting vehicles. Based on the data from the ADDoT (2009) and Raeside (2015), Euro II diesel articulated trucks are most common in the case study region. Two HGVs were modelled for material transportation: a small (<10 tonnes) truck with a payload capacity of 3.3 tonnes and a medium (10–20 tonnes) truck with a payload capacity of 9.5 tonnes (DSV Global Transport and Logistics, 2019). Fuel consumption and exhaust emissions of these HGVs were taken from SimaPro databases with the default 100% load factor for the outward journey.

7.4.3 *On-site equipment transportation to the construction site*

Road construction sites require different types of equipment: pavers, asphalt rollers, compactors, and excavators, among others. HGVs used for transporting construction equipment to the site were modelled based on the actual case study data and local resources (ADM, 1997; Department of Transport Abu Dhabi, 2018; Maraqa et al., 2018). Three types of articulated trucks were modelled: small (<10 tonnes), medium (10–20 tonnes) and large (>20 tonnes) and load factor was based on the actual weight of individual construction equipment being transported.

7.4.4 *Construction*

The type of construction machinery used on-site, fuel consumption, fuel-type and the operating hours determine the total environmental impact from this stage. Existing pavement LCA literature (Giani et al., 2015; Turk et al., 2016; Vidal et al., 2013; Whyte, 2012) recommends using local resources to accurately calculate the emissions from this stage. This study used the actual tender document and bill of quantities for the case study highway section project along with local data (Department of Transport Abu Dhabi, 2018; Environment Agency - Abu Dhabi, 2012; Maraqa et al., 2018) to determine the equipment type. Additionally, data from the equipment supplier (Caterpillar Inc., 2011) was used to calculate fuel consumption and operating hours for the construction machinery (Table 7.3).

Table 7.3 LCI of construction machinery

Road component	Machinery type and model	Operating time (h)	Fuel consumption (l/h)
Site excavation	Caterpillar 972H wheel-loader	39	21
Backfill – aggregates	Caterpillar 844 compactor	19.5	62
	Caterpillar 939C track-loader	39	15
Backfill – silica sand	Caterpillar 939C track-loader	78	15
Geotextile fabric	Caterpillar D6K track-type tractor	39	21.5
Utility marking	Caterpillar 966H wheel loader	19.5	16.9
Granular sub-base course	Caterpillar 844 compactor	19.5	62
Unbound-base course	Caterpillar 966H wheel-loader	19.5	16.9
	Caterpillar 416E loader	117	11.4
Asphalt-base course Asphalt binder course	Caterpillar CB-434D compactor	780, 780	11.4
Asphalt wearing course	Caterpillar AP-800D paver	780	28.4
Asphalt prime coat	Caterpillar CB-564D compactor	780	10.45
Asphalt track coat	Caterpillar 345D excavator	390	45.6
Bituminous surface treatment	Caterpillar TH560B articulated trucks	234	15
Milling machine	Caterpillar PM622 cold planner	396	76
Concrete works	Caterpillar dump-trucks 6x4 12 cub.yd	250	20.2
	Caterpillar CP-663E	500	19
	Caterpillar water-truck 4000Gal.	250	14.2

7.4.5 Applying LCA in construction, and M&R stages emissions

Routine maintenance involves pavement skin patching, repairing concrete barriers and kerbs, etc. (Stripple, 2001). Rehabilitation is a major maintenance activity to dismantle and replace the pavement section course(s) that have reached the end-of-life due to wear and tear. The frequency and extent of repair works are based on the pavement section, strength, daily traffic load, weather cycles and availability of funds to the local municipality. Celauro et al. (2017) considered repaving of asphalt wearing course after every 4 years. Scheving (2011) notes that for an asphalt road supporting heavy traffic load (>12000 vehicles/day/lane), the wearing course should at least be replaced every 6 years. Due to the high strength of asphalt base course compared to the unbound-base course (Pavement Interactive, 2019; Rys et al., 2017) and the difference between service life of different pavement sections (Huang, 2007), the rehabilitation frequencies are also different. Considering these factors, the current study assumes only wearing course milling and repaving after every 5 years due to: traffic load on the case study highway section (>12000 vehicles/day), thick asphalt base section, budgeting constraints and current practice in the field. Since the M&R stage again involves material extraction and processing, material and equipment transport and construction equipment operation, the LCI of these stages (Tables 7.1 – 7.3) is used including the dismantling/milling equipment used after the end-of-life of the wearing course section.

7.5 LIFECYCLE IMPACT ASSESSMENT (RESULTS) AND INTERPRETATION (DISCUSSION)

Lifecycle impact assessment (LCIA) calculates and provides the environmental impact results of the case study functional unit based upon the earlier established LCI and the selected assessment method. ReCiPe midpoint method can calculate environmental impacts across the indicators in Table 7.4 (Goedkoop et al., 2009; Hasan et al., 2019). ReCiPe assesses environmental impacts by three different perspectives of *individualist* (I), *hierarchist* (H) and *egalitarian* (E). Hierarchist perspective is used in this study based on the scientific consensus with regards to technology development, adaption capacity and time-frame (PRé Consultants, 2018; Vidal et al., 2013). The results relating to the *environmental impact reduction effects* of different alternate options are presented below.

Table 7.4 Environmental impact reduction results, % reduction compared to the baseline case

Environmental impact indicators	**Pre-construction earthworks**	**Asphalt pavement section** (*% reduction compared to virgin HMA & virgin aggregates case*)							**Concrete works** (*% reduction compared to Portland cement case*)	
	60% RCW backfill (*% reduction compared to virgin backfill case*)	**80% RCW u-base course**	**25% RCW sub-base, 80% u-base**	**10% RAP a-base, binder & wearing**	**15% RAP a-base, binder & wearing**	**25% RAP a-base, 15% RAP binder & wearing**	**Virgin WMA & virgin aggregates**	**25% RCW sub-base, 80% RCW u-base, 25% WMA RAP a-base, 15% WMA**	**~65% GGBFS case - concrete barriers & kerbs**	**~65% GGBFS case - traffic & lighting systems**
Climate change/global warming potential (GWP)	16.33%	1.3%	1.41%	3.96%	5.93%	7.05%	6.23%	14.75%	26.37%	3.19%
Stratospheric ozone depletion (OD)	16.2%	0.61%	0.66%	6.25%	9.34%	11.09%	0.20%	11.99%	5.53%	0.11%
Ionizing radiation (IR)	24.77%	0.61%	0.67%	5.02%	7.53%	8.94%	0%	9.61%	5.76%	0.27%
Photochemical ozone formation (POzF)	18.29%	2.50%	2.71%	3.57%	5.53%	6.46%	1.86%	11.11%	12.28%	0.98%
Particulate matter formation (PMF)	14.26%	0.83%	0.91%	3.69%	5.57%	6.58%	2.35%	9.88%	7.49%	0.22%

Photochemical oxidants formation (POxF)	18.26%	2.44%	2.64%	3.7%	5.7%	6.67%	1.83%	11.22%	12.2%	0.96%
Acidification	14.54%	0.94%	1.02%	3.76%	5.69%	6.71%	0.87%	8.65%	9.47%	0.27%
Freshwater eutrophication	15.6%	0.18%	0.2%	1.04%	1.55%	1.85%	0%	2.05%	0.49%	0.96%
Marine eutrophication	14.59%	0.24%	0.26%	1.6%	2.4%	2.85%	0%	3.11%	0.63%	0.90%
Terrestrial eco-toxicity	17.37%	0.3%	0.32%	0.52%	0.78%	0.93%	0.05%	1.31%	0.66%	0.95%
Freshwater eco-toxicity	16.45%	0.07%	0.08%	0.43%	0.65%	0.77%	0%	0.85%	0.29%	0.81%
Marine eco-toxicity	16.53%	0.08%	0.09%	0.47%	0.71%	0.84%	0%	0.93%	0.34%	0.83%
Human toxicity (HT)	15.9%	0.07%	0.08%	0.39%	0.57%	0.69%	0.01%	0.78%	0.64%	0.90%
Land use	9.31%	0.22%	0.24%	6.74%	10.11%	11.99%	0%	12.23%	0.37%	0.62%
Mineral resource depletion	17.28%	0.49%	0.58%	0.57%	0.85%	1.02%	0%	1.0%	6.46%	0.13%
Fossil fuel depletion (FFD)	17.39%	0.66%	0.72%	6.96%	10.43%	12.36%	1.92%	15.02%	13.68%	0.68%
Water consumption	0.32%	0.35%	0.69%	1.83%	2.75%	3.27%	0.05%	1.46%	0.34%	0.94%

7.5.1 Pre-construction alternate material option: RCW for pavement backfill

The LCA results for the pre-construction earthworks show that significant environmental impacts are generated from this stage (Table 7.4). Initially, the baseline GWP impact was 2901.41 tonnes CO_2eq. for the earthworks stage. After 60% replacement of crushed gravel aggregates by RCW as the backfill material, the GWP impact reduced by 16.33% (2427.64 tonnes CO_2eq.). FFD exhibited a similar trend with the impact value decreasing to 27.25 TJ from 32.98 TJ, around 17.39% lower. The overall observation was that the environmental impact reduction ranged from 0.32% to 24.77%. The lowest impact reduction (0.32%) was noted for water consumption while IR impacts were reduced by 24.77%.

These results were expected due to the following reasons. Firstly, quarry machinery uses fossil fuel which was reduced with the addition of RCW. Secondly, the transport distance of the RCW processing plant was lower (~70km) than the virgin aggregate production plant (~300km). On the other hand, water consumption impact mainly arises from the water required for aggregate plant operations which are similar for both backfill material alternatives. The significant difference in IR between the two backfill alternatives was because of the excess steel required for quarry operations and production. Significant quantities of NO_x are generated due to electricity consumption in crushing and screening RCW. However due to transport distance variations; significant reduction was found in POxF (18.26%), POzF (18.29%) and eutrophication (14.59%) indicators. Land use impact reduction was 9.31% as the infrastructural requirements are lower for recycling construction waste, which minimises the agricultural land damage.

7.5.2 Alternate material for pavement: RCW sub-base and unbound-base courses

The environmental impact assessment results of the pavement work using baseline case materials exhibited that around 127.55 tonnes CO_2eq. (3.86%) GWP and 1.584 TJ (1.7%) FFD are caused by the use of crushed gravel as a sub-base and u-base aggregate material. In order to estimate the impact of reducing crushed gravel use, two different RCW cases were studied: u-base with 80% RCW case; and 25% RCW sub-base with 80% RCW u-base case. Similar to Section 7.5.1 results, partially (80%) replacing crushed gravel by RCW for u-base resulted in a GWP reduction of 54.805 tonnes CO_2eq. and 0.687 TJ decline in FFD.

The environmental impacts were slightly reduced with the additional replacement of gravel in the sub-base course by 25% RCW. The GWP reduction in the "25% RCW sub-base, 80% RCW u-base" case was 4.93 tonnes CO_2eq. higher than the 80% RCW u-base course case. Likewise, the POzF impact difference was 35.27 kg NO_xeq. (0.213%) and the FFD difference was 0.062 TJ (0.06%). It can be implied from these results that once an optimum material replacement for crushed gravel has been achieved in the sub-base and u-base courses, any further replacement may not yield a significant reduction in the environmental impacts.

7.5.3 Pavement alternate material option: RAP

Three asphalt pavement recycling cases were investigated using different RAP percentages with virgin crushed aggregates for sub-base and u-base courses. Initially, 10% RAP content was used for a-base, binder, and wearing courses. Results showed that land use impacts were decreased by 6.74% and OD reduced by 6.25% compared to the baseline case. GWP declined by 167.424 tonnes CO_2eq. (3.96%) and the energy consumption in terms of FFD reduced by 7.23 TJ (6.96%). These reductions in the environmental impacts can be attributed to the difference in the needs for quarry operations and asphalt binder processing, and the less transport distance required for RAP compared to the virgin aggregates. Regarding the use of 15% RAP content in asphalt courses, higher environmental impact reduction results were obtained (Table 7.4). In this case, GWP decreased by 250.601 tonnes CO_2eq. (5.93%), OD by 9.34%, land use by 10.11% and energy consumption by 10.43%; this was again primarily due to differences in asphalt binder production between the different alternatives.

Building on these results, the RAP content in the asphalt mix for the a-base course was increased by another 10% RAP. The reduction in FFD and air emissions in this case (25% RAP a-base, 15% RAP binder & wearing courses) compared to the baseline case are shown in Table 7.4. FFD exhibited the highest reduction with 12.84 TJ (12.36%) lower value than the baseline. It was then followed by land use (11.99%), OD (11.09%) and GWP (7.05%). Consequently, due to the overall impact reduction from RAP usage for this case, it was flagged as best performing across all midpoint impact categories.

7.5.4 Pavement alternate production temperature: Warm-mix asphalt (WMA)

After only comparing WMA (containing zeolite additives) and HMA pavement sections (Table 7.4), it was observed that the air emissions and energy consumption were only slightly reduced. The volume of natural gas fuel in the asphalt plant reduced due to the lower heating requirements. However, the production of synthetic zeolite additives may have increased the impacts from the material production and processing stage. Overall, the lifecycle impacts from WMA were only marginally less than HMA. The lifecycle energy consumption reduced by 1.996 TJ (1.92%) while GWP reduced by 6.23% as shown in Table 7.4. Impact reduction for POzF and POxF exhibited similar trends with a respective difference of 0.316 tonnes NO_xeq. (1.86%) and 0.322 tonnes NO_xeq. (1.83%) between the HMA and WMA pavement sections, for these two indicators. These differences in the environmental damages were due to the differences between fuel requirements. Other impact categories, e.g., IR, eutrophication, eco-toxicity, and land use were not affected. Thus, even though the use of WMA reduced environmental impacts to some degree, its real potential is coupling WMA with high RAP content and other material alternatives to achieve reduction across all indicators. These results are similar to the findings by Vidal et al. (2013), where the GWP reduction between HMA and zeolite-based WMA was only 13%. Butt and Birgisson (2016) also showed that due to the production of additives for WMA mixtures, the difference in lifecycle GWP between hot-mix and warm-mix samples was only 12% and the difference in energy consumption was only 2.58%.

7.5.5 Collective environmental benefits of alternate options on pavement construction

The above results showed that using recycled materials as the alternate option and replacing HMA by WMA as the production technique individually yielded significant environmental impact reduction. The collective environmental impact reduction for the best performing RCW and RAP percentages is now assessed coupled with WMA. As shown in Table 7.4, energy consumption exhibited the highest reduction as FFD decreased by 15.61 TJ (15.02%). The OD was reduced by 11.99%, the POxF reduced by 1.968 tonnes NO_xeq. (11.22%) and PMF by 0.801 tonnes $PM_{2.5}$eq. (9.89%).

GWP impact was also significantly reduced compared to the baseline pavement section, exhibiting 623.54 tonnes CO_2eq. (14.75%) reduction. These environmental impact reductions were contributed by both alternative material usage across the pavement sections and the lower production temperatures of WMA. However, the 12.23% (20750.65 m2a crop eq.) reduction in land use impact was only attributable to

RCW and RAP usage. Water consumption, freshwater, and marine eco-toxicity impacts were only marginally reduced with a respective reduction of 1.46%, 0.85%, and 0.93%. Crushing, screening and producing RCW at recycling plants consumed water volume similar to gravel production. Similarly, construction waste from bricks etc. is sometimes covered in paint which contains lead and other heavy metals that generate leachate and cause groundwater contamination.

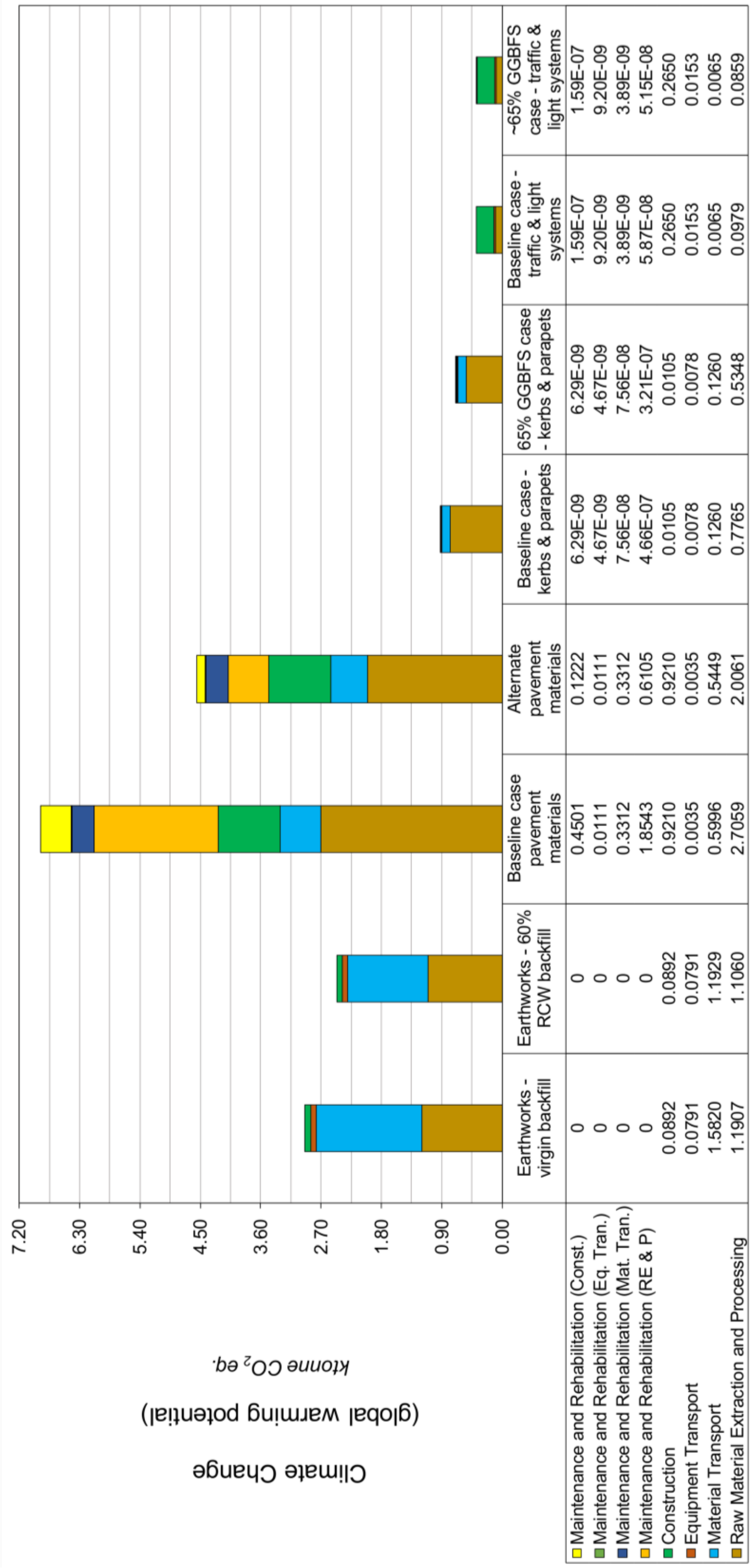
7.5.6 Traffic barriers, signs, kerbs and light systems: Alternate options for concrete works

In order to perform a comprehensive environmental impact reduction assessment on the use of alternate options for roadworks in the case study region, partial replacement (~65%) of OPC by GGBFS was performed (Table 7.4). GGBFS generated higher benefits for barriers and kerb works compared to foundation works for traffic signs and light due to the higher volume of concrete used for constructing the former roadworks component.

The GWP results above show that the primary contributor to greenhouse gases is the OPC content in the concrete mix as the impact value reduced by 241.75 tonnes CO_2eq. (26.37%) for traffic barrier and kerbs, and by 12.03 tonnes CO_2eq. (3.2%) for traffic signs and light foundation works. FFD results for traffic kerbs and barriers reduced by 13.68% with GGBFS introduction as they were influenced by mining operations for OPC admixtures: gypsum, clinkers, and limestone. Due to the heavy energy consumption involved in kiln heating during clinker production, GGBFS addition caused a decline in fuel demand. Furthermore, gypsum and limestone mining generates excessive quantities of sulphur dioxide, particulate matter, and nitrogen oxide (NO_x) pollutants. The environmental impact reduction results for POzF as 12.28% (0.339 tonnes NO_xeq.), POxF as 12.2% (0.342 tonnes NO_xeq.) and acidification as 9.47% (0.191 tonnes SO_2eq.) were obtained after 65% GGBFS content. These results are also indicative of the effect of OPC admixtures on the overall emissions.

7.5.7 Environmental impacts and reduction potential distribution across lifecycle stages

Environmental impacts for the best performing cases from each alternate option were further investigated in detail to identify the impact reduction for each stage of the pavement and associated roadworks lifecycle. The "**alternate pavement materials**" for pavement is based on Section 7.5.5 and during M&R 85% RAP in WMA *wearing course* was used. The RAP content used for M&R is from milling the case study pavement and is transported to the asphalt plant.



	Earthworks - virgin backfill	Earthworks - 60% RCW backfill	Baseline case pavement materials	Alternate pavement materials	Baseline case - kerbs & parapets	65% GGBFS case - kerbs & parapets	Baseline case - traffic & light systems	~65% GGBFS case - traffic & light systems
Maintenance and Rehabilitation (Const.)	0	0	0.4501	0.1222	6.29E-09	6.29E-09	1.59E-07	1.59E-07
Maintenance and Rehabilitation (Eq. Tran.)	0	0	0.0111	0.0111	4.67E-09	4.67E-09	9.20E-09	9.20E-09
Maintenance and Rehabilitation (Mat. Tran.)	0	0	0.3312	0.3312	7.56E-08	7.56E-08	3.89E-09	3.89E-09
Maintenance and Rehabilitation (RE & P)	0	0	1.8543	0.6105	4.66E-07	3.21E-07	5.87E-08	5.15E-08
Construction	0.0892	0.0892	0.9210	0.9210	0.0105	0.0105	0.2650	0.2650
Equipment Transport	0.0791	0.0791	0.0035	0.0035	0.0078	0.0078	0.0153	0.0153
Material Transport	1.5820	1.1929	0.5996	0.5449	0.1260	0.1260	0.0065	0.0065
Raw Material Extraction and Processing	1.1907	1.1060	2.7059	2.0061	0.7765	0.5348	0.0979	0.0859

Figure 7.5 Climate change impacts and reduction across lifecycle stages

Figure 7.5 shows that earthworks contribution to total GWP impact of baseline case roadworks (11.123 ktonnes CO_2eq.) was 26% and FFD contribution was 15% to the total FFD of 219.896 TJ. Extraction and processing of crushed gravel and sand backfill caused 40% of the GWP emissions for the earthworks. This contribution was increased (~45%) when 60% RCW was used. However, it was offset by the reduction in material transport contribution to the GWP. For earthworks using virgin backfill materials, transporting materials caused 54% of the GWP emissions which was reduced to 48% with the 60% RCW option. Similar trends were observed for energy consumption results shown in Figure 7.6 below. A reduction in the material transport FFD share (from 61% to 55%) offset the increase in material extraction and processing share, which had increased to 37% from 33%. In general, material transport remained the largest contributor to the environmental impacts caused during earthworks due to the excessive transport distance from quarries in Fujairah to Abu Dhabi. Environmental impact contributions of construction equipment transport to the project site remained 3-4% due to the machinery used for this component of the roadworks.

Pavement section works generated 62% of GWP and 80% of the FFD impact caused by the complete baseline case. For the impact distribution within the pavement section works, raw material extraction and processing stage was the largest contributor. The environmental impacts were considerably reduced between baseline case pavement section and alternate materials case. This was mainly due to less raw materials demand for aggregates and bitumen and shorter transport distance. The share of raw material sub-stage within the M&R stage was also considerably reduced between the baseline case (27%) and alternate pavement materials case (13%). These results were caused by recycling 85% of the milled RAP from the case study pavement section's wearing course in the mixing plant and then used for repaving. Overall, the GWP for pavement section works reduced by 34% (2.33 ktonnes CO_2eq.) while FFD reduced by 48% (84.71 TJ), with the most significant reductions in the material extraction and M&R stages.

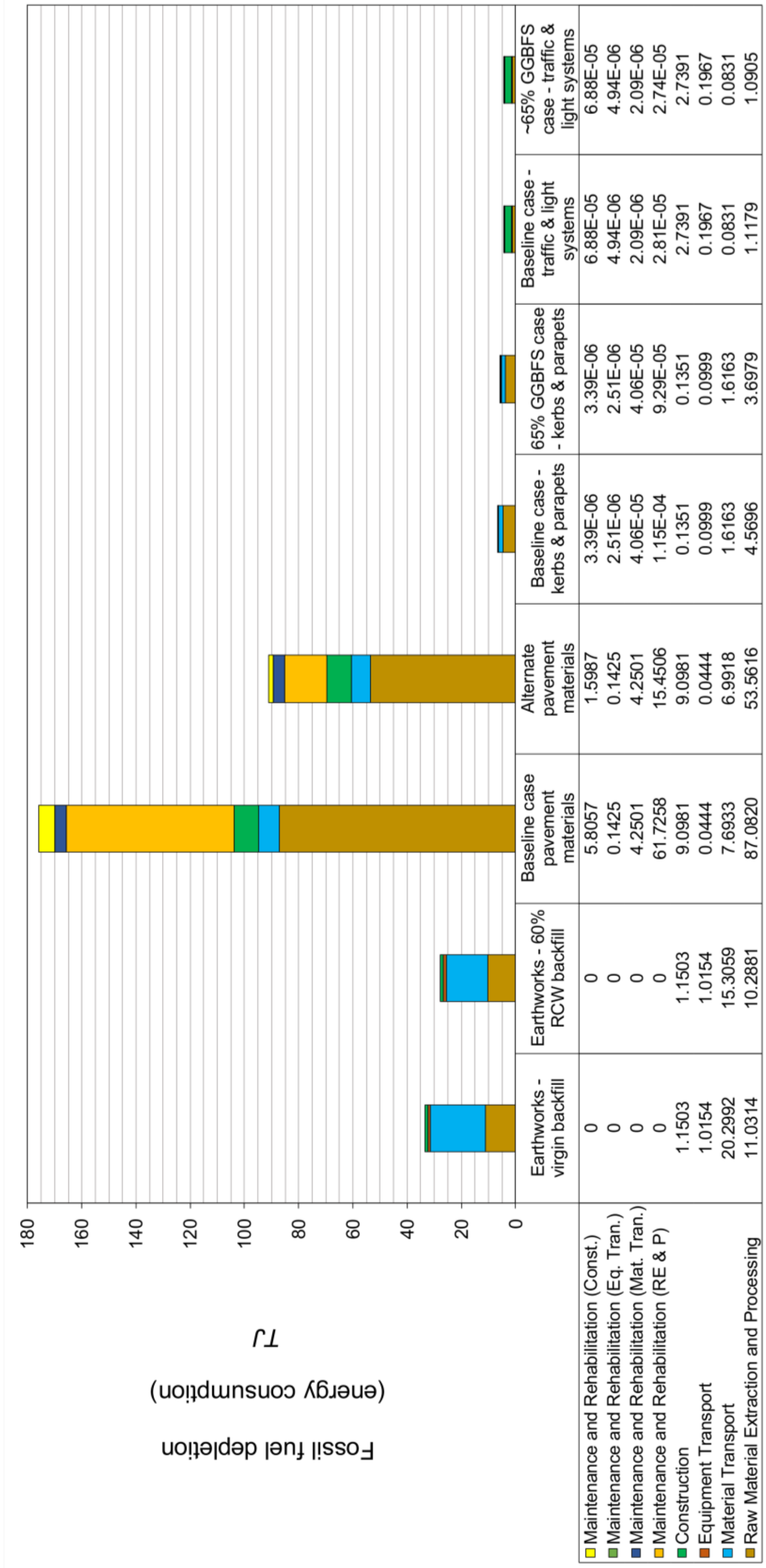


Figure 7.6 Fossil fuel depletion impacts and reduction distribution across lifecycle stages

The concrete barriers, kerbs, and parapet works were responsible for 8% of the GWP and 3% of FFD impacts. The majority (84%) of their GWP and FFD (71%)

contributions were caused by material extraction and processing stage. The use of GGBFS considerably reduced these impacts as shown in Figure 7.5 and Figure 7.6. The GWP share from this stage reduced to 79% while the FFD contribution decreased to 67%. On the other hand, concrete foundations for the traffic signs and light systems were the only component of the roadworks where the construction stage generated the highest environmental impacts during the entire lifecycle. This is due to the diesel fuel consumed for operating the heavy on-site construction machinery.

7.6 UNCERTAINTY ASSESSMENT

Due to the extent of the large inventory data, a certain degree of uncertainty is introduced in the LCA results because of the uncertainties in LCI data. Accurately acknowledging for these uncertainties is specifically important when two alternates are being compared, as any projected environmental impact reduction benefits of alternate cases can be offset by uncertain input data. Monte Carlo simulations are performed using the in-built uncertainity assessment function in SimaPro to calculate uncertainties of LCIA results with 95% confidence interval. For each case, SimaPro simulation performs 1000 iterations. Figure 7.7 reports the comparison between Monte Carlo simulation results for the baseline and alternate materials pavement works.

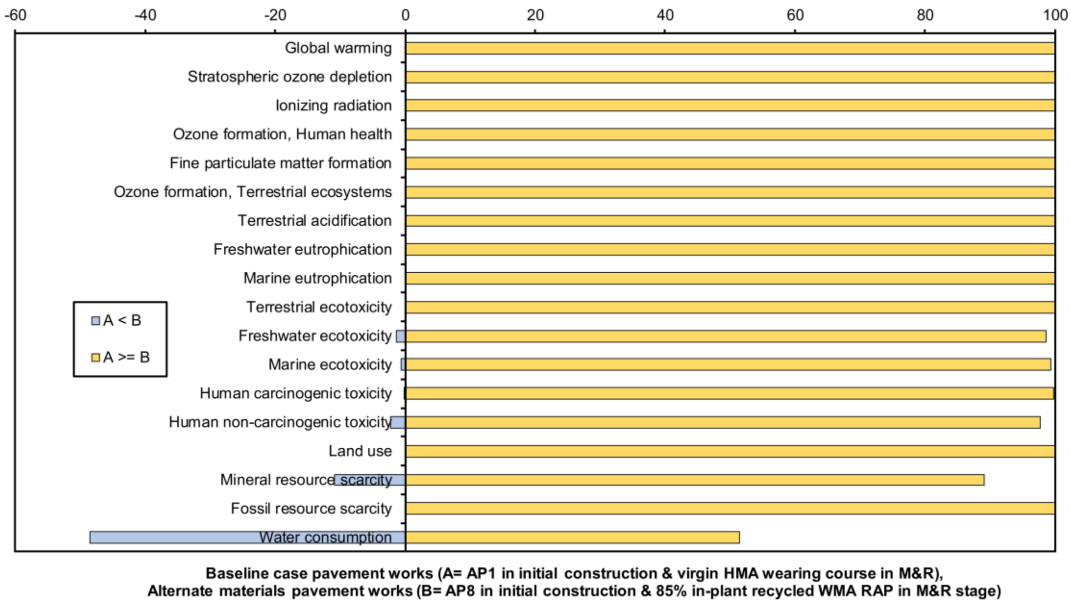


Figure 7.7 Monte Carlo uncertainty assessment results for pavement works, baseline case against alternate materials and warm-mix asphalt case

The probability that the impact values for alternate pavement materials are lower than the baseline case is in the 90%–100% range for the majority of indicators. However, the water consumption impact for the baseline case pavement works was higher than the "alternate materials case" in 52% of the simulated cases. This is due to the volume of water required for producing RCW at construction waste recycling facilities; which is obtained from a variety of freshwater, marine and wastewater resources that can amplify the uncertainties in input data.

Figure 7.8 reports the Monte Carlo simulation results for the GWP impacts generated by concrete works. The coefficient of variation (CV) values are admissible. CV values for concrete works conducted as part of kerbs, parapets, and barriers ranged between 6.01% – 6.7%. For the concrete roadworks due to traffic signs and light system foundations, the CV values ranged from 3.8% – 3.9%.

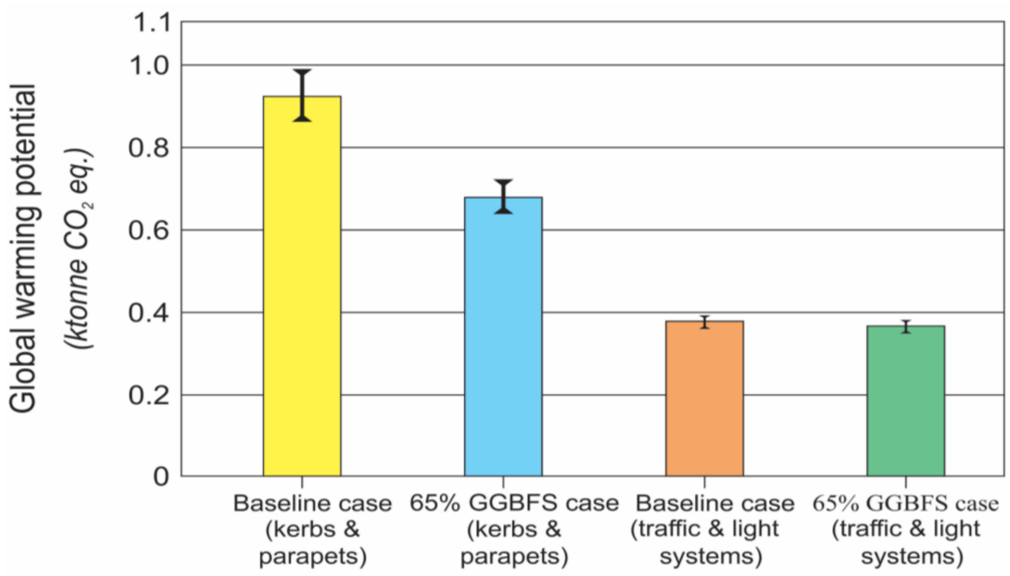


Figure 7.8 Global warming potential uncertainty assessment for concrete works, baseline vs alternate

7.7 Case study GWP and FDD impacts and comparison with roadworks LCA literature

The roadworks LCA literature covered in the earlier sections highlights that several studies have assessed the environmental impact reduction in pavement works by using RCW and RAP as alternate material options, and WMA instead of HMA as an alternate production technique. Figure 7.9 compares the findings of some of these studies against the results of the current study in terms of GWP impact. It shows that the GWP values of this study are at least 29% higher. This difference is attributable to the consumption of higher bitumen consumption for the case study highway section than the studies (Biswas, 2014; Giani et al., 2015; Celauro et al., 2017) in Figure 7.9. The “alternate materials case – complete works” uses RCW, RAP and WMA for pavement works and GGBFS as partial replacement of Portland cement (~65%), as stated in Section 7.5.7. It also includes impacts for complete roadworks: earthworks, pavement courses, concrete works for traffic barriers, kerbs, parapets, traffic signs, and light systems.

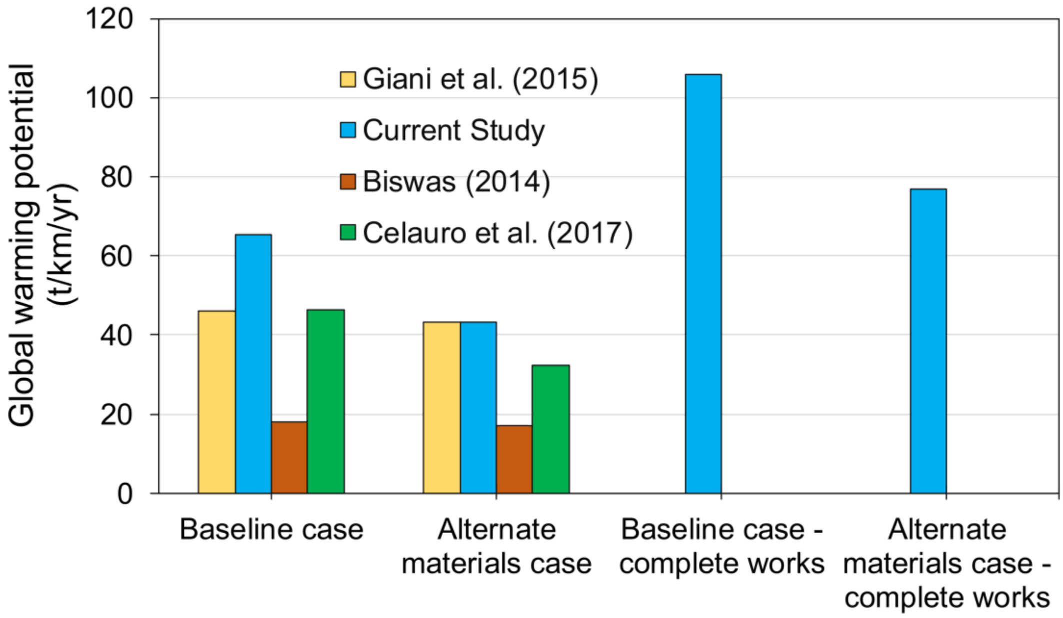


Figure 7.9 Comparative assessment of global warming results, road LCA against the current study

However, the current study also reported a significantly higher reduction in GWP emissions after using WMA combined with alternate material options (*25% RCW sub-base, 80% RCW unbound-base, 25% WMA RAP asphalt-base and 15% WMA RAP binder & wearing courses*). In the current study, the GWP impact for pavement section works reduced by 34%, whereas Giani et al. (2015) reported a 6% reduction in GWP after using both WMA and RAP. Biswas (2014) reported a 5% reduction after using RCW (both during initial construction and M&R stages) and RAP (in M&R stage only). The 30% GWP impact reduction reported by Celauro et al. (2017) was comparable to the findings of the current study. These observations further iterate the need for region-based LCA studies as well as the high environmental benefits that can be achieved in the case study region due to the use of low-temperature asphalt mixes (warm and cold mix) and alternate construction material options. The reduced transport distance required for alternate materials, compared to virgin materials, may have also contributed to these results.

7.8 DISCUSSION AND CONCLUSION

The existing literature on roadworks and pavements suggest that the use of virgin materials (asphalt, aggregates, concrete, etc.) carry a significant environmental burden which may reduced by using alternate options (e.g., RAP, GGBFS concrete and RCW). Given this, the environmental benefits associated with recycled or alternate material use may carry a significant cost component which should be kept at a reasonable level to maintain competitiveness of these options (refer to Section 2.3.6). Additionally, in some regions, such as the UAE (as studied here), there is a considerable lack of research on the long-term environmental benefits that can be obtained from the application of such alternate material options, especially from a local real-world project-based perspective (Maraqa et al., 2018). These factors, coupled with the reliance on traditional construction practices and lack of local empirical data on the benefit of alternate/recycled material usage, has resulted in these recycled/alternate approaches not being widely used in practice in the region.

This study aimed to fill this gap by presenting a comprehensive LCA of roadworks on a 3.5km long highway section in Abu Dhabi. Environmental impacts across all components of a road section were accounted: earthworks; pavement section courses; concrete barriers, kerbs and parapets; and, the concrete foundation works for traffic signs and light systems. In general, the raw material stage was the highest contributor to GWP as it generated 63.96% of baseline case emissions. The construction stage accounted for the second-highest (~21.78%), followed by material (~14.18%) and equipment transport (0.05%).

The use of RCW as an alternate backfill material holds promise as the GWP value reduced by 16% with the use of 60% RCW. RCW use in sub-base and u-base courses also reduced impacts from asphalt pavement section, for e.g., 59.736 tonnes CO_2eq. reduction in GWP and 11.68 GJ reduction in energy (FFD) impact. However, these reductions only account for approximately 1.4% of the total environmental impacts of the entire pavement sections.

Although the use of WMA instead of HMA reduced environmental impacts, e.g., GWP by 6.23% and FFD by 1.92%, the most notable reductions were due to RAP addition in the asphalt mix. This was primarily due to large environmental burdens associated with production of bitumen, hydrated lime filler and synthetic zeolite additives. The 25% RAP content in the a-base course and the 15% RAP content in the binder and wearing courses coupled with WMA resulted in significantly lower environmental impacts across all indicators. For example, FFD and GWP impact values decreased in the order of 15%. Two options were compared during the rehabilitation stage of the milled wearing course. As an important advantage of WMA is the potential to use high RAP content in the production mix, 85% in-plant WMA recycling of milled RAP was assessed against virgin HMA asphalt. This resulted in the reduction of GWP by 59% and FFD by 70%. Comparing baseline OPC-concrete for roadworks against GGBFS-concrete, GWP exhibited the highest reduction (~19%) followed by FFD (~9%), POxF (~8.4%), POzF (~8.3%) and acidification (6.12%).

These results of the current study were also assessed against those reported in pavement LCA literature. A key advantage of the current study was the higher benefit (e.g., 34% for GWP and 48% FFD) of using alternate options compared to previous studies. This is mainly due to the pavement section design, transport distance, material type, and production variations. The uncertainty assessment by Monte Carlo simulation also confirmed that the high environmental impacts of roadworks in the case study region can be reduced by alternate material use to around 99% probability.

It should be noted here that these benefits of alternate and recycled material approaches on real-world road projects from the UAE were only evaluated from an environmental perspective and were only focused on the roadworks component of the transport system. Subsequent chapters shall evaluate the environmental benefit of traffic management strategies (Chapter 8) as well as analysing the lifecycle cost-environmental-social impacts of applying alternate approaches to both roadworks and traffic components of the road transport system (Chapter 9) to evaluate the comparative benefits from a holistic perspective.

7.9 References

AASHTO. (2012). Standard specification for use of reclaimed asphalt shingles (RAS) as an additive in hot mix asphalt (HMA). Vol. MP 15-09. Washington, DC: American Association of State Highway Transportation Officials.

Abergel, T., Dean, B., & Dulac, J. (2017). *Towards a zero-emission, efficient, and resilient buildings and construction sector: Global Status Report 2017*. Retrieved (25/08/2019) from www.worldgbc.org/sites/default/files/UNEP%20188_GABC_en%20%28web%29.pdf. Paris, France

Abou-Senna, H., Radwan, E., Westerlund, K., & Cooper, C. D. (2013). Using a traffic simulation model (Vissim) with an emissions model (MOVES) to predict emissions from vehicles on a limited-access highway. *Journal of the Air & Waste Management Association, 63*(7), 819-831. DOI: 10.1080/10962247.2013.795918.

Abu Dhabi City Municipality. (2010). *Sustainability guideline for Abu Dhabi municipality, IRI employees and consultants*. Abu Dhabi, United Arab Emirates: Abu Dhabi Municipality, Projects Roads and Infrastructure Design Section.

ADM. (1997). Standard specifications for road and bridge construction. Abu Dhabi, UAE: Abu Dhabi Municipality.

Abu Dhabi Department of Transport - ADDoT. (2009). *Surface transport master plan – A vision for connecting Abu Dhabi*. Abu Dhabi, United Arab Emirates.

Almeida-Costa, A., & Benta, A. (2016). Economic and environmental impact study of warm mix asphalt compared to hot mix asphalt. *Journal of Cleaner Production, 112*, 2308-2317. DOI: 10.1016/j.jclepro.2015.10.077.

Alzard, M. H., Maraqa, M. A., Chowdhury, R., Khan, Q., Albuquerque, F. D. B., Mauga, T. I., & Aljunadi, K. N. (2019). Estimation of greenhouse gas emissions produced by road projects in Abu Dhabi, United Arab Emirates. *Sustainability, 11*(8), 2367. DOI: 10.3390/su11082367.

Anastasiou, E. K., Liapis, A., & Papayianni, I. (2015). Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials. *Resources, Conservation and Recycling, 101*, 1-8. DOI: 10.1016/j.resconrec.2015.05.009.

Anthonissen, J., Van den bergh, W., & Braet, J. (2016). Review and environmental impact assessment of green technologies for base courses in bituminous pavements. *Environmental Impact Assessment Review, 60*, 139-147. DOI: 10.1016/j.eiar.2016.04.005.

AzariJafari, H., Yahia, A., & Ben Amor, M. (2016). Life cycle assessment of pavements: Reviewing research challenges and opportunities. *Journal of Cleaner Production, 112*, 2187-2197. DOI: 10.1016/j.jclepro.2015.09.080.

Balaguera, A., Carvajal, G. I., Albertí, J., & Fullana-i-Palmer, P. (2018). Life cycle assessment of road construction alternative materials: A literature review. *Resources, Conservation and Recycling, 132*, 37-48. DOI: 10.1016/j.resconrec.2018.01.003.

Bank, W. (2019). CO_2 emissions (metric tons per capita). Retrieved (02/06/2016) from data.worldbank.org/indicator/en.atm.co2e.pc. Carbon Dioxide Information Analysis Centre, Environmental Sciences Division, Oak Ridge National Laboratory.

Batouli, M., Bienvenu, M., & Mostafavi, A. (2017). Putting sustainability theory into roadway design practice: Implementation of LCA and LCCA analysis for pavement type selection in real world decision making. *Transportation Research Part D: Transportand Environment, 52*, 289-302. DOI: 10.1016/j.trd.2017.02.018.

Biswas, W. K. (2014). Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia. *The International Journal of Life Cycle Assessment, 19*(4), 732-744.

Blankenagel, B. J. (2005). *Characterization of recycled concrete for use as pavement base material.* (Master of Science). Retrieved (02/06/2016) from scholarsarchive.byu.edu/etd/640. Brigham Young University, Provo, Utah.

Blengini, G. A., & Garbarino, E. (2010). Resources and waste management in Turin (Italy): The role of recycled aggregates in the sustainable supply mix. *Journal of Cleaner Production, 18*(10), 1021-1030. DOI: 10.1016/j.jclepro.2010.01.027.

Butt, A. A., & Birgisson, B. (2016). Assessment of the attributes bases life cycle assessment framework for road projects. *Structure and Infrastructure Engineering, 12*(9), 1177-1184. DOI: 10.1080/15732479.2015.1086388.

Caterpillar Inc. (2011). Caterpillar performance handbook 41. Peoria, Illinois: Caterpillar Incorporated. pp. 1474.

Celauro, C., Corriere, F., Guerrieri, M., Lo Casto, B., & Rizzo, A. (2017). Environmental analysis of different construction techniques and maintenance activities for a typical local road. *Journal of Cleaner Production, 142*, 3482-3489. DOI: 10.1016/j.jclepro.2016.10.119.

Department of Transport Abu Dhabi. (2018). *Standard construction specifications part 1*. Abu Dhabi, UAE: Department of Transport Abu Dhabi.

DSV Global Transport and Logistics. (2019). Trucks and trailers types. Retrieved (02/06/2016) from www.ae.dsv.com/road-freight/trailer-types-and-dimensions.

Elchalakani, M., Aly, T., & Abu-Aisheh, E. (2014). Sustainable concrete with high volume GGBFS to build Masdar City in the UAE. *Case Studies in Construction Materials, 1*, 10-24. DOI: 10.1016/j.cscm.2013.11.001.

Environment Agency - Abu Dhabi. (2012). Greenhouse gas inventory for Abu Dhabi Emirate – Inventory results executive summary. Retrieved (4/11/2018) from www.ead.ae/documents/pdf-files/AD-greenhouse-gas-inventory-eng.pdf. Environment Agency - Abu Dhabi.

Giani, M. I., Dotelli, G., Brandini, N., & Zampori, L. (2015). Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling. *Resources, Conservation and Recycling, 104*, 224-238. DOI: 10.1016/j.resconrec.2015.08.006.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A., Struijs, J., & Zelm, R. (2009). ReCiPe 2008, PRé Consultants. *University of Leiden, Radboud University, RIVM, Nijmegen. Den Haag, the Netherlands: VROM (Dutch Ministry of Housing Spatial Planning and Environment)*.

Guo, S., Hu, J., & Dai, Q. (2018). A critical review on the performance of Portland cement concrete with recycled organic components. *Journal of Cleaner Production, 188*, 92-112. DOI: 10.1016/j.jclepro.2018.03.244.

Hasan, U. (2015). *Experimental study on bentonite stabilisation using construction waste and slag.* (M.Phil.). Curtin University, Perth, Western Australia, Australia.

Hasan, U., Whyte, A., & Al Jassmi, H. (2019). Critical review and methodological issues in integrated life-cycle analysis on road networks. *Journal of Cleaner Production, 206*, 541-558. DOI: 10.1016/j.jclepro.2018.09.148.

Hill, N., Brannigan, C., Wynn, D., Milnes, R., Van Essen, H., den Boer, E., van Gijlswijk, R. (2012). EU transport GHG: Routes to 2050 II. The role of GHG emissions from infrastructure construction, vehicle manufacturing, and ELVs in overall transport sector emissions.

Hoque, N., Biswas, W. K., Mazhar, I., & Howard, I. (2019). LCSA framework for assessing sustainability of alternative fuels for transport sector. *Chemical Engineering Transactions, 72*, 103-108. DOI: 10.3303/CET1972018.

Huang, Y. (2007). *Life cycle assessment of use of recycled materials in asphalt pavements.* (Ph. D.). Newcastle University, Newcastle upon Tyne, UK.

ISO 14040. (2006). Environmental management – Life cycle assessment – Principles and framework (Vol. 14040:2006(E), pp. 20). Geneva, Switzerland: International Organization for Standardization.

Kim, T., Tae, S., & Chae, U. C. (2016). Analysis of environmental impact for concrete using LCA by varying the recycling components, the compressive strength and the admixture material mixing. *Sustainability, 8*(4). DOI: 10.3390/su8040389.

Mahesh, S., Ramadurai, G., & Shiva Nagendra, S. M. (2018). Real-world emissions of gaseous pollutants from diesel passenger cars using portable emission measurement systems. *Sustainable Cities and Society, 41*, 104-113. DOI: 10.1016/j.scs.2018.05.025.

Maraqa, M., Chowdhury, R., Mauga, T., Albuquerque, D., Alzard, M., Khan, Q., Sherif, M. (2018). *Assessing the carbon footprint of road projects and related sustainability initiatives in Abu Dhabi*. Abu Dhabi, UAE.

Moretti, L., Mandrone, V., D'Andrea, A., & Caro, S. (2018). Evaluation of the environmental and human health impact of road construction activities. *Journal of Cleaner Production, 172*, 1004-1013. DOI: 10.1016/j.jclepro.2017.10.250.

Pavement Interactive. (2019). Retrieved (4/11/2018) from www.pavementinteractive.org/reference-desk/pavement-types-and-history/pavement-types/asphalt-concrete-base-acb.

Praticò, F. G., Vaiana, R., & Iuele, T. (2015). Permeable wearing courses from recycling reclaimed asphalt pavement for low-volume roads. *Transportation Research Record: Journal of the Transportation Research Board, 2474*, 65-72. DOI: 10.3141/2474-08.

PRé Consultants. (2016). SimaPro 8.5.2© manual. San Francisco, California: PRé Consultants.

PRé Consultants. (2018). SimaPro database manual – Methods library. San Francisco, California: PRé Consultants.

Quaassdorff, C., Borge, R., Pérez, J., Lumbreras, J., de la Paz, D., & de Andrés, J. M. (2016). Microscale traffic simulation and emission estimation in a heavily trafficked roundabout in Madrid (Spain). *Science of the Total Environment, 566-567*, 416-427. DOI: 10.1016/j.scitotenv.2016.05.051.

RAD International Road Construction L.L.C. (2013). Asphalt production. Retrieved (4/11/2018) from www.rad.ae/site/index.php/en/asphalt-factory/asphaltproduction

Raeside, J. (2015). Middle East emissions legislation. Retrieved (4/11/2018) from www.integer-research.com/industry-insight/emissions-legislation/middle-east.

Rathje, E. M., Rauch, A. F., Folliard, K. J., Trejo, D., Little, D., Viyanant, C., Esfeller, M. (2002). *Recycled asphalt pavement and crushed concrete backfill: Results from initial durability and geotechnical tests* (FHWA/TX-02/4177-2). Retrieved (4/11/2018) from Austin, TX.

Rys, D., Judycki, J., Pszczola, M., Jaczewski, M., & Mejlun, L. (2017). Comparison of low-temperature cracks intensity on pavements with high modulus asphalt concrete and conventional asphalt concrete bases. *Construction and Building Materials, 147*, 478-487. DOI: 10.1016/j.conbuildmat.2017.04.179.

Santos, J., Ferreira, A., & Flintsch, G. (2015). A life cycle assessment model for pavement management: road pavement construction and management in Portugal. *International Journal of Pavement Engineering, 16*(4), 315-336. DOI: 10.1080/10298436.2014.942862.

SCAD. (2014). *Statistical yearbook of Abu Dhabi*. Abu Dhabi, United Arab Emirates: Statistics Centre – Abu Dhabi (SCAD) Retrieved (4/11/2018) from www.scad.ae/Release%20Documents/SYB-2014_V1.1_EN.pdf.

Scheving, A. G. (2011). *Life cycle cost analysis of asphalt and concrete pavements.* (Master of Science). Reykjavík University, Reykjavík, Iceland.

Stripple, H. (2001). *Life cycle assessment of road. A pilot study for inventory analysis*. Gothenburg, Sweden.

Tarefder, R. A., & Pan, J. (2014). *Field and laboratory evaluation of warm mix asphalt (WMA) – Phase 1* (NM13MSC-04). Albuquerque, NM.

Turk, J., Mauko Pranjić, A., Mladenovič, A., Cotič, Z., & Jurjavčič, P. (2016). Environmental comparison of two alternative road pavement rehabilitation techniques: cold-in-place-recycling versus traditional reconstruction. *Journal of Cleaner Production, 121*, 45-55. DOI: 10.1016/j.jclepro.2016.02.040.

Ventura, A., Monéron, P., & Jullien, A. (2008). Environmental impact of a binding course pavement section, with asphalt recycled at varying rates. *Road Materials and Pavement Design, 9*(sup1), 319-338. DOI: 10.1080/14680629.2008.9690172.

Vidal, R., Moliner, E., Martínez, G., & Rubio, M. C. (2013). Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. *Resources, Conservation and Recycling, 74*, 101-114. DOI: 10.1016/j.resconrec.2013.02.018.

Vieira, C. S., & Pereira, P. M. (2015). Use of recycled construction and demolition materials in geotechnical applications: A review. *Resources, Conservation and Recycling, 103*, 192-204. DOI: 10.1016/j.resconrec.2015.07.023.

Wang, T. (2013). *Reducing greenhouse gas emissions and energy consumption using pavement maintenance and rehabilitation: Refinement and application of a life cycle assessment approach*. (Ph.D.). Civil and Environmental Engineering, University of California, Davis, Ann Arbor, MI. pp. 374.

Whyte, A. (2012). *Life-cycle assessment of built asset waste materials-sustainable disposal options* (1^{st} Ed.). Saarbrücken, Germany: Lambert Academic Publishing (LAP).

Yang, K.-H., Jung, Y.-B., Cho, M.-S., & Tae, S.-H. (2015). Effect of supplementary cementitious materials on reduction of CO_2 emissions from concrete. *Journal of Cleaner Production, 103*, 774-783. DOI: 10.1016/j.jclepro.2014.03.018.

Yi, I., Itsubo, N., Inaba, A., & Matsumoto, K. (2007). Development of the interregional I/O based LCA method considering region-specifics of indirect effects in regional evaluation. *The International Journal of Life Cycle Assessment, 12*(6), 353. DOI: 10.1065/lca2007.06.339.

Zhao, S., Huang, B., Shu, X., Jia, X., & Woods, M. (2012). Laboratory performance evaluation of warm-mix asphalt containing high percentages of reclaimed asphalt pavement. *Transportation Research Record, 2294*(1), 98-105. DOI: 10.3141/2294-11.

Zhao, S., Huang, B., Shu, X., & Woods, M. (2013). Comparative evaluation of warm mix asphalt containing high percentages of reclaimed asphalt pavement. *Construction and Building Materials, 44*, 92-100. DOI: 10.1016/j.conbuildmat.2013.03.010.

CHAPTER 8

MICROSIMULATION PROJECTION OF CURRENT AND FUTURE ENERGY CONSUMPTION AND EXHAUST EMISSIONS FROM URBAN HIGHWAY VEHICLES: SCENARIO ANALYSES OF REDUCTION MEASURES IN ABU DHABI

8.1 ABSTRACT

Economic and population developments and excessive reliance on passenger cars in the United Arab Emirates have resulted in growing traffic congestion, large energy consumption and exhaust CO_2, NO_x and PM pollutant emissions from road transport in its metropolitan regions. The current study presents the assessment of energy consumption and exhaust pollutant emissions from vehicle operations on a high traffic density 3.5 km long 5-lane dual-carriageway section in the City of Abu Dhabi over the period from 2015–2045. High-resolution traffic microsimulation models were developed using actual traffic counts (for a representative week), vehicle exhaust emissions and fuel consumption data. These models accurately simulated the real-world vehicle volume, speed-time and acceleration-deceleration profiles for urban passenger cars, minibus and coach, and light and heavy-duty traffic. Traffic growth models and advancements in vehicle fuel technology and Euro emission-control engine standards were used to project future traffic counts, fuel technology and consumption across all vehicle types. Projected traffic data and traffic microsimulation models were utilised to assess the energy consumption and exhaust pollutants' reduction potential of traffic management scenarios namely: business-as-usual; public bus transport case; public bus rapid transit service case; and, a traffic demand-responsive autonomous vehicle-based bus rapid transit service case, at the vehicle level. The results show that traffic energy consumption, and exhaust pollutant emissions have a direct relationship. Both energy consumption and exhaust emission rates are dependent upon traffic volume, and the traffic flow rate factors of: vehicle speed-time curves; acceleration-deceleration; and, braking rate. Over the 30 years analysis period, the "Bus Case" option reduced energy consumption, CO_2, NO_x and PM exhaust emissions by 25%, 24%, 29%, and 18%, respectively. BRT reduced 35%, 35%, 45% and 20% of the accumulative vehicle energy consumption, CO_2, NO_x, and

PM exhaust emissions. AV-BRT resulted in the highest reduction in energy consumption (56%), CO_2 (55%), NO_x (50%) and PM (25%) exhaust emissions. Results show that public transport promotion is the most effective and easy-to-implement energy and emission reduction strategy in the UAE urban regions. However, emission regulation and a switch to natural gas etc. for public transport vehicles, from diesel fuel, is needed to achieve these target energy conservation and emissions reduction goals of the local authorities.

8.2 INTRODUCTION

Road transport networks are essential for modern societies, directing people and resources within and among cities. However, today's roads are subject to excessive traffic congestion that increase energy consumption and exhaust pollutant emissions from the transport sector around the world. In United States, transport sector is the 2^{nd} largest contributor to greenhouse gas (GHG) emissions, while the emissions data from other G8 countries and European Union found transportation sectors contributing around $2/3^{rd}$ of the total GHG emissions (Andersen et al., 2013; Hasan, Whyte, & Al Jassmi, 2018a and Lepert & Brillet, 2009). A majority of these CO_2, nitrogen oxides (NO_x) and particulate matter (PM) air pollutant emissions are generated from the fuel consumed by passenger vehicles. For example, the passenger car fleet has been forecasted to remain the single largest contributor to environmental emissions within the transport sector in Australia for the year 2020, accounting for around 49,384 gigagrams CDE (Bureau of Infrastructure, 2009). Thus, fossil fuel consumption and the resulting emissions from passenger vehicle fleet highly escalate the environmental impacts from road traffic, which has made it one of the "hot topics" focused on various green initiatives to conserve/save energy and emissions reduction.

Many energy consumption and pollutant emission reduction scenarios are analysed in the literature to assess the long-term impact of various traffic management strategies developed by the transport policy-makers. McCollum and Yang (2009) note that vehicle fuel consumption, fuel type, urban population growth and most significantly, travel demand, are the key factors for achieving lower pollutant emissions. However, the mobility patterns (i.e., travel mode choice, demand, and frequency) of municipal residents are ever-changing and heavily dependent on the traffic management strategy of policy-makers, its benefits, and shortcomings. Peng et al. (2015) observed that in order to reduce energy consumption and pollutant emissions, transport policymakers seek public transport services that cater to passenger needs and reduce reliance on private vehicles by increasing public transport usage. Mikhail et al. (2013) note that by ensuring a shift of around 20–30% of private vehicle passengers towards public transport, significant reductions can be obtained in the total energy demand from transport network, CO_2 and PM emissions. Thus, it can be rationalised that the public-transit systems (shared vehicles, buses, bus/light-rail rapid transit, etc.) open a window of opportunity for any city to reduce its transportation-related environmental burdens (Batarce, Muñoz, & Ortúzar, 2016) as effective traffic management strategies.

In addition to tackling the private vehicle demand through public transport, alternate fuel technologies: compressed natural gas (CNG), hydrogen fuel cell, electric and hybrid-electric; which arguably generate less environmental burdens than conventional diesel and petrol vehicles; are also proposed in the research literature (Hoque et al., 2019). McKenzie and Durango-Cohen (2012) estimated that due to the differences in energy input, the greenhouse gas (GHG) emissions from CNG bus operations in the United States were 747 CDE/mile lower than diesel buses. They also noted that emissions from hybrid diesel-electric (834 CDE/mile) and hydrogen fuel cell (1088 CDE/mile) were even lower but were dependent upon infrastructural support and energy-supply (fuel) pathways. The energy consumption and GHG emissions of different fuel types were also investigated by Lajunen and Lipman (2016) through vehicle simulation models of various driving cycles representative of city-bus operations. Their results exhibited that the energy consumption and pollutant emissions from buses are highly dependent upon accurate modelling of the driving behaviour, power-train technology and bus operation cycles. Generally, electric buses exhibited the lowest GHG emissions (~180 g/km CDE), followed by hybrid (~600 g/km CDE) and CNG (~900 g/km CDE) compared to diesel buses.

Shared mobility is another traffic management strategy operated by private or public-private partnerships to reduce passenger vehicle traffic in cities by actively promoting car-sharing. Chen and Kockelman (2016) found through scenario analyses that the energy consumption during vehicle operation is likely to reduce by 1.04 MJ/passenger-kilometre-travelled and GHG emissions by 71.54 g/passenger-kilometre-travelled CDE due to the travel mode shift in favour of shared vehicles. Other latest studies have also been examining the energy conservation and emission reduction potential from private car traffic by coupling shared mobility with the advent in autonomous vehicles (Howard & Dai, 2014) due to reduced air drag and cooperative braking. Brown, Gonder, and Repac (2014) estimated that shared autonomous vehicles (SAVs) may generate up to 90% fuel energy savings, however, these energy savings are highly dependent upon travel demands, fuel technology of autonomous vehicles, and transportation service distribution.

Conversely, researchers such as Currie (2018) argue that the benefits from car-sharing are somewhat overestimated in comparison to dedicated public transit vehicles even in the case of SAVs. Although the traffic management and the corresponding energy conservation data from SAV simulation or actual trials are arguably limited, SFCTA (2017) reports that the average occupancy of popular shared services like Uber is 0.66 passengers per trip which hardly acts as a traffic management strategy. The real potential of autonomous vehicle technology may lie in autonomous public transport buses. Alessandrini and Mercier-Handisyde (2016) argue that the results from Europe's pilot trial study "CityMobil2" not only show the energy conservation potential of autonomous buses, but also social acceptance towards such vehicles.

Globally many studies have attempted to estimate the energy consumption and pollutant emission reduction using vehicle inventories on several traffic management scenarios. The GHG and energy policy analysis tool "Long-range Energy Alternatives Planning system (LEAP)" was used by Peng et al. (2015) to perform analysis of Tianjin-China's urban passenger transport sector under different scenarios. Their results showed that public transport promotion may result in reducing energy consumption by 22% and GHG emissions by 22.6% over the 30-year analysis period. In another study, Guo et al. (2016) used "Computer Programme to calculate Emissions from Road Transport (COPERT) IV" model inventories to assess the energy conservation and pollutant reduction benefits of alternate fuel technologies; such as; CNG, hybrid electric and liquid natural gas (LNG); and, traffic management strategies. The authors found that alternate fuel vehicles alone may not generate significant reductions in emissions, whereas traffic management may be able to cut GHG emissions in half. In order to estimate high-resolution emissions, international vehicle emissions or IVE (Pathak et al., 2016) model has been used by Barth et al. (2007). The IVE model with GPS data loggers containing detailed spatial characteristics and fuel energy consumption information of Indian (Pune city) local passenger car; heavy vehicles; and, public bus traffic was used. The authors expressed the need for traffic models with detailed driving behaviour (cruising, acceleration, and braking) information to assess the actual energy consumption of vehicles.

The United Arab Emirates has one of the highest per capita GHG emissions in the world (23.3 tonnes per capita CDE) and a significant share of these emissions is contributed by the fuel energy demands from the transportation sector. The car traffic in the United Arab Emirates has been increasing dramatically due to the construction boom, population growth (~25% in 2005–2008) and travel demand share of private vehicles. An extensive traffic management plan "Surface Transport Master Plan 2030" developed by the ADDoT (2009) estimates that currently, car trips account for approximately 80% of the "total travel mode split" in the Emirate of Abu Dhabi. This excessive reliance on private vehicles is arguably the primary cause of the road transport sector accounting for 18 Mt CDE of GHG emissions in the city. There are virtually no water-based public transport options available in the port coastal City of Abu Dhabi. The hot climate and high humidity levels in the UAE (Khamis, 2014) and the Gulf Cooperation Council (GCC) region (Aljoufie, 2017) is argued to make it difficult for car users to shift towards the other active transport modes common in "developed" cities (walking and bicycling).

Several traffic management strategies have been assessed by the local transport authorities in both field trials and feasibility estimates; such as: Masdar's personal rapid transit (PRT) project; congestion charges on inner/outer cordons; a system of ferry services; global fuel tax; parking fee hike in inner-city areas; expansion of existing public bus networks; new bus rapid transit lanes; and, constructing high-speed public tram services. Upgrading the existing public bus network into a more comprehensive system has also been analysed, particularly increasing the bus frequency in high-demand areas by the year 2030 (ADDoT, 2009) as the public bus service frequency is not currently optimised using the traffic peak hours. The Masdar Institute in Abu Dhabi has investigated the use of single-cabin electric SAVs for a personalised rapid transport service to discourage energy consumption and pollutant emissions from petrol and diesel cars (Masdar, 2018). However, such vehicles can only act as the first- and last-mile feeder services (Thomopoulos & Givoni, 2015). Nonetheless, accurate estimation of the energy savings and GHG emission reduction with high spatial and temporal resolution is still needed. There is also a considerable absence of peer-reviewed studies on the energy and emission reductions from the transport sector in the UAE and GCC region. Peng et al. (2015) advocate that the traffic demand, transport policy, vehicle and population distributions are region-specific characteristics that are different across cities. Thus traffic management scenarios aimed at reducing transport energy and pollutant impacts should be separately assessed on "regional" driving characteristics.

Traffic microsimulation models (such as Vissim, Aimsun, Sidra Intersection, etc.) have been widely accepted as tools to estimate the energy and pollutant-control benefits of various traffic management strategies (Song, Yu, & Zhang, 2012) when combined with vehicle emission inventory models. A traffic management strategy of optimised traffic signals was assessed by Stevanovic et al. (2009) in terms of traffic fuel energy savings by employing "Comprehensive Modal Emission Model (CMEM)" along with Vissim microsimulation models. Chen and Yu (2007) investigated the energy and pollutant emissions impact of a bus rapid transit lane scenario as a traffic management strategy to control private vehicle flow in Beijing. The authors used Vissim and CMEM to estimate that due to the difference in fuel energy consumption caused by variations in stop-delay and braking behaviour, the pollutant emissions might increase by around 10.68%. The significance of driving behaviour to reduce traffic energy consumption and emissions under different traffic management scenarios was also noted by Abou-Senna et al. (2013) using Vissim and MOVES emission models. On the other hand, Quaassdorff et al. (2016) observed that a combination of Vissim with the microscale emission model VERSIT+ is better equipped to assess the energy and emission reduction potential of various traffic management strategies in a region-specific context by providing extremely fine temporal and spatial resolution.

8.2.1 Research aim

Building upon the literature review above, the aim of the current study is to obtain a detailed assessment of the transport sector energy consumption and pollutant emission reduction potential in a case study location in Abu Dhabi city. The study develops high-resolution microsimulation models to examine different public bus transport system policy scenarios, and identify long-term policy implications. Real-world data on traffic counts and flow is used to develop microsimulation models that were subsequently validated against local driving behaviour. Traffic simulations results were used to calculate the total energy consumed and pollutant emissions by each vehicle type at the studied Abu Dhabi city location. Furthermore, the overall energy consumption and pollutant emissions of three traffic management scenarios were also compared. The data gathered for the current study and the subsequent energy, emissions and policy findings may be useful for future transport sector studies in the UAE and the GCC region, as to the best of the authors' knowledge, no such study on energy consumption and pollutant emissions of this region currently exists.

8.3 METHODOLOGY

The goal of the current study is to assess the long-term energy consumption and pollutant emission reduction potential of various public bus transport-based traffic management strategies aimed at decreasing the overall energy and environmental impact of the transport sector in Abu Dhabi, UAE. The local bus network is expected to receive heavy government investments for upgrades by 2030 towards meeting the energy conservation and pollutant emission-control objectives of the local authorities. On the other hand, several autonomous bus trials are underway globally towards a large-scale futuristic, less energy-intensive and low emission service application. This chapter uses the energy and emission benefits from both of these strategies for scenario analysis on public transport uptake in Abu Dhabi over the next 30 years. Traffic data from local agencies are collected for a case study highway section and modelled using a microsimulation modelling tool. The base year for analysis is set as 2015 and traffic is gradually increased to model the traffic growth of subsequent years up to a projected year 2045 to reflect a 30-year analysis period based on the vehicle lifecycle datasets and inventory data from the literature (Chinery, 2010; ADDoT, 2009).

8.3.1 Case study model

The case study location is a 3.5km stretch of a major five-lane dual-carriageway road, Sheikh Zayed bin Sultan Street (within Abu Dhabi city highway network). This highway section is among the highest traffic density roads in Abu Dhabi city and has undergone major extension in 2009 and 2019 to tackle the growing traffic needs. The traffic counts were initially estimated by the Abu Dhabi Department of Transport (ADDoT) and the Abu Dhabi Municipality (ADM) between 07/2014 and 07/2016 for inbound traffic. The locations of all the traffic count stations are illustrated in Figure

8.1. These stations collected information about vehicle types, routes, and traffic intensity. Another median traffic count in 2015 was also gathered by the ADM covering all of the traffic count stations in Figure 8.1. The base year for the current study was set as 2015 as it was the latest common traffic count year between both in-bound and out-bound traffic volumes.

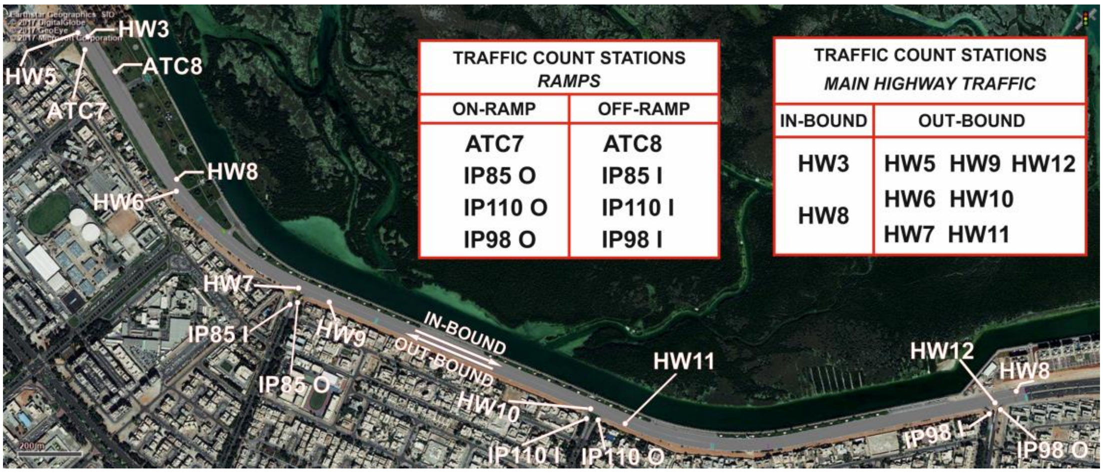


Figure 8.1 Case study section of Sheikh Zayed bin Sultan Street and traffic count station locations

The purpose of using actual traffic counts is to minimise any uncertainties from the energy and emissions reduction potential of the different traffic management strategies. Traffic data for representative weeks in the base year was used to model and validate the case study road segment and origin-destination matrices of the different vehicles for the simulation of the current traffic situation in the case study area. In the current study future traffic volumes are also projected to assess the energy consumption and pollutant emission variations of different traffic management scenarios by the year 2045. Kazim (2003) and Chinery (2010) have performed scenario studies on passenger car growth in the UAE and have recommended an exponential function of time and annual vehicle growth rate to project the future number of vehicles as follows:

$$N = N_o \times e^{g_r(t-t_o)}, \quad t_o \le t \le t_1, \qquad \text{Equation (8.1)}$$

Where "N" is the number of vehicles in the year "t", "N_O" is the initial number of vehicles in the base year "t_o" and the annual vehicle growth rate is "g_r" which is taken as 6% for UAE based on the estimates proposed by Chinery (2010). Additional traffic models are then created here for each subsequent year using the project traffic levels.

8.3.2 Traffic management scenario design

The literature review above shows that public transport implementation and upgrade is a common strategy for managing travel demand while also reducing environmental emissions. The results from Chapter 6 on the passenger travel behaviour and public-accorded desiderata for value-added bus service show that the passengers in the case study Abu Dhabi region prefer the existing bus-station distribution (Section 6.5.4.1), however, they highlighted the need for optimised journey time (Section 6.5.4.2) and increased service frequency (Section 6.5.4.3).

Given this, three public transport policy scenarios are developed and assessed against the existing base case traffic conditions (i.e., *business-as-usual scenario*). *Public transport bus case* is the first alternate traffic management scenario as the case study route does not currently have any public bus service, despite the heavy traffic load and potential demand (refer to Section 6.5.4). To address the need for frequent and rapid public transport (Sections 6.5.2.3 and 6.5.4.3), a second public bus transport scenario of *public bus rapid transit service case* is developed. Literature review from Chapter 3 shows that AVs, particulary in the form of on-demand (Section 3.3.1) and AV public bus transit service (Section 3.3.3) can be implemented in near future to improve public transit uptake and reduce passenger reliance on private cars. Additionally, passengers surveyed on the case study Abu Dhabi region also highlighted the need for a frequent public bus service optimised to target peak office hours (Section 6.6). As such, a third hypothetical scenario of a traffic demand-responsive *AV-based BRT service case* is developed.

Fuel consumption and exhaust emissions are regulated by various emission standards around the world, e.g., Euro I-VI standards. The UAE relies heavily on imported vehicles to meet its travel needs and no specific regulations were implemented prior to the year 2000 (Raeside, 2015). Euro IV emissions standard vehicles started rolling out from 2005 and mandated by 2018 (Ahmed, 2011). New vehicles are now recommended to have Euro V (GSO, 2014) and Euro VI fuel technology engines by 2030 to achieve the low exhaust emissions and energy conservation objectives of the Abu Dhabi transport authorities.

Table 8.1 European exhaust emissions standard distribution for vehicles in the UAE

Euro standard	Global regulation year	Introduction date in UAE	Small and regular cars		Minibus and coach		Light truck		Traditional and autonomous bus		Heavy truck	
			2015	2045	2015	2045	2015	2045	2015	2045	2015	2045
Euro I and earlier	1992	2007	31.67%	4.72%	67.5%	3.33%	62.22%	1.39%	66.94%	0%	52.78%	4.93%
Euro II	1996	2010	33.47%	1.39%	20.28%	15.42%	20.56%	12.5%	19.17%	18.75%	29.44%	5.42%
Euro III	2000	2013	27.78%	1.25%	11.94%	13.75%	13.75%	13.75%	13.61%	13.75%	17.5%	8.13%
Euro IV	2005	2015	6.94%	14.58%	0.181%	20.69%	3.33%	25.28%	0.167%	20.97%	0.194%	18.19%
Euro V	2009	2018	0.14%	16.39%	0.097%	8.89%	0.139%	13.89%	0.11%	8.61%	0.083%	9.93%
Euro VI	2014	2020	0%	61.67%	0%	37.92%	0%	33.19%	0%	37.92%	0%	53.40%

Therefore, for this scenario evaluation study, the introduction of Euro emission standard-compliant fuel engines has been projected as shown in Table 8.1. The actual share of each Euro-type vehicles in each year is dependent upon the age distribution of vehicles in that year. The vehicles with Euro I and earlier fuel technology occupy 31.7% share in the base year 2015 and Euro II with 33.5% share, with the share of the subsequent Euro standards (Euro III-VI) improving each subsequent year to constitute 78.06% share by the year 2045.

8.3.2.1 Do nothing or business-as-usual: Traffic management scenario 1 (BAU)

The BAU scenario assumes that the current lane configuration on the case study highway section shall continue without any modifications. The five lanes in each carriageway shall continue to be dedicated to conventional mix-vehicle type traffic. Following the current situation on the case study route, no public transport is provided on the road. Assuming consecutive growth in economy and vehicle sales, the traffic continues to grow 6% every year based on the secondary growth models from literature (Section 8.3.1), until the year 2045. The vehicle weight classes in the collected traffic counts are used to establish the vehicle fleet breakdown as: small-size cars (length ≤ 4.5m and engine size ≤ 2.5 litres); regular-size cars; minibus and coaches; light-duty vehicles (LDV); and, heavy trucks. The detailed mode share distribution between various vehicle types is shown in Table 8.2. It is also assumed that following the two recent extensions, i.e., in 2009 and 2019, and lack of adjacent vacant land, no extra budget is allocated for future extension works.

The vehicle fuel policy is assumed to be consistent with the current trends where the majority of passenger cars (small and regular) are petrol vehicles (Sgouridis et al., 2016; Sgouridis, Helmers, & Al Hadhrami, 2018) followed by diesel and other fuel technology types (Chinery, 2010) as also shown in Table 8.2. The fuel energy consumption of these cars is based on the average value of the majority of vehicles in each class. The vehicle sales report from Fox (2016) states that majority (32%) of the passenger vehicles sold in the UAE region during past few years were Toyota followed by Nissan (16.6%), Mitsubishi (11.1%), Hyundai (7.1%), BMW (4.8%) and Ford (3.5%). Among the individual vehicle makes; Toyota Corolla and Camry, Land Cruiser and Pajero SUV were the most common models. Passenger taxi vehicle policy is dominated (80–85%) by Toyota Camry vehicle share (AbuHijleh & Nik, 2013), and as such, it is modelled within the passenger car category with UAE average car occupancy rate. Following the current vehicle sales and policy trend in the UAE, the average age of all cars is assumed as 5.2 years (Staff Report, 2015) and the average age for other vehicle types is assumed as 6.39 years (EYGM Limited, 2012).

8.3.2.2 Public bus transport service: Traffic management scenario 2 (bus)

The ADDoT currently operates the local public bus service with over 95 bus routes served by approximately 650 buses (ADDoT, 2011) in various key locations of Abu Dhabi. The information gathered by authors from the publically available intercity bus schedules and the "Surface Transport Master Plan" (ADDoT, 2009) indicate that these public bus services typically operate hourly or half-hourly frequency, using buses with around 50 passenger seats regardless of the peak/off-peak traffic demand. Results from detailed Abu Dhabi traffic surveys (Mott MacDonald & Steer Davies Gleave, 2008) show that the average passenger car occupancy in the city is 1.7 and public bus occupancy is in the range of 40-60% of the passenger seats.

The "Surface Transport Master Plan" estimates that the current mode share of public transport in daily passenger traffic is approximately 20%. The plan also acknowledges that the majority of buses operate on diesel fuel technology, with CNG buses only recently introduced in the region. It is assumed that if a bus service is introduced in the case study area with the current city-wide average bus headway of 30 minutes between two buses, the passenger mode share may switch to the existing mode-share profile in the areas of Abu Dhabi where such services have been already provided, i.e., 20% for public transport and a total of 80% for small- and regular-size car traffic (Table 8.2). The total number of car passengers for the BAU case (CP_j^{BAU}) is determined first by multiplying the total car traffic count from the counting stations in Figure 8.1 with the "average car occupancy" value of 1.7. It is then used to calculate the reduction in the car traffic for the "Bus" scenario as follows:

$$CT_j^s = \frac{CP_j^{BAU} \times CS_j^s}{\text{avg. car occupancy}}, \qquad \text{Equation (8.2)}$$

Where "CT" is the car traffic of category "j" (small/regular) car, "s" represents any of the considered traffic management scenarios, and "CS" is the mode share of "j" type cars in the scenario "s". The traffic count for other vehicle types is assumed to be the same as the BAU scenario with only the passenger car traffic reduced due to the bus service operating alongside the existing traffic by the year 2045. Traffic growth model from Equation (8.1) is used to project future traffic levels. The fuel technology, fuel energy consumption and the CO_2 emissions are detailed in Table 8.2. A majority of the public transport buses operated in the Abu Dhabi bus fleet are diesel, however, the Abu Dhabi DoT has tested turbocharged six-cylinder engine buses powered by CNG delivering 310 hp as well as starting to convert existing bus fleet to CNG-powered engines. Based on the characteristics of the Abu Dhabi bus fleet and the findings by Chinery (2010) on gradual penetration of CNG vehicles, around 29% of bus fuel is assumed to be CNG-based. However, the UAE already has an extensive CNG distribution network, CNG bus use may significantly improve in the coming years.

8.3.2.3 Bus rapid transit service: Traffic management scenario 3 (BRT)

The transportation policy objectives set by the local transport decision-makers set comprehensive plans to improve the public transport uptake in the UAE. In the Abu Dhabi city region, a demand-responsive bus network is planned to provide a reliable service with peak period frequencies of at least 4 buses per hour (ADDoT, 2009) over the long-term. The current service frequency is not generally varied throughout the day to address the peak hour traffic demand. The local transport authorities also aim to establish bus rapid transit service lines across high traffic density areas in the city. Many of these projects have already commenced with further potential network expansion plans currently under consideration. As a potential traffic management scenario on the case study highway route, the frequency of bus service is increased (headway = 15 minutes) to match the 4 buses/hour target. The extreme left lane on both carriageways is constrained to only serve the public BRT service. The BRT service is considered to operate constantly at the same service frequency level (i.e., headways) by the year 2045. Due to a significant increase in the BRT travel time compared to the bus scenario, it can be logically argued that more passengers may choose to travel by public transport, following the conclusions by Wu and Pojani (2016). Thus, mode share of public transport service is slightly increased to 25%. The vehicle fuel technology is assumed to remain unchanged throughout the years. Table 8.2 further lists the detailed vehicle fuel consumption parameters.

8.3.2.4 Autonomous vehicle-based BRT: Traffic management scenario 4 (AV-BRT)

The AV-BRT scenario is a future-based theoretical scenario which is an escalation of the high-speed tram service policy plans and the BRT scenario. The low energy consumption benefits of autonomous vehicles that were investigated in this study include vehicle-to-vehicle communication to minimise the gaps between vehicles and the acceleration-deceleration rate to increase fuel economy (Fagnant & Kockelman, 2015) and space utilisation, gear-shift perfection and improved speed-flow profiles. The fuel technology of autonomous vehicles being developed currently is mainly based on electric powertrains. Although the complete adoption of electric fuel engines in transport sector may drastically reduce the energy consumption and exhaust pollutant emissions, many uncertain factors in the Abu Dhabi and GCC region still remain. The energy-intensive need for air-conditioned vehicles due to the hot Middle Eastern climate, large investment required in fuel distribution infrastructure and upgrades of power generation grids to reduce reliance on electricity generation by fossil fuels in the UAE (Treyer & Bauer, 2016) and the global uncertainty in travel range of electric vehicles still need further research.

Conversely, manufacturers such as Ford Motor Company, are already researching CNG or electric-CNG hybrid autonomous vehicles (Giarratana, 2018). The focus of the current chapter is to assess the reductions in fuel energy consumption and exhaust pollutants due to the reduction in private car use and improved traffic flow profile from a regional and site-specific point-of-view. As such it is assumed that hypothetical autonomous buses utilise existing CNG fuel distribution networks for their energy needs (Table 8.2). On the case study highway section, the extreme left lane on both carriageways is restricted to only serve the AV-BRT service. Hasan, Whyte, and Al Jassmi (2018b) performed an investigation of the travel habits of Abu Dhabi residents and found that public bus transport use can be increased by increasing bus service frequency during peak traffic hours and by providing a dedicated BRT service due to the resulting reduction in passenger journey time on buses. In the AV-BRT scenario, peak hour bus frequency is increased to 5 minutes headway between two buses while the off-peak service frequency is unchanged from the BRT scenario. The mode share of public bus service is increased to 35% during peak hours and 25% during off-peak hours, which is still less than the 41% public transport mode share estimated by the preferred public transport traffic management scenario of the "Surface Transport

Master Plan”. Therefore, the actual benefits of implementing the improved public transport strategy may be more than the conservative calculations in this study.

8.3.3 Vehicle modelling system

This study utilises Vissim as microsimulation vehicle modelling system to model the traffic flow behaviour, queue formation and delays on a case study area under different traffic management scenarios by taking into account the interaction between passenger cars, light- and heavy-duty vehicles, and public bus transport service. Vissim is a behaviour- and time step-based microsimulation model capable of analysing vehicle transit under traffic control strategies by taking into account the interactions between several types of vehicles (Bloomberg & Dale, 2000). Fellendorf and Vortisch (2010) argue that since Vissim is based on the link-connector system, it is capable of accurately modelling the complex geometries of actual roads to represent the real-world traffic movement patterns and flow behaviours of the driver-vehicle-fuel units. To that end, the vehicle acceleration-deceleration and speed-time parameters in Vissim can be stochastically varied to consider the “car-following” logic of drivers under traffic management scenarios based on the relative distances and speeds compared to surrounding vehicles.

8.3.4 Calculation of pollutant emissions and energy consumption

The exhaust emissions model VERSIT+ developed by TNO Laboratories is used alongside Vissim to analyse the real-world high-resolution energy and emission impacts. It is preferred over other models due to its capability of importing complex vehicle speed-acceleration spatial trajectories and predict the emission rates (g/h) for each vehicle class modelled in Vissim. The VERSIT+ model is based on more than 12,000 vehicle types, fuel energy consumption, vehicle make and model, fuel technology and 246 emission algorithms for each type and category representing real-world driving conditions (de Coensel et al., 2012; Quaassdorff et al., 2016). The model uses multivariate regression techniques to calculate the traffic emissions (TE_j) for each of the vehicle classes by taking into account the g/km emission factors ($E^F_{j,k,l}$) based on fuel energy consumed due to actual driving patterns (Margreiter et al., 2014) in terms of speed-time profile. It also considers engine response to aggressive acceleration-braking as well as cold-started engines.

The pollutant emissions based on VERSIT+ are calculated using the EnViVer emission modelling tool containing the real-world driving conditions representative of several on-road and laboratory trials of vehicles to accurately account for the driving behaviour, speed and traffic control measures for the different road types. The emissions calculations are determined from vehicle age, engine fuel consumption based on the injection technology (Euro I, Euro II, Euro III, Euro IV, Euro V and Euro VI engines), fuel technology (diesel, petrol, CNG, electric) and their distribution over fleet (Ligterink et al., 2008). The traffic exhaust emissions (TE_j) are calculated as follows (Linton, Grant-Muller, & Gale, 2015):

$$TE_j = \sum_{k,m} (E^F_{j,k,l} \times TV_{k,m} \times L_m), \qquad \text{Equation (8.3)}$$

Where $E^F_{j,k,l}$ is the g/km emission factor for "j" pollutant, vehicle class "k" and speed-time profile "l", per hour traffic volume is "$TV_{k,m}$" on a road section "m" of road length "L_m". The vehicle categories (light-duty, heavy-duty, passenger cars, bus, minibus, and coach, etc.), vehicle size, fuel technology, and engine fuel consumption standards are input into the model. EnViVer then calculates the pollutant emissions based on these factors and the fuel consumption of vehicles which is dictated by the relevant Euro standards. The energy consumption values were calculated based on the fuel consumption of each vehicle type, fuel and vehicle distribution in the traffic and the average CO_2 emissions per litre of each fuel type (Bohm & Häger, 2015). The lifecycle inventory (LCI)[7, 8] which is used in this study to calculate the pollutant emissions and energy consumption is shown in Table 8.2.

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7 Vehicle share is based on https://www.export.gov/article?id=United-Arab-Emirates-Automotive.
https://gulfnews.com/news/uae/environment/new-car-fuel-economy-standard-for-uae-1.1903057.
https://www.khaleejtimes.com/article/20110514/ARTICLE/305149834/1002.
http://www.constructionweekonline.com/article-49209-higher-emission-standards-reshaping-uae-vehicle-fleets/ 1/.
https://members.wto.org/crnattachments/2014/tbt/ARE/14_4732_00_e.pdf.

8 Fuel distribution is based on Davis, Diegel, & Boundy (2008), ADDoT (2009), Chinery (2010), Sgouridis et al. (2018), Sgouridis et al. (2016)

Table 8.2 LCI data for CO_2 emission factors and fuel consumption by vehicle type, fuel and analysis year

Vehicle type	Vehicle share in each scenario (%)	Fuel type distribution (%)	Emission standard	Euro I & earlier	Euro II	Euro III	Euro IV	Euro V	Euro VI	Data sources
Small-size cars (Length ≤ 4.5m)	BAU: 45.5%	Petrol: 99.6%	Emission Factors (kg/km)	0.2168	0.2168	0.2120	0.1990	0.1890	0.1774	Romilly (1999), Simons (2016), DIRDC (2019), and ABS (2019)
	Bus: 36.4%		Fuel Consumption (kg/km)	0.0962	0.0727	0.0665	0.3542	0.3377	0.3219	
	BRT: 32.3%	Diesel: 0.3%	Emission Factors (kg/km)	0.1936	0.1936	0.1810	0.1730	0.1660	0.1587	
	AV-BRT: 29.57%		Fuel Consumption (kg/km)	0.0598	0.0598	0.0578	0.0546	0.0528	0.0511	
		CNG/Other : 0.1%	Emission Factors (kg/km)	0.1875	0.1750	0.1660	0.1550	0.1470	0.1373	
			Fuel Consumption (kg/km)	0.0500	0.0500	0.0528	0.0585	0.0554	0.0525	
Regular-size cars (Length: 4.5m - 6m)	BAU: 37.54%	Petrol: 99.6%	Emission Factors (kg/km)	0.4231	0.4120	0.3163	0.3080	0.3120	0.3038	Romilly (1999), Simons (2016), DIRDC (2019), and ABS (2019)
	Bus: 30.032%		Fuel Consumption (kg/km)	0.0876	0.0787	0.0784	0.0743	0.0709	0.0676	
	BRT: 26.719%	Diesel: 0.3%	Emission Factors (kg/km)	0.3118	0.3080	0.2480	0.2450	0.2870	0.2835	
	AV-BRT: 24.40%		Fuel Consumption (kg/km)	0.1231	0.0940	0.0736	0.0688	0.0668	0.0648	
		CNG/ Other: 0.1%	Emission Factors (kg/km)	0.2809	0.2664	0.2477	0.2399	0.2427	0.2350	
			Fuel Consumption (kg/km)	0.1071	0.1125	0.0734	0.0697	0.0663	0.0630	
Minibus & coach	All scenarios : 4.735%	Diesel: 100%	Emission Factors (kg/km)	0.4410	0.4410	0.3438	0.3398	0.3353	0.3315	Romilly (1999), and
			Fuel Consumption (kg/km)	0.0899	0.0915	0.0899	0.0765	0.0882	0.1016	

(6m - 8m)										DIRDC (2019)
Light truck/LGV (8 - 10m)	All scenarios: 6.64%	Petrol: 97.4%	Emission Factors (kg/km)	0.2541	0.2383	0.2383	0.2383	0.2383	0.2383	Zanni and Bristow (2010), DIRDC (2019), and ABS (2019)
			Fuel Consumption (kg/km)	0.1300	0.1220	0.0965	0.0958	0.0906	0.0856	
		Diesel: 2.5%	Emission Factors (kg/km)	0.2461	0.2406	0.2404	0.2404	0.2402	0.2402	
			Fuel Consumption (kg/km)	0.1250	0.1210	0.1040	0.1007	0.1007	0.1007	
		CNG/ Other: 0.1%	Emission Factors (kg/km)	0.2217	0.2081	0.2401	0.2354	0.2031	0.1991	
			Fuel Consumption (kg/km)	0.1690	0.1690	0.1521	0.1503	0.1413	0.1328	
Traditional public transport bus	BAU: 0%	Diesel: 71%	Emission Factors (kg/km)	1.2174	1.1840	1.2389	1.1161	1.0890	1.0200	Romilly (1999), Wang et al. (2011), Kuschel, Cooper, and Metcalfe (2017) Nanaki et al. (2017), and ABS (2019)
	Bus: 16.61%		Fuel Consumption (kg/km)	0.2912	0.3036	0.2976	0.2541	0.2348	0.2081	
	BRT: 24.02%	CNG: 29%	Emission Factors (kg/km)	1.1000	1.2500	1.1392	1.2627	1.1278	1.1221	
	AV-BRT: 0%		Fuel Consumption (kg/km)	0.4635	0.2223	0.2055	0.3102	0.3141	0.2047	
Autonomous public transport bus	BAU: 0%	CNG: 100%	Emission Factors (kg/km)	1.1000	1.2500	1.1392	1.2627	1.1278	1.1221	
	Bus: 0%		Fuel Consumption (kg/km)	0.4635	0.2223	0.2055	0.3102	0.3141	0.2047	
	BRT: 0%									
	AV-BRT: 29.06%									
Heavy truck (10m - 12m)	All scenario: 5.586%	Diesel: 100%	Emission Factors (kg/km)	0.6845	0.6726	0.6726	0.6524	0.6410	0.6218	Zanni and Bristow (2010), and ABS (2019)
			Fuel Consumption (kg/km)	0.2890	0.2890	0.2404	0.2404	0.2355	0.2306	

8.4 RESULTS AND DISCUSSION

8.4.1 Current traffic situation

Traffic counts from representative weekday traffic datasets of the base year 2015 were used to provide the origin-destination matrix in the BAU scenario. The current weekly traffic count results for the different vehicle types are graphed at hourly resolution in Figure 8.2 below. The period from 4th May–7th May 2015 and 10th May 2015 represents typical working days for Abu Dhabi city. The peak in traffic between 7:00 am and 8:00 am during workdays corresponds to the morning rush hours due to the start of the workday, particularly significant for passenger car traffic in terms of small-size cars (~8700 vehicles) and regular-size cars (~7200 vehicles).

The period between 2:00 pm–3:00 pm represents the high traffic densities during lunch hours which again show a rise in general traffic with a substantial increase in private vehicle traffic. The evening peak hours between 7:00 pm–8:00 pm also exhibit a similar trend corresponding to the end of workday traffic. The period from 8th May–9th May 2015 represents the weekend. The traffic peak period trends are hence indicative of the typical non-working days flow patterns. For example, the 5:00 pm–7:00 pm passenger vehicle peak may show the travel activities of local residents for leisure purposes.

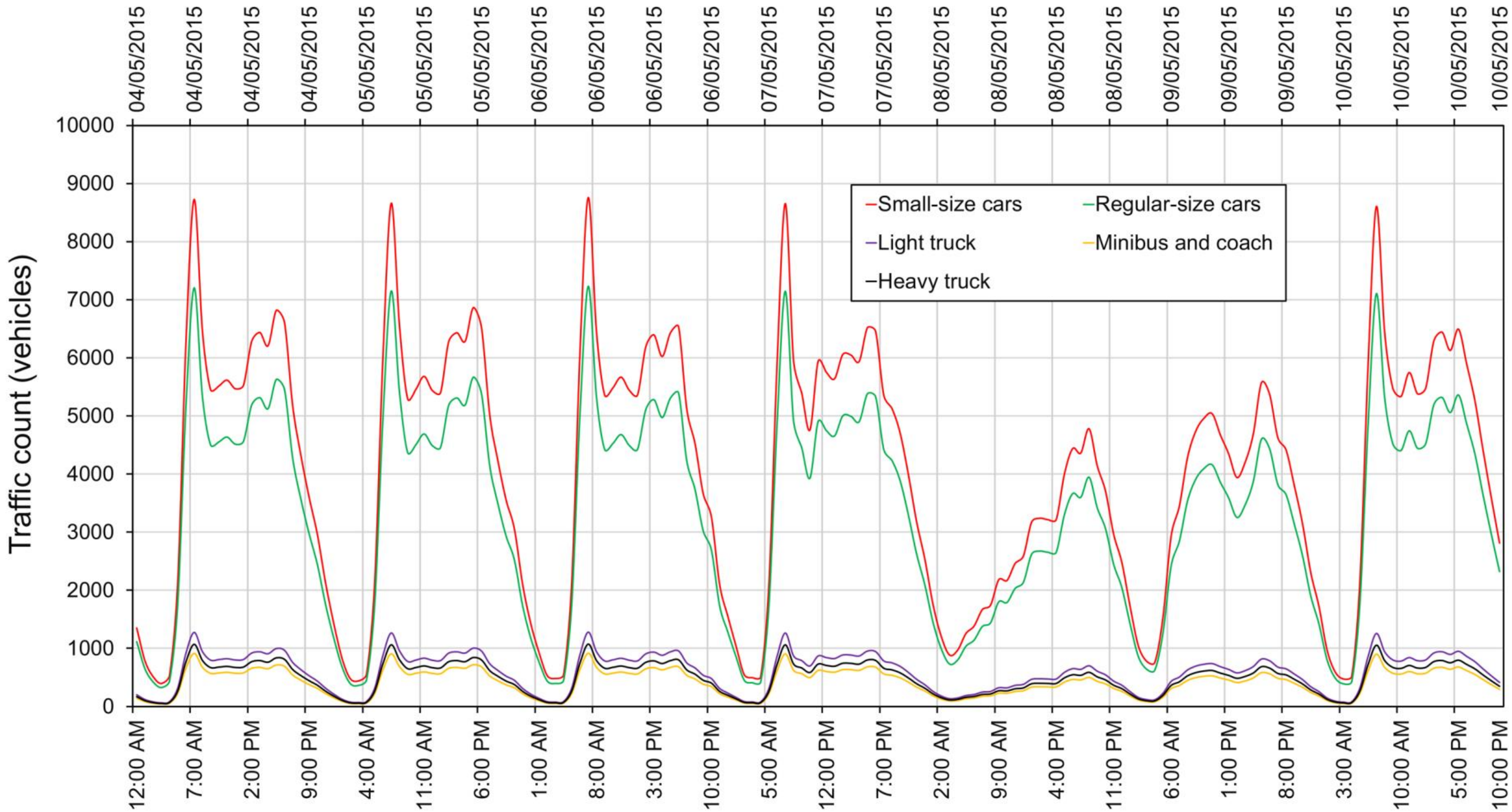


Figure 8.2 Current weekly traffic on case study highway section by vehicle type (BAU, year 2015)

8.4.2 Projected energy consumption and exhaust emissions distribution in the BAU scenario

The BAU energy consumption due to the fuel consumed by the vehicles was dominated by private car traffic caused by the larger vehicle population share of small- and regular-size cars. Figure 8.3 shows that during the base year 2015, the energy consumption for small-size cars was the highest at 360.66 TJ, followed by regular-size cars (174.96 TJ) and heavy trucks (174.75 TJ). The CO_2 and PM exhaust emissions were also highest for small-size cars (20.772 kilo-tonnes CO_2 and 2.134 tonnes PM) and regular-size cars (17.904 kilo-tonnes CO_2 and 1.644 tonnes PM) followed by heavy trucks (9.342 kilo-tonnes CO_2 and 0.936 tonnes PM). These comparatively higher exhaust emissions and energy consumption indicated that more attention should be focused on addressing the high traffic volume of private cars.

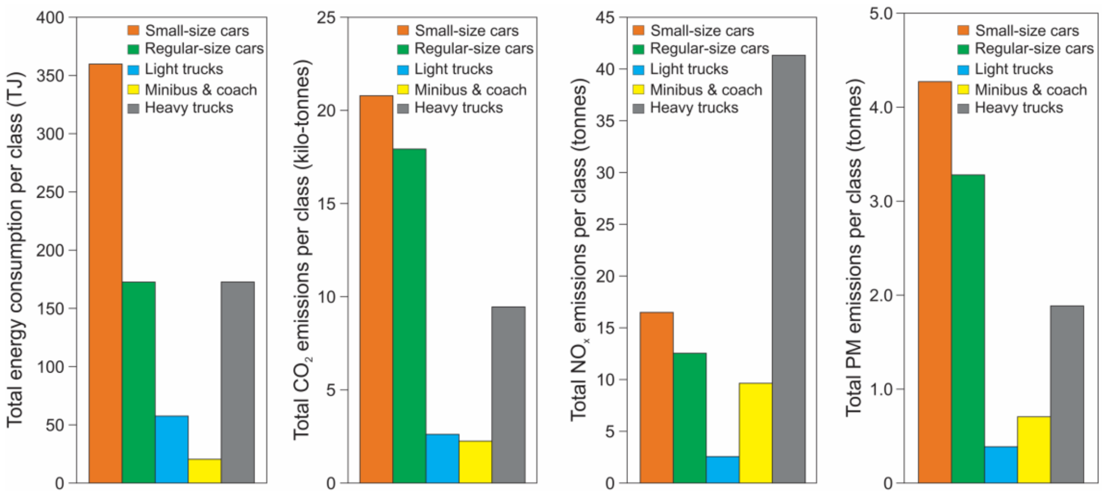


Figure 8.3 Total energy consumption and CO_2, NO_x and PM emissions by vehicle type for the base year 2015 in BAU scenario

The significant energy consumption associated with heavy trucks is due to the high calorific value of diesel fuel used by the heavy-duty engines. In the case of NO_x emissions, the diesel fuel consumed by heavy trucks yielded the highest exhaust emission of 41.373 tonnes. Small- and regular-size cars also exhibited high NO_x emissions, i.e., 12.559 tonnes and 16.293 tonnes. The higher NO_x exhaust emissions of heavy trucks were caused by the higher volume of diesel fuel consumed by trucks compared to passenger cars that largely relied on catalyst-based petrol engines. Similarly, the difference between the two types of petrol cars (small- and regular-size) was caused by the category of fuel consumed and the differences among the incylinder combustion processes of both types of cars due to the make and model variations. In UAE, a significant portion of regular-size cars, e.g., Land Cruisers, BMWs and Mercedes, etc., use RON 98 high-octane fuel which has a lower NOx emission rate than the RON 95 low-octane fuel used in the prevalent small-size cars such as Toyota Corolla and Hyundai Accent, etc.

The vehicle population in the UAE is expected to continuously grow over the years due to population growth, economic development and demand for private passenger cars. Traffic modelling has demonstrated that the rate of energy consumption and the rate at which exhaust pollutants are emitted from the vehicles on the case study highway section will increase several fold in the next 30 years (Figure 8.4) if no attempts at improvement is made. Gao et al. (2019) note that the frequent acceleration and deceleration of vehicles account for large fuel use in high traffic density areas. Similarly, the energy consumption rate for the case study highway was also determined by the traffic density, vehicle flow rate, acceleration-deceleration, and speed. The traffic volume increased with each subsequent year which then corresponded to a rapid reduction in engine speed and vehicle velocity as the studied highway section approaches a saturation flow rate. These findings are evident in Figure 8.4 which shows that even though over the years more Euro V and Euro VI energy and pollutant-control vehicles are introduced into the daily traffic and the older models are retired, the accumulative energy consumption and exhaust emissions are significantly dependent upon the engine operating conditions, traffic flow rate, fuel economy, and acceleration-deceleration rate.

Figure 8.4 shows that the energy consumption and the exhaust emissions rate continued to increase in the subsequent years and the highest values were observed during the last 10 years, i.e., from 2035–2045. During the base year 2015, the energy consumption rate for small-size cars was 41.54×10^3 MJ/h, 20.154×10^3 MJ/h for regular-size cars and 20.129×10^3 MJ/h for heavy trucks. The reason for these results was the low fuel economy of small-size cars, particularly in traffic congestions, large total travel distance of both types of passenger cars due to the larger share in the traffic, and larger fuel economy of heavy-duty engines. After considering all vehicle types, the total energy consumption rate for the entire vehicle fleet on the case study highway section for the last 10 years was 2.91 times higher than the combined energy consumption rate of vehicles during the initial 20 years.

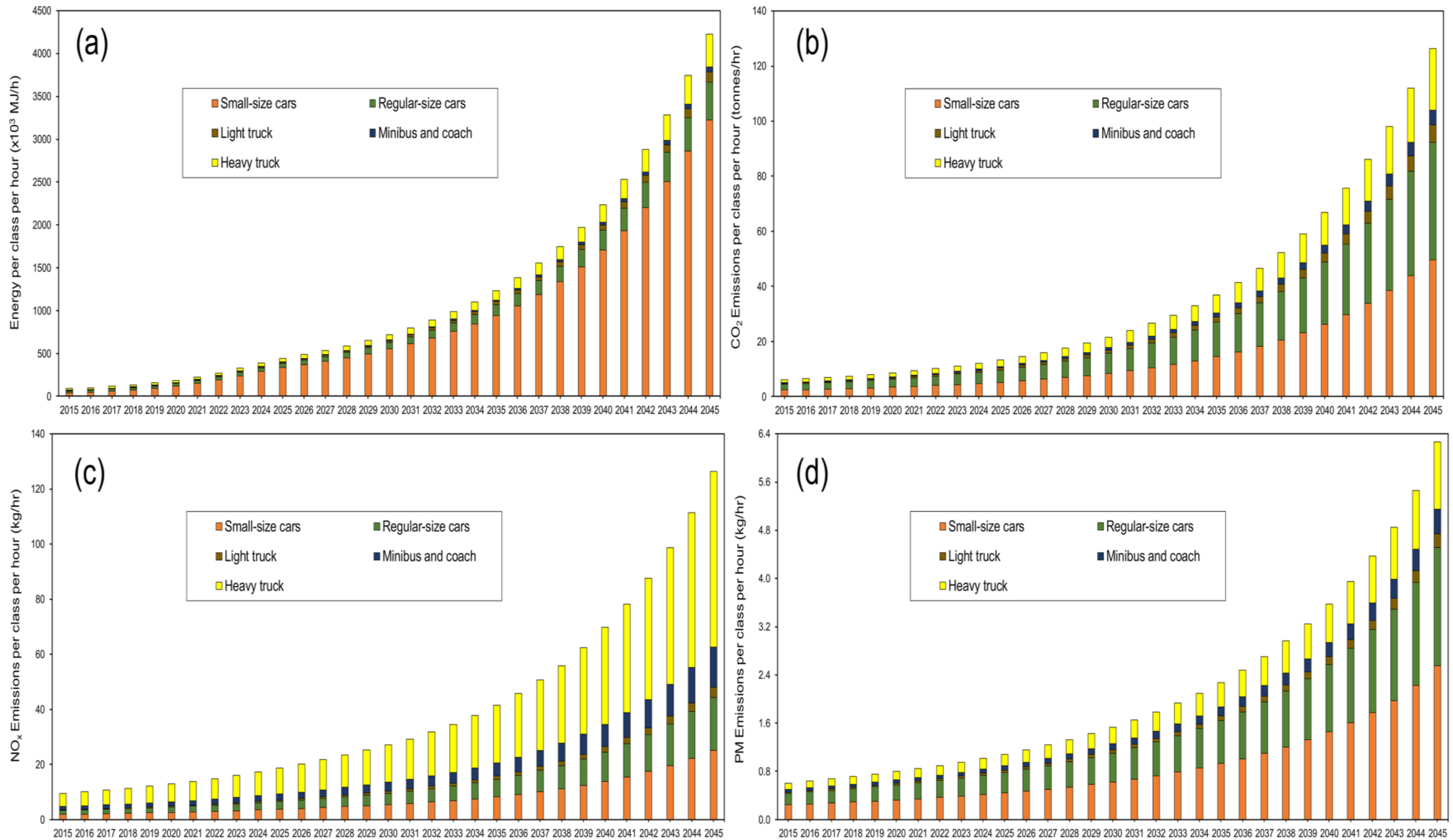


Figure 8.4 Energy consumption and exhaust pollutant emissions rates by vehicle types in the business-as-usual (BAU) scenario, years 2015–2045

The minimum overall vehicle energy consumption rate was 91.224×10^3 MJ/h observed for the base year 2015 and the highest value of 4225.18×10^3 MJ/h was calculated for the year 2045 which was 46.32 times higher than the base value. The exhaust emission rates further confirmed the results of total emissions for base years in terms of individual contribution by each vehicle type as: CO_2, NO_x and PM for small-size cars (2.393 tonnes/hr for CO_2, 1.877 kg/hr for NO_x and 0.246 kg/hr for PM), regular-size cars (2.062 tonnes/hr for CO_2, 1.446 kg/hr for NO_x and 0.189 kg/hr for PM), heavy trucks (1.076 tonnes/hr for CO_2, 4.766 kg/hr for NO_x and 0.108 kg/hr for PM) followed by light trucks (0.306 tonnes/hr for CO_2, 0.269 kg/hr for NO_x and 0.021 kg/hr for PM) and minibus and coaches (0.264 tonnes/hr for CO_2, 1.098 kg/hr for NO_x and 0.039 kg/hr for PM). Similar to the accumulative energy consumption rate, the exhaust pollutant emissions rates were minimum for the base year due to the high acceleration-deceleration in the subsequent years caused by growth in traffic. The CO_2, NO_x and PM exhaust emissions rates during the years 2035–2045 were respectively 2.65, 2.08 and 1.83 times higher than the combined emissions rates for the initial 20 years period. The maximum values reached 126.379 tonnes/hr (CO_2), 126.369 kg/hr (NO_x) and 6.267 kg/hr (PM) for the accumulated emissions rates of the year 2045, respectively accounting for 20.71, 13.36 and 10.37 times higher values than the base year 2015.

It is noteworthy that the passenger car traffic remains problematic in the case study region. Energy consumption rate was highest for the car traffic accounting for 67.63% in base year 2015 and 86.80% in year 2045. Similarly, 73.01% of the total yearly exhaust CO_2 emissions rate and 72.05% of the total yearly exhaust PM emissions rate from the traffic fleet were contributed by passenger cars. The NO_x emission rate for heavy trucks is also a huge challenge as it constituted around 50.40% of the annual NO_x emission rate (Figure 8.4). The primary reason behind this observation is the relative majority of high NO_x emissions from older diesel engines. Euro III and earlier heavy-duty diesel engines are more prevalent as Euro V–VI standards have only recently been introduced in the UAE. This may cause low emission trucks to being introduced much later into the vehicle fleet. However, it is argued here that a large scale policy change is needed on the national level to mitigate this issue and initiate stricter emission regulations on diesel fuel and particularly heavy trucks. Conversely, on the case study level, some reduction in the car traffic is needed to meet the energy consumption and exhaust pollutants decrement goals of the local authorities.

8.4.3 Projection of car traffic in traffic management scenarios

The case study highway section represents a key travel route in Abu Dhabi city connecting several outer suburbs to the inner-city and central business district areas and running parallel to the entire Abu Dhabi city. Hence, it is expected that it will also experience the rapid growth in passenger car traffic along with the rest of the UAE mirroring a steady population growth and economic development. The total passenger car traffic on the case study route is thus expected to increase from 57.589 million/year in 2015 to 330.763 million/year in 2045, accounting for an increase of 273.174 million cars in the BAU scenario (Figure 8.5). This indicates that the highway will reach its operational capacity in a few years. After the introduction of a dedicated public transport service and corresponding mode shift of private car passengers in favour of public transport, the expected increase in passenger car population will be around 179.32 million (34.4% less), 151.38 million (44.6% less) and 136.13 million (50.2% less) vehicles for the bus, BRT and AV-BRT scenarios, respectively after 30 years.

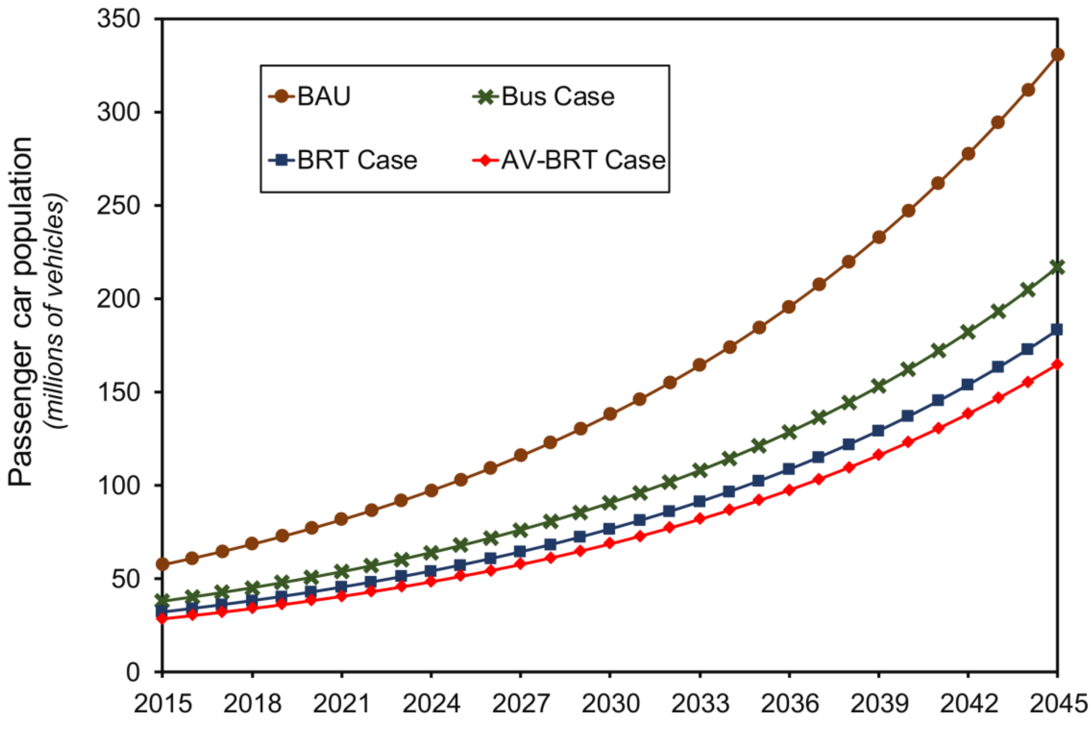


Figure 8.5 Long-term projection of passenger car traffic from 2015–2045, all traffic management scenarios

8.4.4 Energy consumption

The developments in the public transport services in Abu Dhabi city were assessed in the form of different categories of public bus service on the case study highway section. In general, a significant reduction in energy consumption from the traffic in the studied area was observed. Figure 8.6 shows the accumulated energy consumption results for all vehicle types in all traffic management scenarios from the years 2015–2045. The energy consumption for the base year 2015 was estimated at 791.95 TJ which increased at an average yearly growth rate of approximately 14% to attain the year 2045 energy consumption value of 36953.18 TJ after exhibiting an increase of 46.66 times, in the BAU scenario. As discussed earlier, this high energy consumption over the long-term was mainly caused by the passenger car traffic, and traffic modelling projected the significant energy conservation potential of public bus transport-based traffic management scenarios (Figure 8.6).

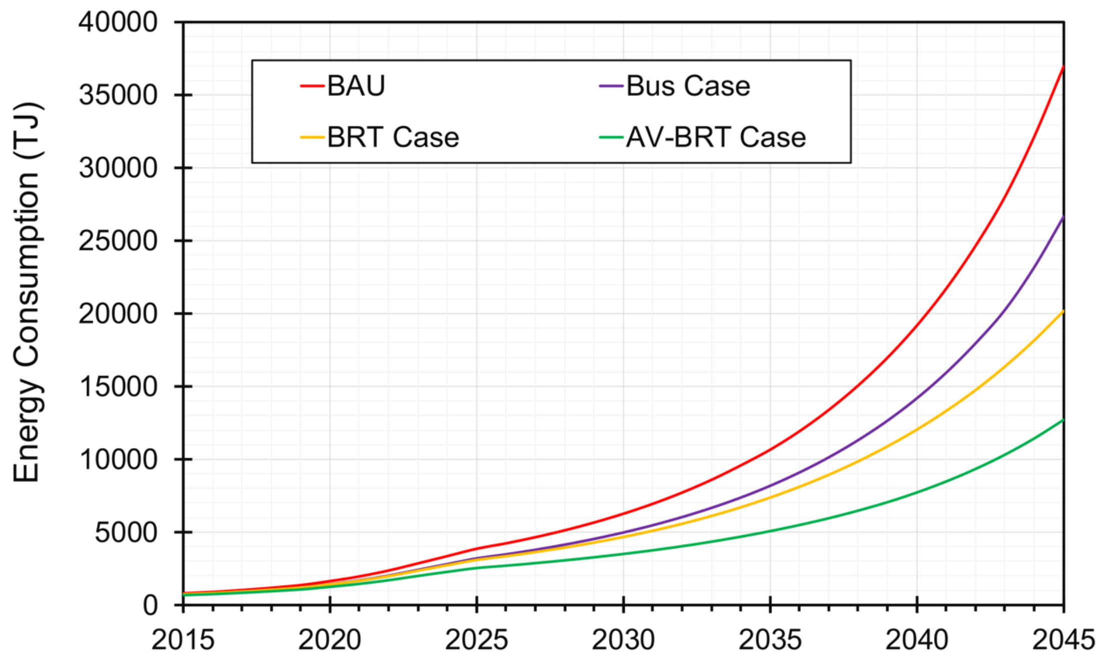


Figure 8.6 Total energy consumption trends in all scenarios, years 2015–2045

The maximum values reached in the year 2045 for the "Bus Case", "BRT Case" and "AV-BRT Case" traffic scenarios were 26685.73 TJ, 20197.66 TJ and 12723.84 TJ, respectively. These results show that the energy consumption reduced by 27.8%, 45.3%, and 65.6%, respectively for the three scenarios in the year 2045. Up to 12% of the accumulated vehicle fuel energy is consumed during this period of the total highway traffic lifecycle considered in this study. These results not only show the dominant role of passenger vehicles in the total energy consumption of the case study highway traffic but also the huge benefit of optimising public transport according to the traffic demand. Additionally, despite the mode shift in favour of public transport, the private car is still assumed as the dominant transport mode accounting for around 53.97% share of the traffic on the case study highway section. It is also noteworthy that the current study only assessed the impact of optimising BRT around peak traffic hours using fast, reliable and interconnected autonomous buses that mainly provided the benefit of automated acceleration-deceleration driving, better vehicle platooning and smooth vehicle speed profile. The energy conservation benefits are therefore from lower fuel consumption, i.e., improved fuel economy, smoother traffic flow behaviour, and the high calorific value of CNG. However, the fuel energy consumption may be further reduced by using electric buses, provided the energy supply grid is adequately developed and not based on fossil fuels for production needs.

8.4.5 Exhaust CO_2 emissions

The exhaust CO_2 emissions from the case study highway section are mainly generated from the petrol fuel consumed by passenger cars and diesel fuel from heavy vehicles. Out of all the exhaust emissions considered in the current study, the CO_2 emissions are the most environmentally-significant due to the higher global warming potential of CO_2. As no public transport is originally provided in the BAU scenario and as mentioned above other passenger transit options in northern hemisphere and mediterranean cities, walking and bicycling, are difficult to encourage due to the extreme hot climate (Khamis, 2014), the alternate traffic management scenarios assess the CO_2 emissions reduction from the provision of hypothetical public transport service. The accumulative CO_2 exhaust emission reduction potential of public bus service was estimated as 300.68 kilo-tonnes (27.2%) in the "Bus Case" scenario compared to the BAU scenario for the year 2045 as shown in Figure 8.7.

Figure 8.7 also shows that the BRT and AV-BRT scenarios yielded a higher reduction potential of 499.28 kilo-tonnes (45.2%) and 722.97 kilo-tonnes (65.4%), respectively, in the year 2045. Similar to the findings of Peng et al. (2015), the exhaust CO_2 emissions trend from vehicles in the case study area is comparable to the energy consumption trend from Figure 8.6 for the 2015-2045 period. On the other hand, the BAU CO_2 emissions from the year 2045 as estimated from microsimulation traffic modelling were 20.87 times higher than the 2015 base year. Exhaust CO_2 emissions exhibited an average growth rate of approximately 11% which is significantly higher than the estimates of Hickman and Banister (2007), Ou et al., Zhang, and Chang

(2010), Piecyk and McKinnon (2010) and Peng et al. (2015) based on city-wide emissions; and results from specific road emission case studies by Yu and Lu (2012), Barandica et al. (2013) and Santos, Ferreira, and Flintsch (2015).

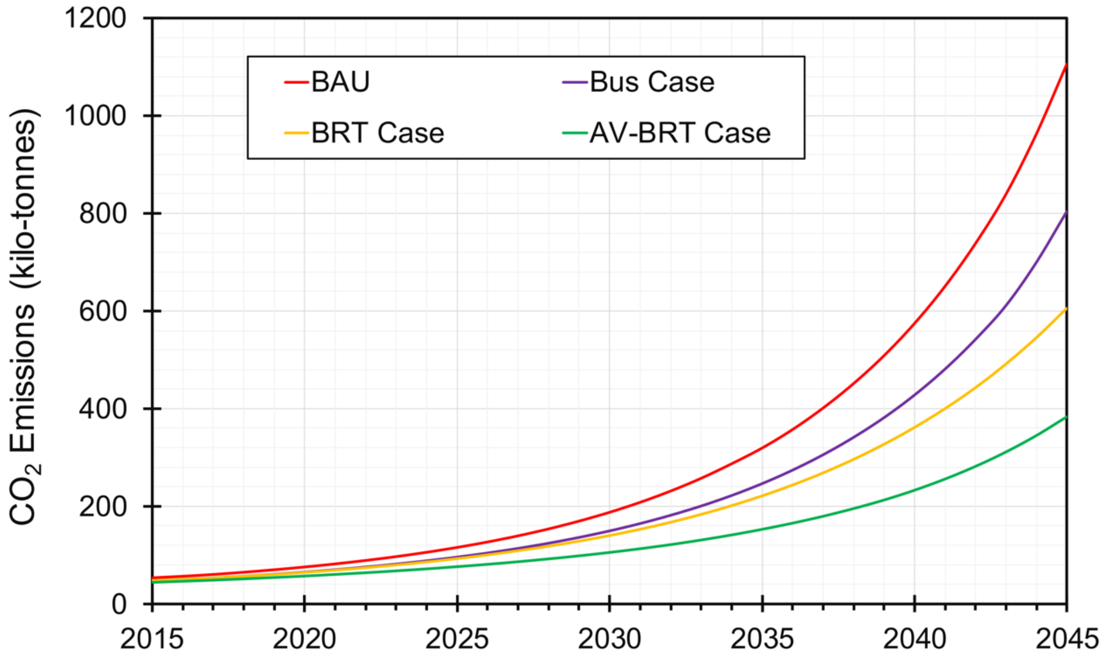


Figure 8.7 Total exhaust CO_2 emissions trends in all scenarios, years 2015–2045

8.4.6 Exhaust NO_x emissions

The BAU scenario results for the year 2015 exhaust NO_x emissions presented in Section 8.4.2 earlier show that the NO_x emissions share of the diesel fuel consumed by heavy trucks is significantly larger than other vehicle types. Figure 8.8 shows that over the long-term, the NO_x emissions grow at an average rate of 9.7% to attain the highest value of 1292.23 tonnes in the year 2045 which is 15.74 times higher than the base year NO_x emissions of 82.1 tonnes, in the BAU scenario.

For the NO_x emission reduction potential of the alternate traffic management scenarios in the year 2045: the "Bus Case" exhibited 361.32 tonnes lower emissions (28%); the BRT scenario emissions were 604.48 tonnes (46.8%); and, AV-BRT scenario emissions were 755.13 tonnes (58.4%) lower than BAU. These reductions are caused by the lower NO_x emission potential of the CNG fuel used in bus vehicles and reduction in the total volume of petrol fuel combusted in passenger car engines due to the decline in car traffic. The decrement in NO_x emissions may not only reduce acid rain potential but also influence the smog and PM formation in the densely-populated areas surrounding the key highway analysed in the current study.

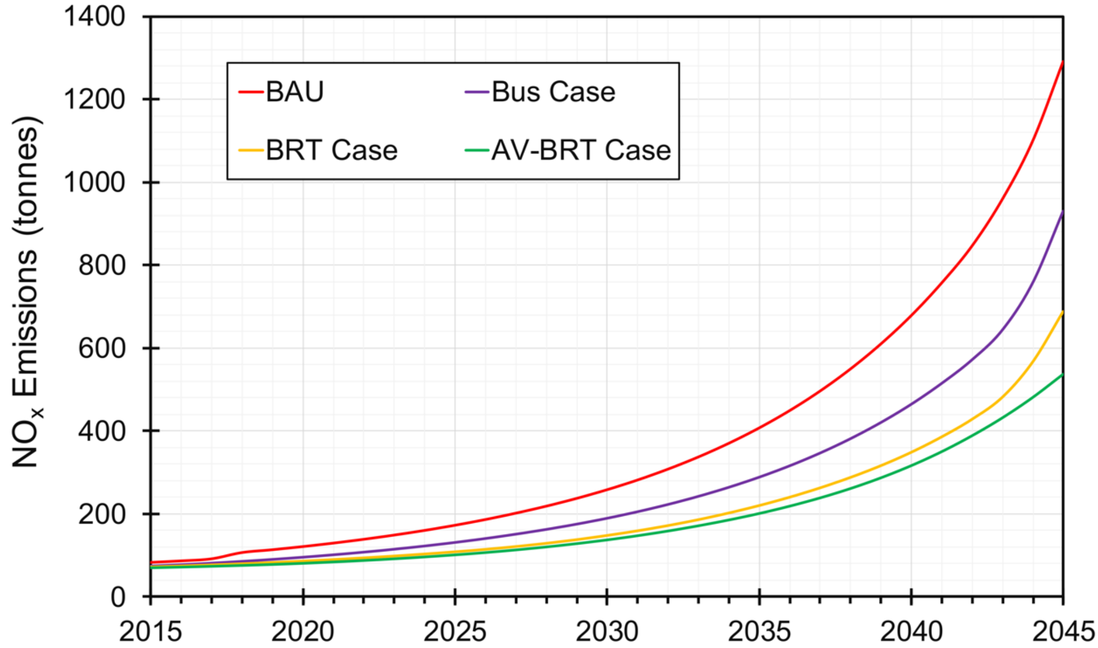


Figure 8.8 Total exhaust NO_x emissions trends in all scenarios, years 2015–2045

8.4.7 Exhaust particulate matter (PM) emissions

The PM emissions in the city of Abu Dhabi has been recorded by local authorities as a significant concern. Currently, much attention is placed on reducing the PM emissions from the transport sector fuel consumption to mitigate the adverse effects like cardiovascular diseases, carcinogenic illness and other associated illnesses (Dennehy, 2018). The PM emissions from the case study highway section were calculated as 55.16 tonnes for the year 2045 in the BAU scenario (Figure 8.9), which grew at an average rate of 8.2% per year from the 5.24 tonnes PM emissions estimated for the base year 2015. A significant share of the PM emissions was caused by diesel and petrol combustion engines of heavy trucks and passenger cars.

The reduction potential of alternate traffic management scenarios in terms of exhaust PM emissions was not significantly realised until about the year 2020 with an average reduction rate of <5% during this period for the accumulative vehicle emissions. Traffic modelling results showed significant reduction potential in the subsequent years as the "Bus Case", BRT and AV-BRT scenarios exhibited an average PM exhaust emissions reduction potential of 18.3%, 20.1%, and 23.8%, respectively for the 2021–2045 period. The exhaust PM emissions for the year 2045 for these three public transport scenarios were 42.76 tonnes, 41.08 tonnes and 34.48 tonnes.

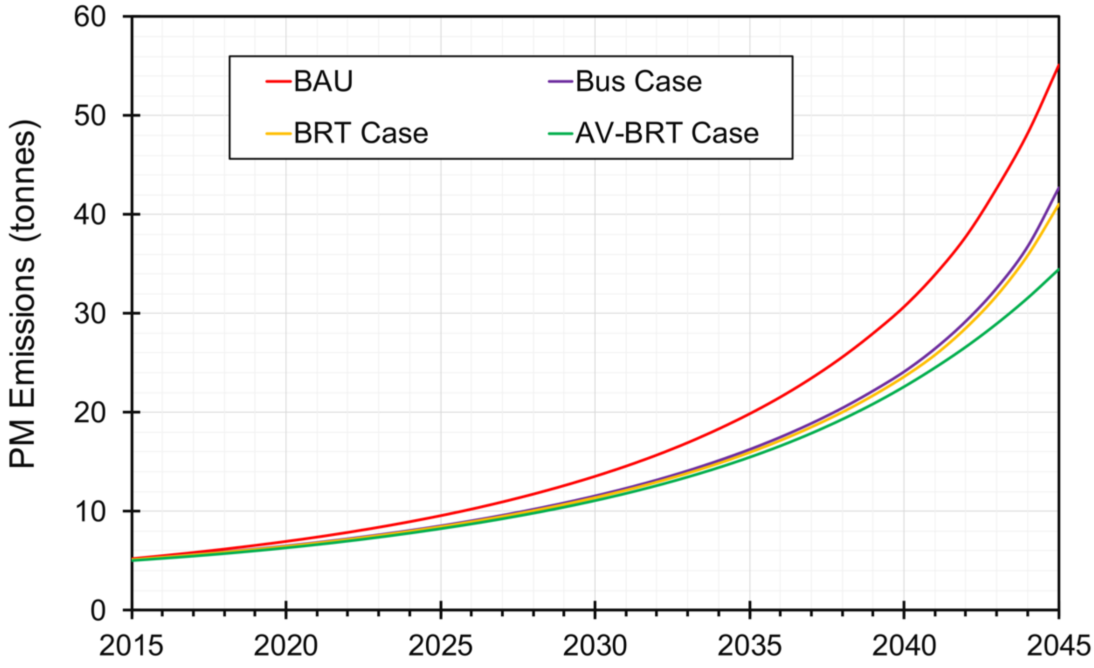


Figure 8.9 Total exhaust PM emissions trends in all scenarios, years 2015–2045

The difference between the PM emission reduction benefits of the "Bus Case" and BRT scenarios was comparatively lower than the AV-BRT scenario over the assessed 30 year period. The reason behind these results, as presented in Figure 8.9, was the lower PM emission from the 100% CNG combustion engines used in the AV-BRT scenario, compared to the higher (71%) share of diesel fuel engines in the "Bus Case" and BRT scenarios.

8.4.8 Long-term policy implications

The total energy consumption and exhaust pollutants (CO_2, NO_x, and PM) emissions for the different traffic management scenarios assessed in this study are illustrated in Figure 8.10. The main causes of energy consumption and CO_2 and PM exhaust emissions are the excessive reliance of (potential) passengers on private car transport, combusted petrol and diesel fuel, and the high emissions from a large number of older Euro III vehicles in the traffic fleet. Although the ADDoT has upgraded its existing bus network routes to include more areas and the bus fleet by adding approximately 120 buses recently, the bus service frequency is not currently optimised for the peak hour passenger transport demand, i.e., little to no variations between bus headways in peak/off-peak traffic. The existing highways are generally built to a high standard but are already reaching their respective operational capacities at peak traffic hours. Overall, the public bus route networks are still developing and the majority of transport is private cars, taxis, private company-operated minibuses and coaches for labours and light- and heavy-duty trucks for freight transport. The maritime/waterway public transport is virtually non-existent and the hot climate renders active transport modes (bicycling and walking etc.) difficult over long distances and between inner and outer city regions that are currently only connected by the highway network.

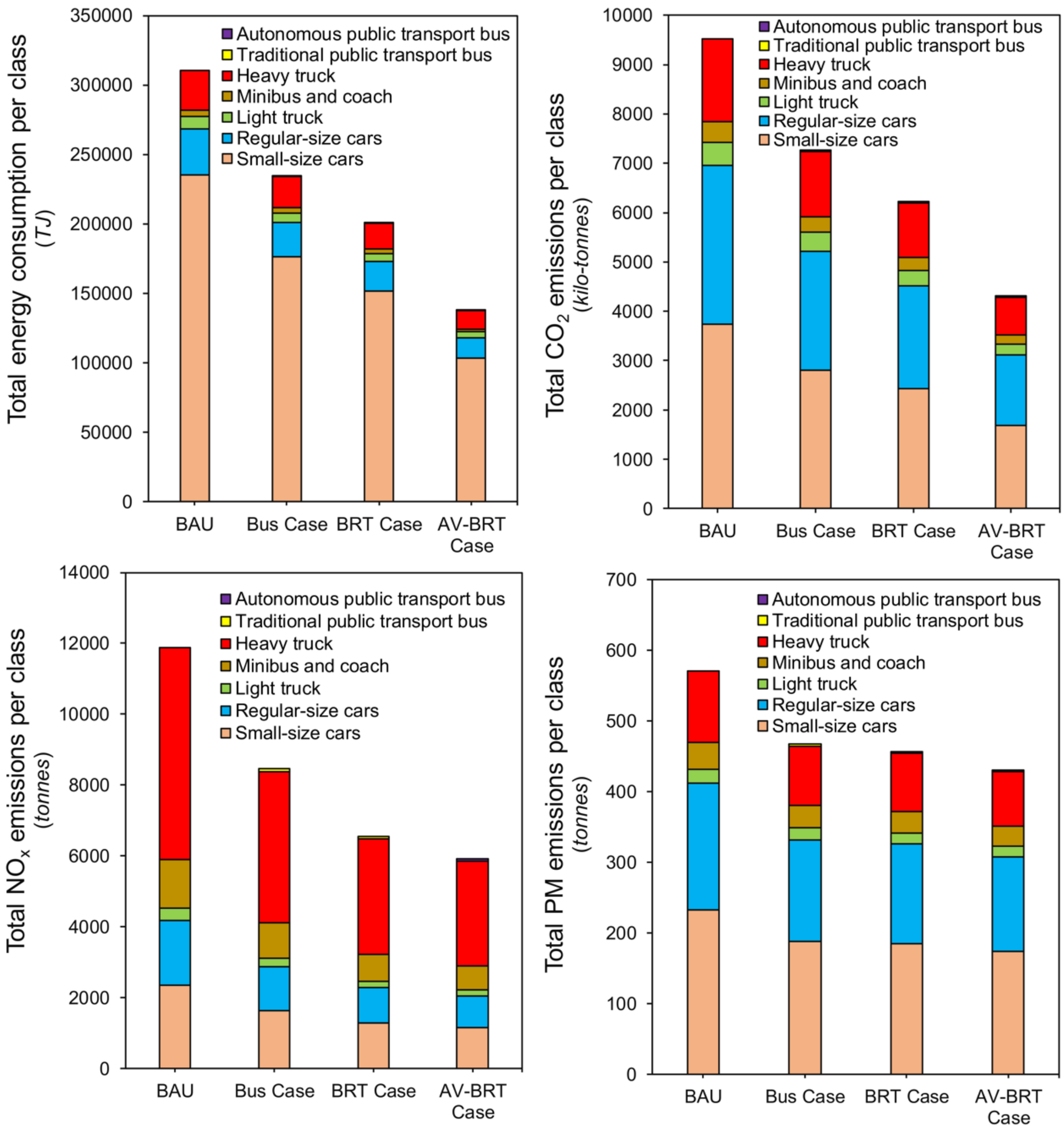


Figure 8.10 Total energy consumption and exhaust pollutant emissions reduction potential in the traffic management scenarios by vehicle type, years 2015–2045

Traffic modelling of the long-term vehicle transport in the Abu Dhabi city by the local transport authorities has demonstrated that the peak hour trips will considerably increase in the next 30 years resulting in worsening of the existing traffic congestion conditions and highway journey times to increase up to six times (ADDoT, 2009). The case study highway, "Sheikh Zayed bin Sultan Street" is one of the key highways in Abu Dhabi city and currently serves more than 9500 vehicles at peak hour in each direction, as counted for the base year 2015. Traffic growth and variations in the vehicle driving characteristics in the subsequent years are modelled in the current study using high-resolution microsimulation models. It was observed that large-scale traffic gridlocks will occur if no improvements are made to the transport network.

The fluctuating traffic flow acceleration-deceleration profile, continuous breaking and higher operating duration of vehicle engines in traffic gridlock situations are undoubtedly expected to increase the total fuel energy consumption of the studied traffic fleet. Figure 8.10 shows that the total energy consumption of the BAU scenario over the 30 years period from 2015–2045 is estimated to be primarily generated from the fuel consumption of small-size cars with 235.301×10^3 TJ energy consumption.

It was followed by regular-size cars with 33.154×10^3 TJ, heavy trucks with 28.646×10^3 TJ, light trucks with 8.746×10^3 TJ and minibus and coach with 4.741×10^3 TJ energy consumption due to engine fuel combustion. Petrol was noted as the most dominant fuel consumed by the passenger cars, followed by diesel and CNG and other alternate fuel types contributing the smallest share. It is noteworthy that the most significant exhaust pollutant emissions by petrol engines of passenger cars are CO_2 and PM. Exhaust CO_2 and PM emissions from cars carry the highest share among the accumulative emissions of all vehicle types. In the BAU scenario, 39.2% (3.733×10^3 kilo-tonnes) of the CO_2 emissions are generated by small-size cars from 2015–2045. Regular-size cars contributed 33.8% (3.218×10^3 kilo-tonnes), heavy trucks added 17.6% (1.679×10^3 kilo-tonnes), light trucks generated 5% (0.478×10^3 kilo-tonnes) and minibus and coaches only contributed 4.3% (0.412×10^3 kilo-tonnes) to the accumulative CO_2 emissions from the vehicle fleet on the studied highway section.

For the studied highway section, Figure 8.10 shows that 232.525 tonnes (40.7%) of the total PM emissions for the 30 year period in the BAU scenario are from small-size cars. These are caused by; substantially large vehicle counts of small-size cars and the resulting higher travel distances compared to other vehicle types, higher primary and secondary organic aerosol emissions from the Euro V and Euro VI petrol cars after atmospheric aging (Platt et al., 2017). The use of diesel particulate filters in modern diesel engines may also influence the comparative PM emissions rates among the studied vehicles. Similarly, PM emissions from regular-size cars were estimated as

179.180 tonnes (31.4%), followed by diesel engine heavy trucks (17.9%) and minibus (6.6%) and light trucks (3.5%) due to the fuel type, fuel combustion technology and volumetric share in the total traffic count of the studied highway section.

Compared to the other exhaust emission categories, heavy-duty diesel engines are recognised for the higher NO_x emissions than the other vehicle engines (Gao et al., 2019). Figure 8.10 shows that for the BAU scenario, approximately 50.4% (5.985×10^3 tonnes) of the accumulative NO_x emissions were generated by heavy trucks. Small-size cars contributed 19.8% (2.357×10^3 tonnes) followed by regular-size cars with 15.3% (1.817×10^3 tonnes). To effectively control the NO_x emissions, further improvement policies regarding freight transport are needed which are outside the scope of the current study focused on passenger transport. The "UAE National Climate Change Plan" (MOCCAE, 2017) and the "UAE Green Economy Report 2018" (MOCCAE, 2018) establish targets for the reduction of energy consumption and exhaust pollutants emissions from the local road traffic as: vehicle fleet fuel energy consumption to be reduced by approximately 19.6% and CO_2 and other pollutant emissions by more than 16% by the year 2030 in addition to promoting ~30% mode shift of car passengers in favour of public transport, at the national level.

The development plans for the Abu Dhabi city are aimed at reducing the current dependence on private cars by increasing the mode share of public transport to 41% and reducing CO_2 emissions by around 35% through the implementation of a future-based preferred scenario. Under this scenario the current transport network needs to be excessively upgraded by adding tram lines and developing clean energy. However, the traffic management scenarios assessed here require fewer changes in the existing infrastructure. Based on the existing governmental reports and the passenger survey conducted by Hasan et al. (2018b) for Abu Dhabi city, Figure 8.10 results show that with only 20% mode shift in favour of public bus transport modelled in the "Bus Case", accumulative vehicle energy consumption from a representative highway section case study can be reduced by 76.396×10^3 TJ (24.6%), exhaust CO_2 emissions by 2.258×10^3 kilo-tonnes (23.71%), exhaust NO_x emissions by 3.409×10^3 tonnes (28.71%) and exhaust PM emissions by 104.307 tonnes (18.25%) over 30 years period from 2015–2045. This scenario only considered replication of the existing city-wide mode share patterns on the case study highway section. Moreover, the current public bus fleet composition is assumed with diesel fuel as the dominant fuel technology as well as the continuance of existing lane configuration on the studied road.

The ADDoT along with other local government agencies is now considering establishing rapid transit lanes in several high traffic demand areas. In the hypothetical BRT scenario assessed in the current study for the 2015–2045 period, energy consumption reduced by 109.842×10^3 TJ (35.37%), exhaust CO_2 emissions by 3.3×10^3 kilo-tonnes (34.66%), exhaust NO_x emissions by 5.337×10^3 tonnes (44.94%) and exhaust PM emissions by 114.986 tonnes (20.12%). Implementing the BRT scenario requires little investment as both BRT and "Bus Case" scenarios can use the existing lanes (with bus lane in BRT separated by road markings) and the current bus routes would require only slight modifications. Although the BRT scenario is capable of achieving the energy consumption and exhaust pollutant emissions reduction aims of the local policy-makers, it still utilises diesel fuel for 71% of its energy needs (refer to Section 8.3.4).

The development of fully autonomous vehicles opens the opportunity for public transport fleet agencies to operate such vehicles on existing route networks. As the ADDoT currently imports vehicles to support its public bus fleet and is also investing in converting diesel engines of many of its existing buses to CNG engines, a hypothetical AV-BRT scenario may match these energy and pollutants reduction measures. It is a supply-side measure, and as such may be easier and quicker to implement (Peng et al., 2015) with little investments. Furthermore, AV-based public transport systems have already been tested in many parts of the world. The results for the AV-BRT scenario show that with a slight modification to the bus fleet, reliance on the already developing CNG fuel grid and bus service frequency variation according to peak/off-peak traffic demand; significant energy and pollutant reductions can be achieved. Figure 8.10 shows that the energy consumption of AV-BRT was 173.16×10^3 TJ (55.75%) lower than the BAU scenario over 30 years period. The CO_2, NO_x, and PM emissions were also significantly lower as 5.213×10^3 kilo-tonnes (54.76%), 5.967×10^3 tonnes (50.24%) and 140.931×10^3 tonnes (24.66%), respectively, in the 2015–2045 period. Although further changes in the energy policy and surface transport are planned for the Abu Dhabi city, all of the public transport-based traffic management scenarios assessed in the current study have been effective in reducing the energy consumption and exhaust pollutants. AV-BRT has been found as the most effective short-term energy conservation and pollution-control measure. However, the creation of secondary clean fuel energy resources for electric fuel and fuel technology improvements should also be assessed for their individual reduction potential.

8.5 CONCLUSION

Private car dominance as the preferred passenger travel mode in the UAE has already resulted in serious traffic congestions in the urban areas. The economic development, population growth, and growing metropolitan areas are projected to result in extremely high energy consumption and exhaust pollutant emissions from road traffic in the coming 30 years or so. The local transport and environmental policy-makers are developing plans to encourage a radical change in the existing mode use distribution from conventional private and public vehicles to clean energy measures and upgrading the existing public transport network with more bus vehicles, autonomous PRT vehicles, high-speed trams and light rail, to cut the energy consumption and exhaust pollutants emissions from the transport sector by year 2050. The methodological approach and high-resolution traffic flow data from microsimulation models presented here provide a detailed assessment of fuel energy and pollutant emissions under different traffic policy scenarios.

The results from the current study on a case study highway section serving large traffic volume (peak hour >9500 vehicles/hour in each direction) in the City of Abu Dhabi show a number of key factors. By introducing a public bus transport line and slightly variating the bus frequency based on traffic demand (as currently being considered by the local authorities), a significant reduction in fuel energy consumption (~35.37%) and exhaust pollutant emissions (>20.12%) can be achieved. The energy consumption rate in the "Bus Case" can be cut by 1186.088×10^3 MJ/h (28.1%), CO_2 emissions rate by 34.745 tonnes/hr (27.5%), NO_x emissions rate by 34.109 kg/hr (27%) and PM emissions rate by 1.595 kg/hr (25.5%) in the year 2045. Similarly, the BRT scenario reduced the year 2045 energy consumption, CO_2, NO_x and PM emission rates by 1904.484×10^3 MJ/h (45.1%), 57.055 tonnes/hr (45.1%), 56.343 kg/hr (44.6%), and 1.608 kg/hr (25.7%), respectively. The results also show that energy use and pollutant generation are not only directly correlated but also highly dependent upon private car ownership. Large-scale policy initiatives to reduce reliance on private cars such as reliable, high-speed and optimised public transport systems are required. The AV-BRT scenario demonstrated that with nominal upgrades of existing bus fleets, smoother acceleration-deceleration behaviour, shorter gaps between autonomous vehicle fleet and abandonment of diesel fuel engines may prove to be the most effective reduction measure in the near future. The highest reduction was estimated for energy consumption as 55.75% (173.16×10^3 TJ), followed by CO_2 emissions as 54.76% (5.213×10^3 kilo-tonnes), NO_x emissions as 50.24% (5.967×10^3 tonnes) and PM emissions as 24.66% (140.931×10^3 tonnes) over the period from 2015–2045.

These reductions in energy consumption and exhaust emissions were mainly generated by reduced reliance (25–35%) of urban passengers on private cars and replacement of diesel by CNG as the fuel source for public transport buses. A general relationship between vehicle count or travel distances and energy consumption was also noted. Energy consumption also exhibited a direct relationship with exhaust pollutants. The significant share of heavy-duty diesel engine vehicles in the exhaust emissions, particularly the 50.4% share of heavy trucks in the accumulative NO_x emissions from vehicles in the 2015–2045 period, highlighted the need for a good freight transport policy and research into alternate fuels for heavy-duty vehicles. Furthermore, the long-term policy implications from the results of the current study are in the context of the unique environment of conditions prevalent to Abu Dhabi, UAE. Significant potential of traffic microsimulation models for road and traffic policy scenario analyses regarding long-term energy conservation and pollution-control was noted which may be useful for similar studies in other regions.

8.6 References

Abou-Senna, H., Radwan, E., Westerlund, K., & Cooper, C. D. (2013). Using a traffic simulation model (Vissim) with an emissions model (MOVES) to predict emissions from vehicles on a limited-access highway. *Journal of the Air & Waste Management Association, 63*(7), 819-831. DOI: 10.1080/10962247.2013.795918.

ABS, A. B. o. S.-. (2019). Catalog #9208.0: Survey of motor vehicle use. Retrieved (4/11/2018) from www.abs.gov.au/ausstats/abs@.nsf/mf/9208.0.

AbuHijleh, B., & Nik, A. (2013). Economic and environmental benefits of using hybrid taxies in Dubai-UAE. *SB13 Dubai: Advancing the Green Agenda Technology, Practices and Policies, Dubai, United Arab Emirates*.

Ahmed, S. (2011). Dubai to have Euro 4 emission norms soon. *Khaleej Times*. Retrieved (4/11/2018) from www.khaleejtimes.com/article/20110514/ARTICLE/305149834/1002.

Alessandrini, A., & Mercier-Handisyde, P. (2016). *CityMobil 2 experience and recommendations* (pp. 52). Retrieved (4/11/2018) from www.citymobil2.eu/en/upload/Deliverables/PU/CityMobil2%20booklet%20web%20final_17%2011%202016.pdf.

Aljoufie, M. (2017). Examining the challenges of bicycle use in Jeddah city. *Procedia Environmental Sciences, 37*, 269-281. DOI: 10.1016/j.proenv.2017.03.058.

Andersen, O., Jensen, C. S., Torp, K., & Yang, B. (2013). *EcoTour: Reducing the environmental footprint of vehicles using eco-routes.* Paper presented at the 14th International Conference on Mobile Data Management (MDM). Milan, Italy: IEEE.

Barandica, J. M., Fernández-Sánchez, G., Berzosa, Á. Delgado, J. A., & Acosta, F. J. (2013). Applying life cycle thinking to reduce greenhouse gas emissions from road projects. *Journal of Cleaner Production, 57*, 79-91. DOI: 10.1016/j.jclepro.2013.05.036.

Barth, M., Davis, N., Lents, J., & Nikkila, N. (2007). Vehicle activity patterns and emissions in Pune, India. *Transportation Research Record, 2038*(1), 156-166. DOI: 10.3141/2038-20.

Batarce, M., Muñoz, J. C., & Ortúzar, J. d. D. (2016). Valuing crowding in public transport: Implications for cost-benefit analysis. *Transportation Research Part A: Policy and Practice, 91*(Supplement C), 358-378. DOI: 10.1016/j.tra.2016.06.025.

Bloomberg, L., & Dale, J. (2000). Comparison of Vissim and CORSIM traffic simulation models on a congested network. *Transportation Research Record, 1727*(1), 52-60. DOI: 10.3141/1727-07.

Bohm, F., & Häger, K. (2015). *Introduction of autonomous vehicles in the Swedish traffic system: Effects and changes due to the new self-driving car technology.* Uppsala University, Uppsala, Sweden.

Brown, A., Gonder, J., & Repac, B. (2014). An analysis of possible energy impacts of automated vehicles. In G. Meyer & S. Beiker (Eds.), *Road Vehicle Automation* (pp. 137-153). Cham: Springer International Publishing.

Bureau of Infrastructure, T. a. R. E. B. (2009). *Greenhouse gas emissions from Australian transport: Projections to 2020*. Canberra ACT.

Chen, K., & Yu, L. (2007). Microscopic traffic-emission simulation and case study for evaluation of traffic control strategies. *Journal of Transportation Systems Engineering and Information Technology, 7*(1), 93-99. DOI: 10.1016/S1570-6672(07)60011-7.

Chen, T. D., & Kockelman, K. M. (2016). Carsharing's life-cycle impacts on energy use and greenhouse gas emissions. *Transportation Research Part D: Transport and Environment, 47*, 276-284. DOI: 10.1016/j.trd.2016.05.012.

Chinery, L. E. (2010). *Modeling transportation in Abu Dhabi: A 25-year projection of emissions under alternative scenarios of the passenger vehicle fleet.* (MSc. Thesis). University of North Carolina at Chapel Hill, Chapel Hill, NC. Available from UNC-Chapel Hill Carolina Digital Repository database.

Currie, G. (2018). Lies, damned lies, AVs, shared mobility, and urban transit futures. *Journal of Public transportation, 21*(1), 19-30.

Davis, S. C., Diegel, S. W., & Boundy, R. G. (2008). *Transportation energy data book: Edition 27*. Retrieved (4/11/2018) from www.info.ornl.gov/sites/publications/files/Pub11639.pdf. Oak Ridge, Tennessee.

De Coensel, B., Can, A., Degraeuwe, B., De Vlieger, I., & Botteldooren, D. (2012). Effects of traffic signal coordination on noise and air pollutant emissions. *Environmental Modelling & Software, 35*, 74-83. DOI: 10.1016/j.envsoft.2012.02.009.

Dennehy, J. (2018). UAE ramps up efforts to tackle air pollution. *The National*. Retrieved (4/11/2018) from www.thenational.ae/uae/environment/uae-ramps-up-efforts-to-tackle-air-pollution-1.782903.

DIRDC. (2019). Australian Green Vehicle Guide. Retrieved (4/11/2018) from www.greenvehicleguide.gov.au.

ADDoT. (2009). *Surface transport master plan - A vision for connecting Abu Dhabi*. Abu Dhabi Department of Transport. Abu Dhabi, United Arab Emirates.

ADDoT. (2011). Bus transportation. Retrieved (4/11/2018) from www.dot.abudhabi.ae/en/info/Bus_Transportation

EYGM Limited. (2012). *Mega trends shaping the Middle East light vehicle market*. Retrieved (4/11/2018) from www.ey.com/Publication/vwLUAssets/Mega_trends_shaping_the_Middle_East_light_vehicle_market/$FILE/EY-Mega_trends_shaping_the_Middle_East_light_vehicle_market.pdf. Abu Dhabi, UAE.

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice, 77*, 167-181. DOI: 10.1016/j.tra.2015.04.003.

Fellendorf, M., & Vortisch, P. (2010). Microscopic traffic flow simulator Vissim. In J. Barceló (Ed.), *Fundamentals of Traffic Simulation* (pp. 63-93). New York, NY: Springer New York.

Fox, T. (2016). *Monthly insights 19 October 2016*. Retrieved (4/11/2018) from www.emiratesnbdresearch.com/plugins/Research/files/Monthly_Insights_October_2016.pdf. Dubai, United Arab Emirates.

Gao, J., Chen, H., Li, Y., Chen, J., Zhang, Y., Dave, K., & Huang, Y. (2019). Fuel consumption and exhaust emissions of diesel vehicles in worldwide harmonized light vehicles test cycles and their sensitivities to eco-driving factors. *Energy Conversion and Management, 196*, 605-613. DOI: 10.1016/j.enconman.2019.06.038.

Giarratana, C. (2018). Will autonomous cars be powered by gas battery or hybrid energy? Retrieved (4/11/2018) from www.trafficsafetystore.com/blog/will-autonomous-cars-be-powered-by-gas-battery-or-hybrid-energy.

GSO, G. S. o.-. (2014). *General requirements-motor vehicles* (GSO 02/01/CD/Update for No. 42:2003). Retrieved (4/11/2018) from www.members.wto.org/crnattachments/2014/tbt/ARE/14_4732_00_e.pdf.

Guo, X., Fu, L., Ji, M., Lang, J., Chen, D., & Cheng, S. (2016). Scenario analysis to vehicular emission reduction in Beijing-Tianjin-Hebei (BTH) region, China. *Environmental Pollution, 216*, 470-479. DOI: 10.1016/j.envpol.2016.05.082.

Hasan, U., Whyte, A., & Al Jassmi, H. (2018a). *Framework for delivering an AV-based mass mobility solution: Integrating government-consumer actors and life-cycle analysis of transportation systems.* Paper presented at the 46th European Transport Conference, Dublin, Ireland.

Hasan, U., Whyte, A., & Al Jassmi, H. (2018b). Life-cycle asset management in residential developments building on transport system critical attributes via a data-mining algorithm. *Buildings, 9*(1). DOI: 10.3390/buildings9010001.

Hickman, R., & Banister, D. (2007). Looking over the horizon: Transport and reduced CO_2 emissions in the UK by 2030. *Transport Policy, 14*(5), 377-387. DOI: 10.1016/j.tranpol.2007.04.005.

Hoque, N., Biswas, W., Mazhar, I., & Howard, I. (2019). Environmental life cycle assessment of alternative fuels for Western Australia's transport sector. *Atmosphere*, 10(7), 398.

Howard, D., & Dai, D. (2014). *Public perceptions of self-driving cars: The case of Berkeley, California.* Paper presented at the Transportation Research Board 93rd Annual Meeting, Washington, D.C.

Kazim, A. (2003). Introduction of PEM fuel-cell vehicles in the transportation sector of the United Arab Emirates. *Applied Energy, 74*(1), 125-133. DOI: 10.1016/S0306-2619(02)00138-1.

Khamis, J. (2014, 27th January). Cycling culture growing in the UAE: Rent-a-bike services introduced in Abu Dhabi, Dubai and Sharjah. *Gulf News*. Retrieved (4/11/2018) from www.gulfnews.com/uae/health/cycling-culture-growing-in-the-uae-1.1282774.

Kuschel, G., Cooper, A., & Metcalfe, J. (2017). *Evaluating bus emissions: What colour, how big and how much is that elephant in the window?* Paper presented at the 39th Australasian Transport Research Forum (ATRF), Auckland, New Zealand.

Lajunen, A., & Lipman, T. (2016). Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. *Energy, 106*, 329-342. DOI: 10.1016/j.energy.2016.03.075.

Lepert, P., & Brillet, F. (2009). The overall effects of road works on global warming gas emissions. *Transportation Research Part D: Transport and Environment, 14*(8), 576-584. DOI: 10.1016/j.trd.2009.08.002.

Ligterink, N., Van Baalen, J., Eijk, A., Mak, W., Broeders, W., & Vortisch, P. (2008). *Predicting local vehicle emissions using VERSIT+ and Vissim.* Paper presented at the 7th European Congress and Exhibition on the Intelligent Transport Systems and Services, Geneva, Switzerland.

Linton, C., Grant-Muller, S., & Gale, W. F. (2015). Approaches and techniques for modelling CO_2 emissions from road transport. *Transport Reviews, 35*(4), 533-553. DOI: 10.1080/01441647.2015.1030004.

Margreiter, M., Krause, S., Twaddle, H., & Lüßmann, J. (2014). Evaluation of environmental impacts of adaptive network signal controls based on real vehicle

Trajectories. *Transportation Research Procedia, 4*, 421-430. DOI: 10.1016/j.trpro.2014.11.032.

Masdar. (2018). Masdar unveils locally manufactured all-electric Eco-Bus at Abu Dhabi Sustainability Week 2018 [Press release]. Retrieved (4/11/2018) from www.masdar.ae/en/media/detail/masdar-unveils-locally-manufactured-all-electric-eco-bus-at-abu-dhabi-susta.

McCollum, D., & Yang, C. (2009). Achieving deep reductions in US transport greenhouse gas emissions: Scenario analysis and policy implications. *Energy Policy, 37*(12), 5580-5596. DOI: 10.1016/j.enpol.2009.08.038.

McKenzie, E. C., & Durango-Cohen, P. L. (2012). Environmental life-cycle assessment of transit buses with alternative fuel technology. *Transportation Research Part D: Transport and Environment, 17*(1), 39-47. DOI: 10.1016/j.trd.2011.09.008.

Mikhail, C., Stephanie, P., Zoe, E., William, E., & Juan, M. (2013). Infrastructure and automobile shifts: Positioning transit to reduce life-cycle environmental impacts for urban sustainability goals. *Environmental Research Letters, 8*(1), 015041.

MOCCAE. (2017). *National climate change plan of the United Arab Emirates 2017 - 2050*. Retrieved (4/11/2018) from www.moccae.gov.ae/assets/30e58e2e/national-climate-change-plan-for-the-united-arab-emirates-2017-2050.aspx. Dubai, United Arab Emirates: Ministry of Climate Change & Environment.

MOCCAE. (2018). *United Arab Emirates state of green economy report*. Dubai, United Arab Emirates: UAE Ministry of Climate Change & Environment.

Mott MacDonald, & Steer Davies Gleave. (2008). Working paper No. 5a results of surveys carried out for enhanced model. Abu Dhabi, UAE: Department of Transport of Abu Dhabi.

Nanaki, E. A., Koroneos, C. J., Roset, J., Susca, T., Christensen, T. H., De Gregorio Hurtado, S., López-Jiménez, P. A. (2017). Environmental assessment of 9 European public bus transportation systems. *Sustainable Cities and Society, 28*, 42-52. DOI: 10.1016/j.scs.2016.08.025.

Ou, X., Zhang, X., & Chang, S. (2010). Scenario analysis on alternative fuel/vehicle for China's future road transport: Life-cycle energy demand and GHG emissions. *Energy Policy, 38*(8), 3943-3956. DOI: 10.1016/j.enpol.2010.03.018.

Pathak, S. K., Sood, V., Singh, Y., & Channiwala, S. (2016). Real world vehicle emissions: Their correlation with driving parameters. *Transportation Research Part D: Transport and Environment, 44*, 157-176.

Peng, B., Du, H., Ma, S., Fan, Y., & Broadstock, D. C. (2015). Urban passenger transport energy saving and emission reduction potential: A case study for Tianjin, China. *Energy Conversion and Management, 102*, 4-16. DOI: 10.1016/j.enconman.2015.01.017.

Piecyk, M. I., & McKinnon, A. C. (2010). Forecasting the carbon footprint of road freight transport in 2020. *International Journal of Production Economics, 128*(1), 31-42. DOI: 10.1016/j.ijpe.2009.08.027.

Platt, S. M., El Haddad, I., Pieber, S. M., Zardini, A. A., Suarez-Bertoa, R., Clairotte, M., Prévôt, A. S. H. (2017). Gasoline cars produce more carbonaceous particulate matter than modern filter-equipped diesel cars. *Scientific Reports, 7*(1), 4926. DOI: 10.1038/s41598-017-03714-9.

Quaassdorff, C., Borge, R., Pérez, J., Lumbreras, J., de la Paz, D., & de Andrés, J. M. (2016). Microscale traffic simulation and emission estimation in a heavily trafficked roundabout in Madrid (Spain). *Science of the Total Environment, 566-567*, 416-427. DOI: 10.1016/j.scitotenv.2016.05.051.

Raeside, J. (2015). Middle East emissions legislation. Retrieved (4/11/2018) from www.integer-research.com/industry-insight/emissions-legislation/middle-east.

Romilly, P. (1999). Substitution of bus for car travel in urban Britain: An economic evaluation of bus and car exhaust emission and other costs. *Transportation Research Part D: Transport and Environment, 4*(2), 109-125. DOI: 10.1016/S1361-9209(98)00028-5.

Santos, J., Ferreira, A., & Flintsch, G. (2015). A life cycle assessment model for pavement management: Road pavement construction and management in Portugal. *International Journal of Pavement Engineering, 16*(4), 315-336. DOI: 10.1080/10298436.2014.942862.

SFCTA. (2017). *TNC's today – A profile of San Francisco transportation network company activity*. Retrieved (4/11/2018) from San Francisco, California, USA: www.sfcta.org/sites/default/files/content/Planning/TNCs/TNCsToday112917.pdf

Sgouridis, S., Abdullah, A., Griffiths, S., Saygin, D., Wagner, N., Gielen, D., McQueen, D. (2016). Re-mapping the UAE's energy transition: An economy-wide assessment of renewable energy options and their policy implications. *Renewable and Sustainable Energy Reviews, 55*, 1166-1180. DOI: 10.1016/j.rser.2015.05.039

Sgouridis, S., Helmers, E., & Al Hadhrami, M. (2018). Light-duty electric vehicles in the gulf? Techno-economic assessment and policy implications. *International Journal of Sustainable Transportation, 12*(2), 92-106. DOI: 10.1080/15568318.2017.1332256.

Simons, A. (2016). Road transport: New life cycle inventories for fossil-fuelled passenger cars and non-exhaust emissions in Ecoinvent v3. *The International Journal of Life Cycle Assessment, 21*(9), 1299-1313. DOI: 10.1007/s11367-013-0642-9.

Song, G., Yu, L., & Zhang, Y. (2012). Applicability of traffic microsimulation models in vehicle emissions estimates: Case study of Vissim. *Transportation Research Record, 2270*(1), 132-141. DOI: 10.3141/2270-16.

Staff Report. (2015). 5.2 years: Average age of cars in UAE. *Emirates 24/7*. Retrieved (4/11/2018) from www.emirates247.com/news/emirates/5-2-years-average-age-of-cars-in-uae-2015-08-15-1.600360.

Stevanovic, A., Stevanovic, J., Zhang, K., & Batterman, S. (2009). Optimizing traffic control to reduce fuel consumption and vehicular emissions: Integrated approach with Vissim, CMEM, and VISGAOST. *Transportation Research Record, 2128*(1), 105-113. DOI: 10.3141/2128-11.

Thomopoulos, N., & Givoni, M. (2015). The autonomous car – A blessing or a curse for the future of low carbon mobility? An exploration of likely vs. desirable outcomes. *European Journal of Futures Research, 3*(1), 14. DOI: 10.1007/s40309-015-0071-z.

Treyer, K., & Bauer, C. (2016). The environmental footprint of UAE's electricity sector: Combining life cycle assessment and scenario modeling. *Renewable and Sustainable Energy Reviews, 55*, 1234-1247. DOI: 10.1016/j.rser.2015.04.016.

Wang, A., Ge, Y., Tan, J., Fu, M., Shah, A. N., Ding, Y., Liang, B. (2011). On-road pollutant emission and fuel consumption characteristics of buses in Beijing. *Journal of Environmental Sciences, 23*(3), 419-426. DOI: 10.1016/S1001-0742(10)60426-3.

Wu, I., & Pojani, D. (2016). Obstacles to the creation of successful bus rapid transit systems: The case of Bangkok. *Research in Transportation Economics, 60*(Supplement C), 44-53. DOI: 10.1016/j.retrec.2016.05.001.

Yu, B., & Lu, Q. (2012). Life cycle assessment of pavement: Methodology and case study. *Transportation Research Part D: Transport and Environment, 17*(5), 380-388. DOI: 10.1016/j.trd.2012.03.004.

Zanni, A. M., & Bristow, A. L. (2010). Emissions of CO_2 from road freight transport in London: Trends and policies for long run reductions. *Energy Policy, 38*(4), 1774-1786. DOI: 10.1016/j.enpol.2009.11.053.

CHAPTER 9

A MULTI-CRITERIA DECISION-MAKING FRAMEWORK FOR SUSTAINABLE ROAD TRANSPORT SYSTEMS: INTEGRATING SOCIAL-COST-ENVIRONMENT-ENERGY FOR A HIGHWAY CASE STUDY IN UNITED ARAB EMIRATES

9.1 ABSTRACT

Demands for sustainability in road transport system management and mobility decision analysis have created the need for integrated tools and frameworks. However, analysts have to balance the respective vantages of the available alternatives within an environment of varying stakeholder goals and priorities. Research into the integration of current and future transport system technologies (e.g., autonomous vehicles) within the traditional design-bid-build decision-making paradigm is also required to acknowledge sustainability's triple-bottom-line social, cost and environmental impacts. Thus, the present study proposes an MCDM framework that establishes the sustainability performance evaluation of any road transport system's project alternatives as a Pareto set utilising: 1) stakeholder engagement to add flexibility in key performance indicators, 2) passenger surveys to identify attributes of a system that encourages mode choice towards public transport, 3) traffic models, lifecycle cost and lifecycle assessment for quantitative assessment, 4) analytic hierarchy process for qualitative assessment, and finally 4) MCDM to rank the sustainability performances of alternatives coupling quantitative and qualitative results. This novel multilevel decision-making framework is then applied to a case study 5-lane dual carriageway road transport system in Abu Dhabi. Eight alternatives with combinations of virgin and recycled material-based roadworks and public transport-based traffic management options are analysed. Results showed that an autonomous vehicle-based bus rapid transit service in conjunction with recycled materials for pavement courses and slag in roadside concrete works significantly reduce the lifecycle cost (51%), reduce energy input (56%) and decrease pollutant burdens (55% CO_2, 50% NO_x, 24% PM). The proposed framework also exhibited strong robustness against variations in indicator weights due to the changing priorities of different stakeholder groups.

9.2 Introduction

Road transport systems are essential for modern societies, directing people and resources within and among cities. The global use of virgin materials for road construction and maintenance and escalating reliance on private vehicle-based road mobility, highlights the need for sustainable construction, operation, and management of such systems. Construction and maintenance cost overruns occur during the asset's lifecycle for respective municipal agencies' management (Caffieri et al., 2017). Conversely, high traffic density and congestions cause operation cost overruns for transport agencies and road users (Babashamsi et al., 2016). Environmentally, these roadworks and traffic fleet components are argued to cause excessive energy consumption and pollutant emissions contributing to global climate change and natural resource depletion concerns (Hasan, Whyte, & Al Jassmi, 2019a). Currie and De Gruyter (2018) argue that these issues are particularly prevalent in cities, due to large populations, economic growth, and demand for large-scale infrastructure projects with limited consideration to the underlying social, economic, and environmental factors.

A strategic response to these issues is echoed in the tactics often implemented by respective local government authorities in many cities. Approaches adapted include; RCW application as road backfill, sub-base/base material; RAP for asphalt courses; and, hot- or cold-in-place recycling techniques for roadworks (Hasan, 2015). Similarly, government authorities often try to alleviate traffic congestion by discouraging motorised travel through the introduction of; good quality public transport (PT) services, car-free precincts, pedestrian zones, and bicycle lanes. However, the long-term success of these strategies towards the larger goal of *sustainable road transport systems* is dependent upon local factors; e.g., material availability, resource supply-chain and extreme weather conditions such as those experienced in the Middle-eastern cities (Kazmi, 2014). These regional factors affect the globalisation of policies and projects on road transport systems, and need to be assessed as a multi-criteria problem to optimise the cost, emissions, and energy performance while also meeting the social aspects related to several stakeholders.

Stakeholder engagement needs to be adequately embedded in the decision-making process for the construction, management and operation of road transport systems (Butt, Toller, & Birgisson, 2015). Two stakeholder groups can be loosely identified: local government road and transport policy-makers and transport operators, and, the system users or passengers. The local government authority planners can not only establish the need and objectives of a road transportation system project in any particular case or region, but also present the key performance indicators or KPIs (Santos et al., 2017) for evaluating the sustainability of existing or new systems.

Additionally, O'Faircheallaigh (2010) proposes that the users of road transport systems should be involved in the decision-making process to ensure user adoption of sustainability-based traffic management initiatives. Particularly, users can help in identifying critical transport system attributes toward private car usage reduction and PT promotion (Upham et al., 2015). Recently, there have been some attempts to embed user/passenger responses within a conventional PT policymaking framework (e.g., Erkul, Yitmen, and Çelik (2016)). However, transportation researchers (Leyden et al., 2017) note that an appropriate framework to ensure proper user engagement within the decision-making process, is still lacking. Hence, there is a significant need for an MCDM framework for transportation systems that can incorporate all (users and government) stakeholders' preferences, along with quantitative project feasibility data.

Provided the cost, pollutant and energy burdens, LCCA and its environmental counterpart, LCA have been extensively used by government planning agencies and researchers likewise to evaluate road transportation system projects. In general, LCCA is applied for identifying the option that is expected to provide the highest return on investment assessed in terms of cost-effectiveness in the long term. According to an estimate by IRF (2010), the construction, operation, and maintenance of pavements alone account for an annual investment of $400 billion globally. Wennström and Karlsson (2016) investigated the implication of road design on the vehicle operation and road maintenance costs and found that the vehicle operating costs to the road users contribute more than 32%, whilst road routine M&R costs account for 33.6% of the total lifecycle costs of a small road section. However, this assessment did not consider user costs due to additional fuel use, vehicle wear-and-tear and time spent in traffic congestions. On the other hand, Yu, Lu, and Xu (2013) found that the user time delay costs during the M&R stages alone, account for more than 25% of the total lifecycle costs of a road transport system in the United States. Gáspár et al. (2016) and Praticò (2017) addressed the applicability of LCCA as a tool for assisting municipal decision-makers after identifying several costs that may be encountered during the project lifecycle of road transportation systems. They emphasised the need for assessing and integrating user and social costs such as vehicle operation costs, PT service disruption and user delays in traffic congestions.

LCA has been applied to the roadworks and traffic components of road transportation systems in recent years to varying extents. Biswas (2014) used 100% RAP in repaving the wearing course asphalt during M&R stage for two-lane Australian road and found 56 tonnes CO_2eq. (38.89%) reduction in carbon footprint. Ventura, Monéron, and Jullien (2008) explored the environmental benefit of replacing the binder course in a pavement case study from France by different percentages (0 – 30%) of RAP. They found that the greenhouse gas (GHG) reduction potential and energy savings from RAP usage increased with increasing recycling percentage. However, Turk et al. (2016) noted that these savings are dependent upon the heating technique in asphalt plants and material transport distance. Mazumder et al. (2016) investigated a 1 km asphalt pavement section subjected to annual average daily traffic (AADT) of 20,000 vehicles over a 50 years lifecycle. They estimated that for a heavy traffic road section, the fossil fuel consumption of WMA (754.95 GJ) was 25.3% lower than HMA (1010.62 GJ). Additionally, they found that the global warming potential (GWP) impact reduced by 26.1% between WMA (34102 Kg CO_2eq.) and HMA (46147 Kg CO_2eq.) and acidification by 29%, thus suggesting the benefit of using WMA for pavement asphalt courses instead of HMA.

In the United States, the transport sector was the 2nd largest contributor to GHG emissions, while the emissions data from other G8 countries and European Union found their transportation sectors as contributing around 2/3rd of the total GHG emissions (Andersen et al., 2013). However, similar to the lifecycle costs, the primary source of pollutant emissions and energy consumption from road transport systems is during its usage stage due to motorised traffic. Hasan et al. (2019) in a detailed state-of-the-art study on road transport systems found that accurately calculating tailpipe emissions and the quantity of fuel energy consumed by traffic fleet is necessary for estimating the impact of the use stage. Alzard et al. (2019) showed that the emissions from use stage can range from 80-97% of the lifecycle emissions depending upon the type of road and the traffic density. Road transport systems promoting shared mobility and PT services have been found to reduce pollutant emissions and energy use in many LCA studies. Chen and Kockelman (2016) showed that shared mobility reduced GHG by 71.54g CO_2eq. per passenger-kilometre-travelled. PT promotion was found to reduce pollutant emissions by 22.6% and lower energy use by 22% for a Chinese urban passenger transport-based case study (Peng et al., 2015). Litman (2019) noted similar reductions in lifecycle cost after shifting passenger trip load to PT services from private vehicles, due to travel time, fuel and vehicle operating cost savings.

On the other hand, the emerging interest in smart cities has paved the way for gradually increasing public acceptance of autonomous vehicles (AVs). A majority of such ventures like the Cambridge Centre for Smart Infrastructures, Greenwich Automated Transport Environment, California's Partners for Advanced Transportation Technology and the European Union's urban transit CityMobil2 (Alessandrini et al., 2015) projects have focused on mass mobility. Global trials by companies such as Navya of its fully autonomous bus shuttle (approximately 11 passenger seating capacity) were conducted in London, Perth, Michigan with Japanese incorporation pending. The trials have found that the general public outlook of AVs as a bus service, is largely positive. The improved platooning of autonomous vehicles due to vehicle-to-vehicle communications is projected by Shladover, Su, and Lu (2012) to improve road lane capacity by approximately 80%. However, the lifecycle implications of a road transport system using AVs for PT still needs to be assessed explicitly.

Management strategists have long been relying on MCDM to aid in objective decisions (Beinat, 2001; Wu, Lin, & Lee, 2010) where analysts have to contemplate several alternatives within an environment of varying goals or a fuzzy environment. Examples are: Dempster-Shafer theory (Dempster, 1968); decision-making trial and evaluation laboratory (DEMATEL); VIKOR; and, multi-attribute utility theory (Wu et al., 2012), etc. Generally, MCDMs work on the principle of facilitating the decision-making process with an evaluation of alternatives based on certain quantifiable KPI set (Eddie, Heng, & Ling, 2005), which are then tabulated into a decision matrix. Each of the criteria set items are then given weightage based upon relative importance to project objectives or priorities of the stakeholders to create a comparison matrix for project alternatives. For evaluating the investment decisions regarding transportation systems, Chikezie, Olowosulu, and Olugbenga (2013) contemplated optimisation of perceived improvement, cost, and M&R method through genetic algorithms.

Some researchers also sought to factor into MCDM the concepts of environmental impacts and energy/resource consumption. Examples of such studies are: sustainable transport evaluation study by Awasthi, Chauhan, and Omrani (2011); the case study by Yang, Lee, and Chen (2016) on sustainability performance evaluation and traffic congestion reduction potential of PT options; and, optimum urban PT service route planning study by Hamurcu and Eren (2018) using MCDM models. One notable shortcoming of these studies was the lack of real-world quantitative data from actual road transportation projects. In addition to using expert judgment for identifying the KPIs, these studies also just used qualitative data (i.e., relative impact weights) from experts to rank the sustainability performance of the different alternatives.

The relative impact weighting is largely motivated by the goals of the government agency or the perceived severity of the affected environmental and cost category by the particular experts (refer to Section 2.4.7). In order to determine the relative impact weights of the different criteria or impact for any MCDM problem, as one of the most popular strategies (Hoque et al., 2019) analytic hierarchy process (AHP) by Saaty (1990) proposes a pairwise comparison. In this technique, experts are requested to represent their preference and criterion importance interpreted on a 1–9 Saaty scale, where a lower number denotes lower level of importance. Based on this relative importance, the *relative weights* are calculated for each criterion (0–1). These relative weights are then used to compile a comparison matrix if the consistency ratio value is less than 0.1 (Dong et al., 2014). AHP has been used in the fields of transportation infrastructure and urban management to varying degree of success to represent the comparative benefits/costs of project alternatives (e.g. prioritisation of Brazilian infrastructure investments by Quadros and Nassi (2015); integration of sustainability in planning and investments on transportation infrastructures in Denmark by Pryn et al., (2015); and, an attempt at evaluating six sustainable transportation modes by Yedla and Shrestha (2003)). A combination of both approaches, AHP-TOPSIS which uses the AHP method for impact weight, has been employed in the fields of production economics, resource marketing, and waste management sectors, but its application for sustainability analyses of road transportation systems is fairly limited.

The literature review conducted above has highlighted that the construction, operation, M&R stages of road transportation systems are not isolated activities and carry environmental loads, energy and resource burdens, along with monetary implications. In order to identify, compare and select a sustainable transportation system, efficient decision-making approaches are required. The results obtained from the existing models are often complex to interpret and on different scales. Current decision-making frameworks assess sustainability performance across only some components of the road transport systems, neglecting system-wide opportunities. Thus, the aim of the current study is to provide an MCDM framework that evaluates: a) stakeholder opinion from both government agency experts and asset users, b) lifecycle cost, c) lifecycle pollutant emissions and d) lifecycle energy consumption of the different alternatives for a road transport system to identify the optimum option.

9.3 Methodological development of proposed MCDM framework

International initiatives such as IPCC (2008) emphasise integrating the three sustainability dimensions of social benefits (stakeholder-related), lifecycle cost, and environmental impacts. It is essential to provide an integrated multi-criteria assessment framework that is simple, reliable and practical. Figure 9.1 (Hasan, Whyte, & Al Jassmi, 2018a) illustrates the robust multi-criteria optimisation framework proposed in this study to evaluate the trade-offs between sustainability parameters based on empirical relations, public demand, and expert judgment. Each level in the framework aims to achieve specific objectives with detailed sub-models for calculating empirical values. This framework is developed in Section 4.2 earlier and integrates several assessment criteria based on lifeycle social, cost and environmental aspects optimising any road transport system (under evaluation) using the triple-bottom-line sustainability approach. The framework levels are described in more detail below; while the detailed justifications for selecting the different assessment criteria, their usage in the road transport literature and their integration status in the proposed framework are provided in Sections 4.2.1 and 4.2.1.4.

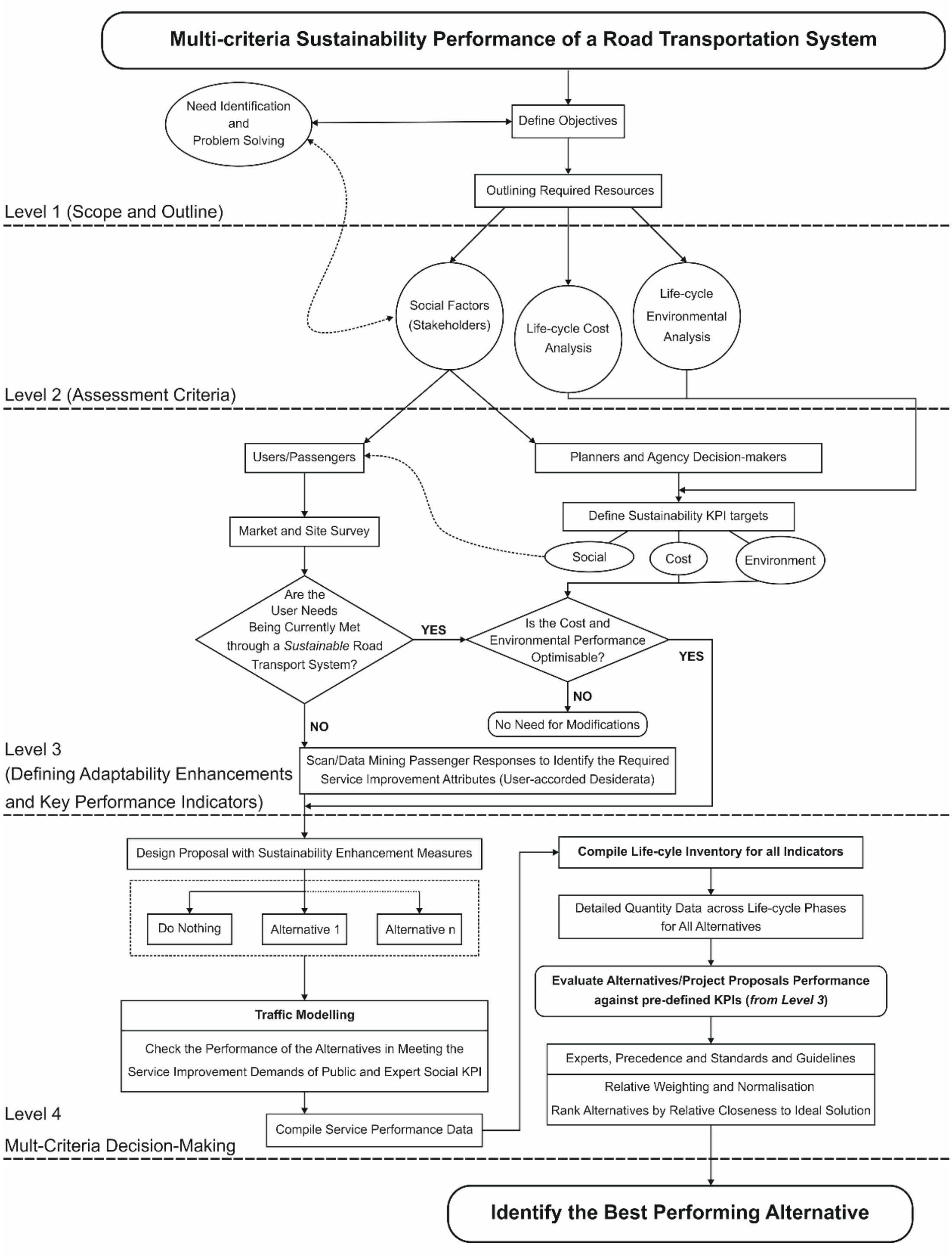


Figure 9.1 Proposed MCDM framework for sustainability performance evaluation of road transportation systems

9.3.1 Level 1 and 2: Scope, outline and assessment criteria

Arbitrariness in proposal and policy-making of road transport system construction or upgrade projects reduces the chances of selecting the best possible alternative. Butt et al. (2015) conducted a detailed review of the decision-making capability of the frameworks in literature aiming at green procurement strategies for road transport systems. The lack of framework with sustainability parameters (cost, environment and social) integration in actual road management practice was notably identified. The study proposed that identification of sustainability performance measures tailored for each project stage may improve the decision system efficiency and maintain consistency. Conversely, Waheed, Hudson, and Ralph (2013) propose that feasibility studies for any built asset must take a comprehensive multilevel approach. Thus, Level 1 is aimed at establishing project *needs*, project *resources,* and *objectives* in a transparent fashion. Today's government agencies and planners also need to tackle the issues of depleting natural construction material resources, decreasing landfill spaces, limited municipal budgets, increasing population and frequent traffic congestions (Giani et al., 2015). Level 2 of the proposed framework sets-up the triple-bottom-line sustainability distribution of the road transport system as; i) social factors related to stakeholders, ii) lifecycle cost, and iii) lifecycle environmental analyses.

9.3.2 Level 3: Stakeholder involvement and defining the KPI targets

Critical reviews on the success of sustainability-based design and management strategies for different components of road transportation systems, such as Redman et al. (2013), Rode et al. (2017), Balaguera et al. (2018), and Hasan et al. (2019) propose that system quality estimation of road projects and supported facilities should reflect stakeholder opinions. This way, decision-makers' acceptance of an integrated LCCA-LCA framework as a viable methodology may be ensured. Similarly, subsequent user adoption of the optimum alternative proposed via LCCA and LCA evaluations performed during proposal comparisons, may be realised. Hoque, Mazhar, and Biswas (2018) note that several cost, social, energy, and pollutant emission indicators for LCCA and LCA studies are explained by the Society of Environmental Toxicity and Chemistry (SETAC) and the United Nation Environmental Programme (UNEP). The authors also note that for effective decision-making, the indicators need to be adjusted and selected based upon the local conditions. Similarly, Cottrill and Derrible (2015) criticised the use of global pre-established indicators without adequate government and public engagement and travel data mining. For example, Miranda and Rodrigues da Silva (2012) used expert panels to select the indicators for sustainability evaluation of new transport projects in a Brazilian city.

The framework proposed here recommends using a group panel of decision-makers and planners from government agencies and industry experts on road transport systems to identify key performance indicators (KPIs) for environmental, cost and social impacts. Additionally, as with the success of any product or service marketed to the general public, the acceptability by the targeted market of the provided transport system is of critical significance. The acceptability of the road transport system and evaluation of the motorised travel on the road asset is, therefore, largely influenced by its general performance as perceived by the system users (Munoz, Ortúzar, & Gschwender, 2009). The second component of stakeholder engagement is to let the transportation policymakers create strategies addressing the daily activities of their customers. Traditionally, transportation agencies perform these passenger surveys to study the current travelling behaviour and disentangle several travel attributes such as a need for PT, service frequency, pricing, coverage, capacity, accessibility and quality that may attract car users to PT (Belgiawan, Ilahi, & Axhausen, 2017). The present study recommends that in order to better identify the shortcomings of the existing system, a survey of the local population and travellers should be performed for any particular road transport system project. Collected datasets would, therefore, produce large sets of variables, a majority of which are interacting or interdependent. Mining this large set of passenger responses may produce improvement suggestions for the existing or new road transport system according to the users.

9.3.3 Cost KPI characterisation: Lifecycle cost analysis (level 3 continued)

Currently, LCCA has become prominent in cost optimisation of highway, pavement and other road projects, yet, the data collection and analysis must be accurately performed (Whyte, 2015). Consensus must be reached in deciding the project-specific cost and design parameters, time horizon, and traffic loading as well as the applicable discount rate value. In order for an effective application of LCCA, its system boundary needs to be extended to cover the expenses to all the stakeholders occurring in the foreseeable stages. In addition to the agency-side ownership and management costs, the costs to users must also be accurately modelled and overall sustainability should take precedence in the decision-making process (Lee, Thomas, & Alleman, 2018). However, the exact determination of future expenditures is uncertain due to market variables and risks such as recession and variations in the velocity of distant cash flows (Galí, 2015). Future costs after "n" years are thus discounted to present value (PV) to provide a more realistic comparison between different alternatives based on initial costs and future costs to the users and government agencies. The following Equation (9.1) is used in literature (Hasan et al., 2019a) for PV calculation of future cost "C_t" occurring in "t" year using discount rate value "i".

$$PV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \qquad \text{Equation (9.1)}$$

Initial costs of road construction, routine maintenance and periodic rehabilitation that are incurred by the stakeholder government agencies need to be included in the analysis. Electricity and other operational and energy costs also form part of agency costs while operation costs of any PT service (if provided) are also inclusive in stakeholder cost. Costs to road transport system users are generated by vehicle operation cost (VOC) and fuel costs. LCCA and subsequent LCA must rely upon consistent data so that the alternatives could be comprehensively compared across both models. The functional unit and system boundary must be kept similar to maintain the consistency of the analysis results.

9.3.4 Emissions and energy KPI: Lifecycle assessment (level 3 continued)

LCA platforms should be able to acknowledge all upstream, direct and indirect processes within the supply chain, specifically usage stage traffic congestions and vehicle emissions (Yu et al., 2013). Whilst such idealisation can be restricted by a lack of transparent and independently accredited data, generally, a comprehensive LCA based on ISO 14040 (2006) guidelines should accommodate this through the involved six stages: raw material extraction; material production and processing; transport system construction; operation and usage; M&R; and, end-of-life. Additionally, the scope of critical indicators must be clearly defined.

Due to the large variety of material alternate options available for road construction, regional differences and significant environmental impact indicators, LCA is performed using: "Centre of Environmental Science (CML) methodology"; "Swedish Environmental Product Declarations"; "ILCD 2011"; IMPACT 2002"; "TRACI 2.1"; "Australian Lifecycle Association Best Practice LCIA Recommendations"; and, the single-issue "IPCC Global Warming Potential method". Another popular global LCA evaluation method, ReCiPe, was first developed in 2008 by Radboud University

Nijmegen, PRé Consultants, CML and the Dutch National Institute for Public Health and the Environment (Goedkoop et al., 2009). It contains over sixteen categories of pollutants and energy performance indicators. These methodologies rely on a large set of databases, e.g., Ecoinvent, which utilise material and process flow profiles to determine the environmental burden of construction and M&R activities. The framework proposed in the current study acknowledges that all such processes in a road transport system should be modelled using a comprehensive approach. This model should account for process in-flows and out-flows in both motorised transport and road components of the entire system towards precise performance evaluations.

9.3.5 Level 4 traffic modelling: Capturing the KPIs for traffic module

Usage stage impacts across all of the sustainability KPIs are dependent on the cost value of user time, fuel consumption, and energy and emission values incurred by detouring or driving through congested roads at low speeds provided that no optimisation is done for the road transport system. Researchers aiming to capture the lifecycle impact of transport systems, such as Yu and Lu (2012) found that the usage stage was the predominant reason for environmental impacts due to traffic density and congestions. Generally, traffic growth patterns and vehicles' fuel economy influence energy consumption and pollutant emissions from the usage stage. Accurately capturing the traffic density and congestion alleviating impacts of traffic management solutions is important for empirically comparing the lifecycle impacts across alternatives. Galatioto et al. (2015) argue that even though emissions for the traffic module can be estimated from Ecoinvent database, microsimulation models with emission modelling add-ons are better equipped for this purpose due to their ability to model speed-flow profiles and driving pattern of each vehicle in the transport system network. However, the system boundaries of current frameworks used for transport system evaluation studies do not acknowledge the significance of this stage. The traffic modelling component in Level 4 of the framework proposed in the current study aims to fill this gap. It investigates high-resolution sustainability performance of the optimisation alternatives during the usage stage in terms of the cost, energy consumption, and pollutant emissions KPIs established in Level 3.

9.3.6 Multi-criteria decision-making (MCDM) model (level 4 continued)

The MCDM model proposed in Level 4 of this study for performing the sustainability analysis across all KPIs is created in six steps, as follows. **Step 1:** Initially, the model is developed for a generic case with *m* possible road transport system alternatives belonging to the set *S* as:

$$S = \{S_1, S_2, S_3, ..., S_m\} \qquad \text{Equation (9.2)}$$

Step 2: The alternatives are then evaluated based upon a generic combination of cost (*C*), energy consumption (*E*) and pollutant emissions (*P*) criteria. These are further quantified using *k* number of sub-criteria or KPIs (details have been discussed in the above Sections 2.2 – 2.5):

$$C = \{C_1, C_2, C_3, ..., C_k\} \qquad \text{Equation (9.3)}$$

$$E = \{E_1, E_2, E_3, ..., E_k\} \qquad \text{Equation (9.4)}$$

$$P = \{P_1, P_2, P_3, ..., P_k\} \qquad \text{Equation (9.5)}$$

Step 3: After the compilation of quantitative values for all cost, energy and environment KPIs, these impact values can be represented in the form of a decision matrix (Equation 9.6), where for example, entry a_{11} represents the value of alternative "1" with respect to criteria "1". The decision matrix shall have values upto a_{mn}, i.e., value of the alternative *m* with respect to the criteria *n*. However, each of the KPI values must also be normalised using linear scale transformation so that different KPI scales can be expressed in terms of a comparable scale as has also been practiced by other researchers (Dong et al., 2014). The normalised decision matrix $\tilde{R}$ containing the normalised values $\tilde{r}$ for each KPI can be calculated as shown in Equations 9.7 – 9.8.

$$R = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \qquad \text{Equation (9.6)}$$

$$\tilde{R} = \left[\tilde{r}_{ij}\right]_{m \times n} \quad i = 1,2,....,\mathrm{m}, \quad j = 1,2,....,n, \qquad \text{Equation (9.7)}$$

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{\left(\sum_{j=1}^{m} \left(a_{ij} \right)^2 \right)^{1/2}} \right), \forall ij \quad j \in KPI$$ Equation (9.8)

Step 4: It involves the conversion of this quantitative KPI inventory into systematic estimates of their impacts weighted and evaluated based upon the analytical objectives of decision-makers. For determining relative weights of the KPIs, this study proposes an expert-oriented approach that reflects the opinion of a group of selected experts. Professionals from the industry (transport service operators) and government officials (municipality department) are consulted to increase practitioner confidence. These experts are normally involved in the decision-making procedure and fiscal investments on road transport systems. The weightings from transportation policy and analysis experts in academia are also included as a moderating factor. Experts are asked to perform pairwise comparison of KPIs using AHP methodology, and the resulting relative weights ($\tilde{w}_j$) are used to create a comparison matrix. After determining the relative weights, weighted normalised matrix $\tilde{V}$ is calculated by multiplying weights ($\tilde{w}_j$) of the evaluation criteria from the comparison matrix with the normalised matrix ($\tilde{r}_{ij}$):

$$\tilde{\upsilon}_{ij} = \tilde{r}_{ij} (\square) \tilde{w}_j \text{ ; and } \tilde{V} = [\tilde{\upsilon}_{ij}]_{m \times n}$$ Equation (9.9)

Step 5: In order to solve the multi-criteria problem of the KPI impacts with different units and at different scales, an uncomplicated and rational concept of assigning expert-subjective reliable priorities to each KPI called the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) developed by Hwang and Yoon (2012) is proposed to rank the alternatives for any road transport system project. The ideal solution (contains all of the best "attainable" normalised values for each criterion) and negative-ideal solution (contains all of the worst "attainable" normalised values for each criterion) are determined.

Ideal solution; $$I^* = \{\tilde{v}_1^*, \tilde{v}_2^*, ..., \tilde{v}_m^*\} = \left\{ \left(\max_i \tilde{v}_{ij} \,|\, j \in benefit \right), \left(\min_i \tilde{v}_{ij} \,|\, j \in cost \right) \right\}$$

Equation (9.10)

Negative-ideal solution; $I^- = \{\tilde{v}_1^-, \tilde{v}_2^-, ..., \tilde{v}_m^-\} = \left\{\left(\min_i \tilde{v}_{ij} \,|\, j \in benefit\right), \left(\max_i \tilde{v}_{ij} \,|\, j \in cost\right)\right\}$

Equation (9.11)

Step 6: The distances of each alternative from the ideal and the negative ideal solution (Awasthi & Omrani, 2009) are calculated by Equations (9.12) and (9.13):

Distance from ideal solution; $d_i^* = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^*\right)^2}, \forall i$ Equation (9.12)

Distance from negative-ideal solution; $d_i^- = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^-\right)^2}, \forall i$ Equation (9.13)

Relative closeness of any ideal solution; $R_{ci}^* = \frac{d_i^-}{d_i^* + d_i^-}, \forall i$; and $0 \le R_{ci}^* \le 1$

Equation (9.14)

The alternatives can then be ranked based upon the relative closeness to the ideal solution. The best performing alternative is expected to have the highest R^*_{ci} value corresponding to the highest sustainability performance of the alternative among others.

9.4 APPLICATION OF THE PROPOSED FRAMEWORK TO A CASE STUDY ROAD TRANSPORT SYSTEM

This study applies the proposed framework to a case study transport system optimisation issue in the City of Abu Dhabi, United Arab Emirates (UAE). The UAE has one of the highest per capita energy consumption (346.29 GJ) and GHG emission (23.3 tonnes CO_2eq.) in the world (Rahman, 2013; SCAD, 2014) due to reliance on private vehicle use, oil production, high population growth (70% from 2005-2013) and its recent economic growth. According to the estimates by Environment Agency - Abu Dhabi (2019), road transport systems contribute more than 63% to the total GHG emissions from the transport sector.

Nearly all of the paved roads in the Abu Dhabi city are constructed using virgin asphalt concrete, with private cars accounting for approximately 80% of the daily passenger traffic (ADDoT, 2009). The passenger traffic fleet itself is largely composed of vehicles with Euro III and earlier engines of size > 2.5 litres (Sgouridis et al., 2016;

Sgouridis, Helmers, & Al Hadhrami, 2018). The road transport system GHG emissions in Abu Dhabi city are 0.571 ktonnes CO_2eq./km-road that are 9.36, 2.46 and 1.89 times higher than those from China, United States, and the United Kingdom, respectively (Environment Agency - Abu Dhabi, 2019; EPA, 2016; ITF, 2010). These statistics provide the argument that there is an urgent need in Abu Dhabi city to not only introduce recycled materials for roadworks, but also promote a shift of passengers towards other travel modes with low pollutant emission and energy consumption rates.

9.4.1 Scope, outline, functional unit and assessment criteria: Levels 1 and 2

The case study location is the *Sheikh Zayed bin Sultan Street* highway in Abu Dhabi city. It is a major asphalt concrete road in the Abu Dhabi road transportation network serving more than 19,000 vehicles during peak hours as per the year 2015 traffic counts. It has undergone two major extension works in 2009 and 2019 due to the increasing traffic congestions. These consecutive extensions works have not only increased the lifecycle costs several fold, but have yet to effectively mitigate the environmental concerns (Alzard et al., 2019). Construction, operation, routine M&R of the 3.5 km long five-lane dual carriageway section and the corresponding daily traffic (usage) on this highway is designated as the functional unit for the current study. Both carriageways (total width = 9.65m) along with the concrete kerbs and barriers separating the carriageways as well as concrete foundation works for traffic lighting and road markings, are included.

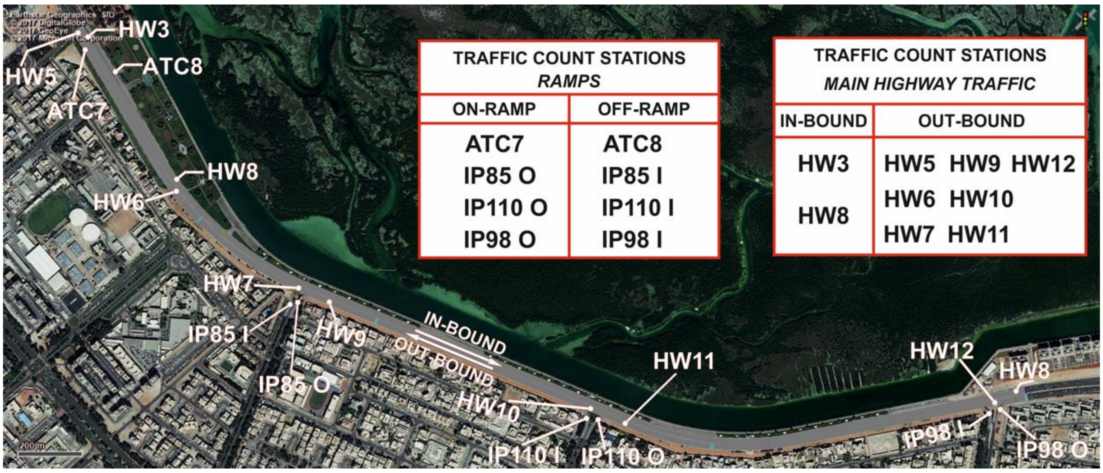


Figure 9.2 Case study section of Sheikh Zayed bin Sultan Street and traffic count station locations (Hasan, Whyte, & Al Jassmi, 2019c)

Figure 9.2 above illustrates the functional unit road section which needs to be optimised based upon the sustainability triple-bottom-line KPI of social (stakeholder), lifecycle cost, pollutant emissions, and energy consumption. Data regarding traffic counts have been collected from Abu Dhabi Municipality and Abu Dhabi Department of Transport based upon the traffic counting stations shown in Figure 9.2. The traffic count year 2015 is selected as base year for lifecycle calculations, while the service life is set at a 30-year analysis period based on the duration recommended in literature (Chinery, 2010; ADDoT, 2009).

9.4.2 Stakeholder involvement in level 3: Sustainability KPI targets and user needs

The first stage of stakeholder involvement as the social part of this framework is to identify the target KPIs for sustainability evaluation by engaging local decision-makers. Several indicators are proposed in literature for road transportation systems. The most used cost indicators are: initial cost; routine M&R costs; transport service provider costs; and, electricity costs for road lighting and traffic signals (Hasan et al., 2019a). Although all of these items are agency-related costs, user costs such as vehicle acquisition and operating (fuel and maintenance) costs, and user time costs have also been recently used by researchers (Lee et al., 2018; Stephan & Stephan, 2016). Similarly, several environmental indicators have been used for estimating pollutant emissions but GHG, PM, acidification (SO_2eq.), and ozone formation (NO_xeq.) emissions are among the most common (Buzási & Csete, 2015; Miranda & Rodrigues da Silva, 2012) which need to be further filtered based upon regional conditions.

The Abu Dhabi Department of Transport (ADDoT, 2009) conducted a group of several workshops inviting experts on road transport systems from around the world to develop sustainability indicators for Abu Dhabi. The international and local experts from the government municipality and transport department postulated that increasing accessibility, *meeting public (user) demands* and encouraging sustainable PT are the most significant social KPIs. *Agency costs* and *user transport costs*, including *vehicle operation costs* and *PT fare costs,* are the most significant cost-KPIs. Climate change potential or GWP measured in terms of GHG (*CO_2eq.*), acidification (*SO_2eq.*) from industrial and material production activities, *PM* and *NO_x* emissions are critical pollutants, specifically in urban regions. In order to promote an overall shift towards energy conservation, *energy consumption* is also a significant KPI. Since these KPIs have already been filtered according to the local conditions in Abu Dhabi by the relevant stakeholders, these are the KPIs chosen for the current study.

It should be noted that many vehicle emissions calculating models (e.g., United States-based MOBILE, ARTEMIS (V3b) HBEFA, etc.) separately calculate the acidification impacts by traffic fleet. However, the SO_2 emission from the traffic fleet is directly based on the sulphur content of the vehicle fuel and any reduction in the fuel energy consumption will result in a similar reduction in the SO_2 emissions (Smokers & Rensma, 2006) and thus it is not separately calculated in the current study. Regarding the user component of stakeholder engagement, results from the travel survey by Hasan, Whyte, and Al Jassmi (2018b) on the case study area selected in this chapter are used to find the shortcomings of the existing road transport system. The authors found that the current system often suffers from excessive traffic congestions due to heavy private car usage. Public bus transport, preferably in form of a BRT service, needs to be provided on the case study route and it must be optimised for peak hours in order to shift users from cars to PT buses.

In summary of the above, eight alternatives are analysed and compared to quantitatively assess the benefits of sustainable approaches based upon combinations of the roadworks (AR) and traffic management (AT) scenarios as: "*AR1, AT1*"; "*AR1, AT2*"; "*AR1, AT3*"; "*AR1, AT4*"; "*AR2, AT1*"; "*AR2, AT2*"; "*AR2, AT3*"; and "*AR2, AT4*". The scenario *AR1* is the baseline case for roadworks where the road section is constructed using virgin materials across all pavement courses, and 100% ordinary Portland cement (OPC) is used for the concrete works for roadside kerbs, barriers, traffic signal, and lighting system foundations. Similarly, the scenario *AT1* is the baseline for traffic assessment where the current traffic fleet distribution (cars: 83.04%; minibus and coaches: 4.735%; light truck: 6.64% and heavy truck: 5.586%) and 6% annual traffic growth rate (Chinery, 2010; Kazim, 2003) is assumed. Recycled materials were used in the *AR2* scenario as 25% RCW in sub-base course and 80% RCW in unbound-base course. For asphalt courses, *AR2* used 25% RAP in warm-mix asphalt (WMA) base, 15% RAP in WMA binder course and 15% RAP in WMA wearing course. For concrete works, 65% replacement of OPC by ground granulated blast furnace slag (GGBFS) was performed. These virgin material replacements are based upon the detailed environmental impact study conducted by Hasan, Whyte, and Al Jassmi (2020). *AT1* also assumes the existing vehicle fuel technology distribution.

Traffic fleet distribution is altered in *AT2* with the introduction of a public bus service (headway = 30 min) to meet the aforementioned public demand. The altered distribution is as follows: cars (66.432%), minibus and coaches (4.735%), light trucks (6.64%), bus (16.61%) and heavy trucks (5.586%) based upon Hasan et al. (2019c).

In *AT3*, a BRT service is introduced with 15 min headway between subsequent bus units. Only the contribution of public buses and passenger cars to the traffic fleet is altered as 24.02% and 59.02%, respectively (Hasan et al., 2019c). A future-based theoretical scenario to reflect the rapidly developing autonomous vehicle technology and the public demand for more frequent (headway = 5 min) bus service around peak hours, an autonomous BRT (AV-BRT) service is assumed on the study route in the *AT4* scenario. This AV-BRT service uses the existing compressed natural gas (CNG) distribution grid (Treyer & Bauer, 2016) for its fuel requirements compared to the 71% diesel and 29% CNG fuel technology distribution used by the conventional vehicle-based buses in *AT2* and *AT3*.

9.4.3 System boundary for lifecycle cost, energy, and emission analyses

Establishing a well-defined system boundary, i.e., lifecycle stages to be analysed across the individual components of a road transportation system is important to ensure transparency and standardised reporting of the cost, energy and environmental KPI results. The lifecycle and components of roadworks are explained earlier (refer to Section 7.3.2). All of the lifecycle stages are considered from raw material extraction, material production and processing, material and equipment transport, construction, operation and routine maintenance, usage (traffic fleet), rehabilitation and end-of-life recycling. This study uses allocation at point of substitution for calculating the lifecycle impacts across all KPIs in LCCA and LCA to avoid multiple allocations within the system. Additionally, the cost of PT bus fares to users and the operating cost of PT to the relevant organisation are separately calculated and thus the revenue from bus fares to PT operator is not credited to avoid double-counting.

The service life of 30 years is modelled from the base year 2015 to a projected year 2045. After every 5 years, the wearing course is milled up to 4.5 cm depth (ADM, 1997); post-30 year pavement reuse is considered outside the system boundary of this study (refer to Section 7.3.2). Similarly, the impacts associated with vehicle manufacturing and the cost of buying the private vehicles incurred by road users are also not included as they are deemed nominal compared to the energy consumption, pollutant emissions, and costs occurring during the usage stage of the vehicles. Figure 9.3, illustrates the system boundary considered in the current study.

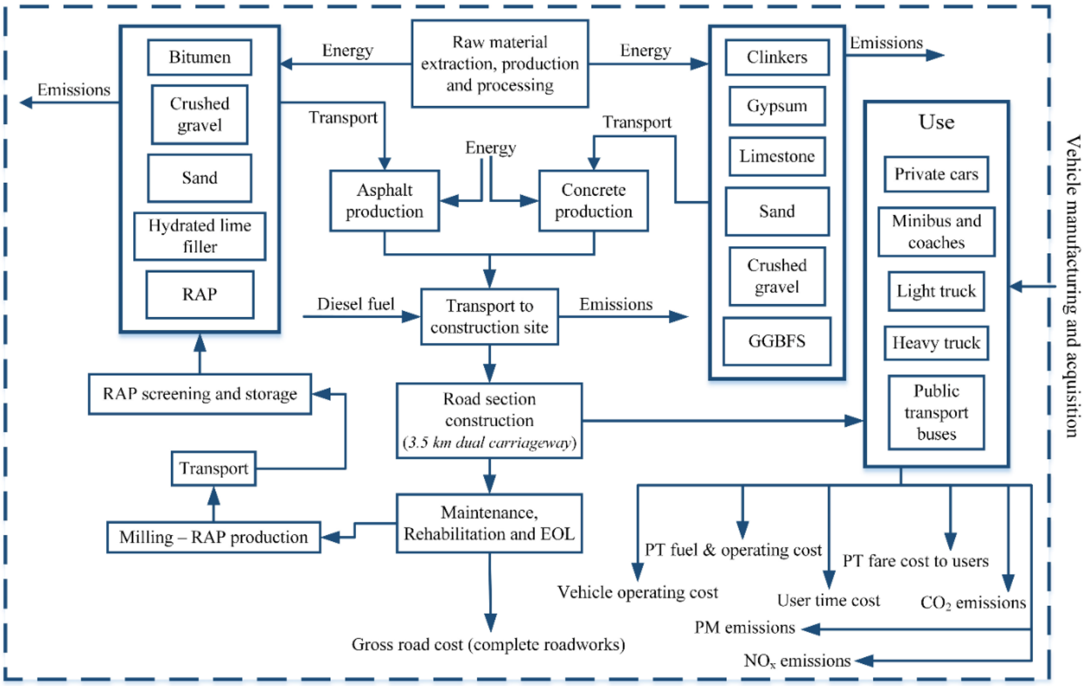


Figure 9.3 System boundary

9.4.4 Lifecycle inventory (LCI) and data sources

An extensive inventory data collection for the LCI development is dependent upon identifying what KPIs are significant during each lifecycle stage of a road transport system as well as properly acknowledging and reporting the local material and resource depletion concerns. Previous studies (Hasan et al., 2019a; Santos et al., 2017) identified the need for local data resources in LCCA and LCA studies. Data needed for performing this study was locally sourced from actual case study contractors, material suppliers, the local municipality (Abu Dhabi City Municipality) and the Abu Dhabi Department of Transport which is responsible for operating the public transport service. Table 9.1 shows the LCI data used across all of the roadworks components for the lifecycle activities.

Table 9.1 LCI data for each component in complete roadworks*

LCI for cost, pollutant emissions, and energy consumption of primary roadworks components

Backfill component	**Water**	**Sand**	**Local silica sand**	**Geotextile fabric (Polypropylene)**	**20MPa concrete**	**Gravel**	**RCW**	**Unit cost (USD)**
Virgin (*AR1*)	454.6 $\times 10^3$litres	19.8 $\times 10^3$ m^3	13.10 $\times 10^3$ m^3	93650 m^2	650 m^3	9100 m^3	-	120.01567
60% RCW (*AR2*)	454.6 $\times 10^3$litres	19.8 $\times 10^3$ m^3	13.10 $\times 10^3$ m^3	93650 m^2	650 m^3	3640 m^3	5460 m^3	68.20652699

Pavement component (*material unit: tonnes*)		**Crushed gravel**	**Sand**	**Virgin bitumen**	**Hydrated lime**	**RCW**	**RAP**	**Unit cost (USD)**
Baseline scenario/*AR1* (virgin HMA & aggregates)	Granular sub-base course	448	-	-	-	-	-	0.03376
	Unbound-base course	12600	-	-	-	-	-	0.03498
	4% bitumen asphalt-base course	6177	2901	384.3	144.1	-	-	2.75602
	4% bitumen asphalt binder course	5719	2686	355.8	133.4	-	-	2.45536
	4.5% bitumen asphalt wearing course	9242	4353	650.9	216.9	-	-	11.42118
Recycled scenario/*AR2* (25% RCW sub-base, 80% RCW u-base, 25% WMA RAP a-base, 15% WMA RAP binder & wearing)	Granular sub-base course	336	-	-	-	112	-	0.028203
	Unbound-base course	10080	-	-	-	2520	-	0.01622
	4% bitumen asphalt-base course	4640	2181	288.2	101.8	-	2402	2.32836
	4% bitumen asphalt binder course	4865	2286	302.4	107.6	-	1334	2.08399
	4.5% bitumen asphalt wearing course	7868	3703	552.5	173.6	-	2170	11.40356

Concrete works component (*material unit: tonnes*)	**Clinker**	**Gypsum**	**Limestone**	**GGBFS**	**Sand**	**Gravel**	**Unit cost (USD)**
AR1 scenario (100% OPC)	416.053	21.897	23.050	-	2090.330	2280.153	4.19946
AR2 scenario (65% GGBFS)	216.809	11.387	-	232.806	2090.330	2280.153	4.16667

* *The lifecycle inventory and data sources are based on Hasan et al. (2020). Cost data is sourced from local agencies and contractors. Only major items in each roadwork component are listed here. Material quantities are only for the construction stage.*

9.4.5 Site clearance, excavation, backfilling and aggregate courses

Initially, dismantled/milled on-site materials are removed and raw materials for new roadworks are produced in plants and transported by road followed by the actual construction process. A mixture of sand and crushed gravel is used as backfill material after the unsuitable soil from the construction site is excavated and removed (Vieira & Pereira, 2015). The ADM (1997) manual also requires natural coarse and fine aggregates to be used as sub-base and unbound-base (u-base) materials spread on the prepared road surface in consecutive < 15cm thick layers to achieve the required total sub-base thickness. Due to the vast amount of construction and demolition waste being globally generated because of construction activities (Hasan, 2015), local RCW is used as partial gravel replacement in the backfill, aggregate sub-base and u-base courses in *AR2* scenario. The RCW proportion is scaled up from the recent Abu Dhabi governmental guidelines of using at least 40% RCW as virgin aggregate replacement in road sub-base course (Department of Transport Abu Dhabi, 2018).

9.4.6 Asphalt production and processing for asphalt concrete courses

Vidal et al. (2013) recommended up to 15% RAP in each asphalt course across the pavement section, while Chesner et al. (2002) recommend 10–30% RAP for wearing course and higher RAP content in underlying pavement courses based upon local conditions. D'Angelo et al. (2008) in one of the earliest HMA vs. WMA studies, observed the CO_2 emission reduction to be approximately 35% while NO_x reduced by 65% in addition to the shorter cooling time of WMA pavements which allowed for a quicker turnover for initiation of traffic operations. The *AR2* scenario used RAP coupled with WMA to meet the KPIs identified by the decision-making stakeholders in Level 3 of the proposed framework (Figure 9.1). Asphalt mix production and emissions data are based on the Marini batch-mixer asphalt plants used in the UAE for both HMA and WMA options and sourced from RAD International Road Construction L.L.C (2013), Vidal et al. (2013) and Hasan et al. (2020).

9.4.7 Material and equipment transportation, construction and M&R

Construction material and equipment transportation to the construction site is also modelled since both operations are an integral part of the pre-construction activities. Actual transport vehicles used for the case study highway project are modelled to calculate energy consumption and pollutant emissions according to the European lifecycle database (ELCD) v3.2. Heavy trucks (<10 tonnes and 10–20 tonnes) with Euro II diesel engines are modelled as transporting vehicles based on the data from ADDoT (2009) and Raeside (2015). The construction stage pollutant emissions and energy consumption burdens are generated from the wide range of construction activities that are performed during roadworks on the construction site, such as equipment operation, material usage, and concrete casting. Since similar operations are conducted in the routine maintenance and periodic major rehabilitation stages, the same data inventory is used. Material quantities, and construction machinery type, operating hours, and fuel consumption are based on the quantity take-off sheets. The tender awarded for the 2009 expansion work on the case study highway section was used to obtain the unit cost which is then adjusted for inflation.

9.4.8 Traffic fleet: Road transport system usage stage

The usage stage of a road transport project is significant for users and government policy-makers as it contributes to the majority of the cost and environmental burdens suffered by both stakeholders. This study uses traffic micro-simulation modelling tool Vissim with the EnViVer emission modeller based on the VERSIT+ tailpipe pollutant emissions database containing more than 12,000 vehicle and fuel types (Quaassdorff et al., 2016). Thus the real-world vehicle volume, speed-time and acceleration-deceleration profiles for the entire traffic fleet under the different traffic scenarios (*AT1 – AT4*) can be modelled at high-resolution. Table 9.2 shows the LCI and data resources used in the current study for calculating the cost, pollutant emissions and energy consumption burdens from the usage stage (traffic fleet) across the established KPIs.

Table 9.2 Lifecycle inventory data for cost, energy consumption and pollutant emissions from the usage stage of the case study road transport system

LCI data for vehicle operation, depreciation, user time and fuel costs			
Cost type	**Per unit cost**	**Basic underlying assumptions for calculations**	**Data sources**
Vehicle cleaning, servicing and maintenance	Car: 0.0157 $/km Minibus: 0.013 $/km HGV/LGV: 0.0158 $/km	Monthly car cleaning, servicing & maintenance cost = $272.294 Showroom private car price (Honda Civic 2019 2.0 EX) = $23,689 Average car age = 5.1 years Average yearly car travel distance = 17400 km	Litman (2017); Staff Report (2015); Tayyeb, Abd El Halim, and Easa (2017); Zaki (2019)
Vehicle depreciation	Car: 0.2066 $/km	Price of 5-year old Honda Civic 2.0 EX model = $8,986	Local market survey
	Minibus: 0.1401 $/km	Adjusted for UAE price conditions	Litman (2017)
	HGV/LGV: 0.066 $/km		
User time cost	2.921 $/km	Hourly income (based on GDP and total population) = $3.894 Work trips = 50%, non-work trips = 50%	ADB (2017); Litman (2019)
PT operating cost	0.0066 $/km	Public transport operating cost is assumed as 5.6 times of total fuel cost based on Mattson (2008)	
PT vehicle acquisition cost	Conventional buses: $130,000/vehicle	Average price of a diesel/CNG bus (based on high-end Scania Interlink, F30B and Higher A30 models)	Local market survey
	Autonomous buses: $350,000/vehicle	Price of a hypothetical bus (based on Navya Autnonomous Shuttle and other price projections)	Ongel et al. (2019); Market surveys
Petrol fuel	0.642 $/litre	Average yearly price for 95-unleaded petrol	ADNOC (2019); John (2018); MOEI (2018)
Diesel fuel	0.704 $/litre	Average yearly fuel price in 2015	
CNG fuel	0.381 $/SCM	Average yearly fuel price in 2015	

LCI data for CO_2 emission factors and fuel consumption by vehicle type, fuel and analysis year*

Vehicle type	Vehicle traffic share in each scenario (%)	Fuel type distribution (%)	Emission standard	Euro I & earlier	Euro II	Euro III	Euro IV	Euro V	Euro VI	Data sources
Small-size cars (Length≤4.5m)	BAU: 45.5%	Petrol: 99.6%	Emission Factors (kg/km)	0.2168	0.2168	0.2120	0.1990	0.1890	0.1774	Romilly (1999), Simons (2016), DIRDC (2019), and ABS (2019)
	Bus: 36.4%		Fuel Consumption (kg/km)	0.0962	0.0727	0.0665	0.3542	0.3377	0.3219	
	BRT: 32.3%	Diesel: 0.3%	Emission Factors (kg/km)	0.1936	0.1936	0.1810	0.1730	0.1660	0.1587	
	AV-BRT: 29.57%		Fuel Consumption (kg/km)	0.0598	0.0598	0.0578	0.0546	0.0528	0.0511	
		CNG/Other: 0.1%	Emission Factors (kg/km)	0.1875	0.1750	0.1660	0.1550	0.1470	0.1373	
			Fuel Consumption (kg/km)	0.0500	0.0500	0.0528	0.0585	0.0554	0.0525	
Regular-size cars (Length: 4.5m - 6m)	BAU: 37.54%	Petrol: 99.6%	Emission Factors (kg/km)	0.4231	0.4120	0.3163	0.3080	0.3120	0.3038	Romilly (1999), Simons (2016), DIRDC (2019), and ABS (2019)
	Bus: 30.032%		Fuel Consumption (kg/km)	0.0876	0.0787	0.0784	0.0743	0.0709	0.0676	
	BRT: 26.719%	Diesel: 0.3%	Emission Factors (kg/km)	0.3118	0.3080	0.2480	0.2450	0.2870	0.2835	
	AV-BRT: 24.40%		Fuel Consumption (kg/km)	0.1231	0.0940	0.0736	0.0688	0.0668	0.0648	
		CNG/Other: 0.1%	Emission Factors (kg/km)	0.2809	0.2664	0.2477	0.2399	0.2427	0.2350	
			Fuel Consumption (kg/km)	0.1071	0.1125	0.0734	0.0697	0.0663	0.0630	
Minibus and coach (6m - 8m)	All scenarios: 4.735%	Diesel: 100%	Emission Factors (kg/km)	0.4410	0.4410	0.3438	0.3398	0.3353	0.3315	Romilly (1999), and DIRDC (2019)
			Fuel Consumption (kg/km)	0.0899	0.0915	0.0899	0.0765	0.0882	0.1016	

Light truck/LGV (8 - 10m)	All scenarios: 6.64%	Petrol: 97.4%	Emission Factors (kg/km)	0.2541	0.2383	0.2383	0.2383	0.2383	0.2383	Zanni and Bristow (2010), DIRDC (2019), and ABS (2019)
			Fuel Consumption (kg/km)	0.1300	0.1220	0.0965	0.0958	0.0906	0.0856	
		Diesel: 2.5%	Emission Factors (kg/km)	0.2461	0.2406	0.2404	0.2404	0.2402	0.2402	
			Fuel Consumption (kg/km)	0.1250	0.1210	0.1040	0.1007	0.1007	0.1007	
		CNG/Other: 0.1%	Emission Factors (kg/km)	0.2217	0.2081	0.2401	0.2354	0.2031	0.1991	
			Fuel Consumption (kg/km)	0.1690	0.1690	0.1521	0.1503	0.1413	0.1328	
Traditional public transport bus	BAU: 0%	Diesel: 71%	Emission Factors (kg/km)	1.2174	1.1840	1.2389	1.1161	1.0890	1.0200	Romilly (1999), Wang et al. (2011), Kuschel, Cooper, and Metcalfe (2017) Nanaki et al. (2017), and ABS (2019)
	Bus: 16.61%		Fuel Consumption (kg/km)	0.2912	0.3036	0.2976	0.2541	0.2348	0.2081	
	BRT: 24.02%	CNG: 29%	Emission Factors (kg/km)	1.1000	1.2500	1.1392	1.2627	1.1278	1.1221	
	AV-BRT: 0%		Fuel Consumption (kg/km)	0.4635	0.2223	0.2055	0.3102	0.3141	0.2047	
Autonomous public transport bus	BAU: 0%	CNG: 100%	Emission Factors (kg/km)	1.1000	1.2500	1.1392	1.2627	1.1278	1.1221	
	Bus: 0%		Fuel Consumption (kg/km)	0.4635	0.2223	0.2055	0.3102	0.3141	0.2047	
	BRT: 0%									
	AV-BRT: 29.06%									
Heavy truck (10m - 12m)	All scenarios: 5.586%	Diesel: 100%	Emission Factors (kg/km)	0.6845	0.6726	0.6726	0.6524	0.6410	0.6218	Zanni and Bristow (2010), and ABS (2019)
			Fuel Consumption (kg/km)	0.2890	0.2890	0.2404	0.2404	0.2355	0.2306	

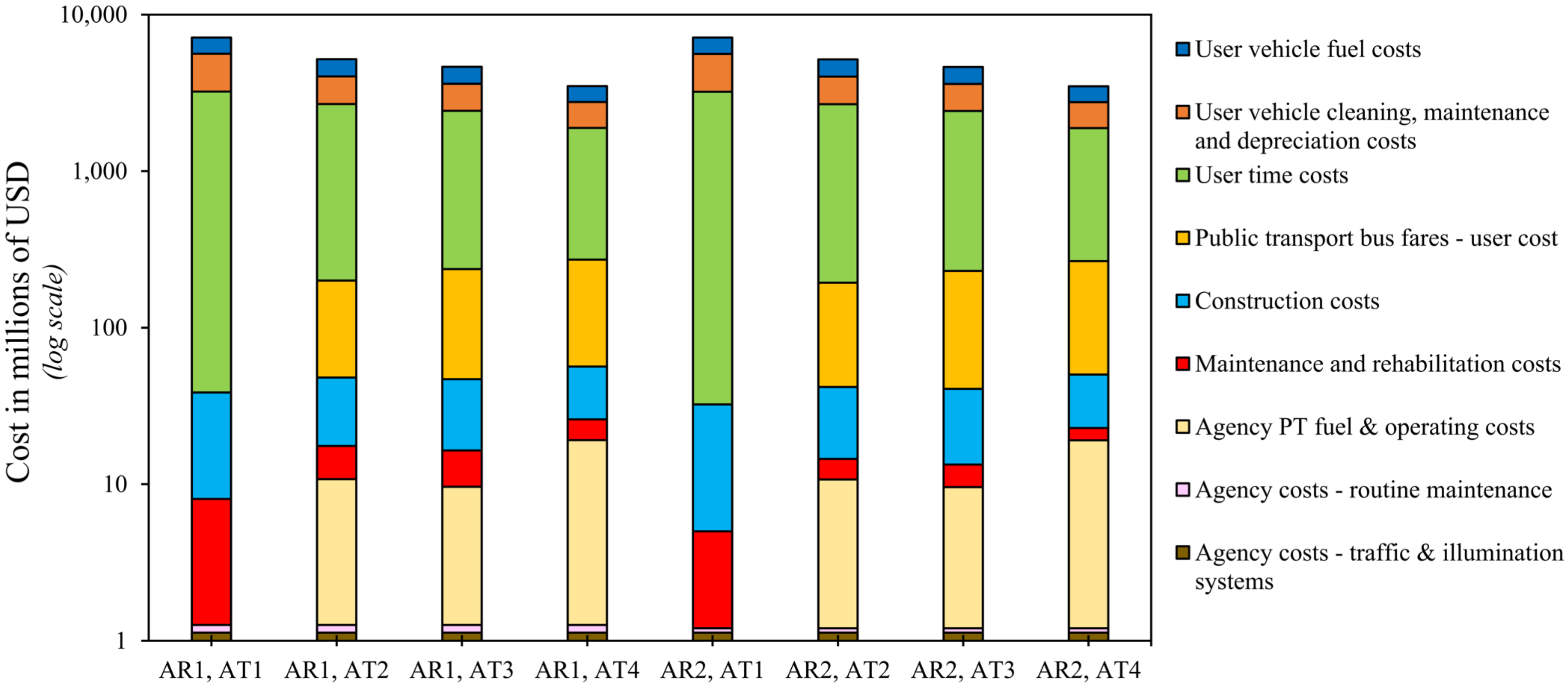
* *The LCI and data sources are based on Hasan et al. (2019c).*

9.5 RESULTS

9.5.1 Performance of alternatives/project proposals across cost KPIs

Figure 9.4 presents the results of the LCCA application on the case study highway transport system for the eight alternatives considered. The cost-related KPIs are based on both agency and user costs as shown in Figure 9.4. Due to the uncertainty in data regarding the decommissioning cost of roadworks in Abu Dhabi, this factor is neglected. All costs are converted to present value in terms of base year 2015 using a discount rate of 5%, as recommended by ADDoT (2009). Results illustrated in Figure 9.4 indicate that overall the costs related to road transport system users are the most significant cost-related KPI across all alternatives. Individually, the road user time costs contributed 44.61%; private vehicle cleaning, maintenance, and depreciation cost 33.64% and fuel cost 21.21% in baseline "*AR1, AT1*" case. As these cost KPIs are largely based on the traffic flow conditions, improving traffic fleet speed-time-density profiles by diverting more users towards public transport resulted in user cost reduction.

Figure 9.4 shows that the initial capital costs for construction of the complete roadworks constituted the largest share of agency-related costs but only generated 0.43% ($27.3 million) to 0.87% ($30.5 million) of the whole lifecycle costs (that ranged from $3,486 million to $7,136 million) in the eight alternatives assessed in this study. After estimating all of the cost KPIs, the baseline case "*AR1, AT1*" is the most expensive alternative (costing $7,136 million in whole lifecycle costs) based on LCCA results, followed by "*AR2, AT1*" and "*AR1, AT2*" cases. The gap between the recycled material-based alternative "*AR2, AT1*" and bus-based alternative "*AR1, AT2*" is mainly due to the savings in user time ($697.68 million less), user vehicle maintenance, cleaning and depreciation costs ($1061.68 million less) and user vehicle fuel costs ($351.12 million less). However, initial construction costs for the recycled material-based "*AR2, AT1*" alternative is $3.164 million less than the alternative "*AR1, AT2*". This cost-saving is decreasingly contributed by the lower cost of RAP, RCW and GGBFS addition in OPC. Additionally, deployment of a PT service incurred extra costs to the operating agency, e.g., $9.51 million in "*AR1, AT2*".



AR1 = Virgin HMA & aggregates (pavement) and 100% OPC (concrete works). → ***Baseline for roadworks***

AR2 = 25% RCW sub-base, 80% RCW u-base, 25% WMA RAP a-base, 15% WMA RAP binder & wearing, and 65% GGBFS (concrete) → ***Recycled scenario for roadworks***

AT1 = No public transport → ***Baseline scenario for traffic fleet***.

AT2 = Conventional public transport. **AT3** = Conventional BRT public transport. **AT4** = Autonomous BRT public transport

Figure 9.4 LCCA results for the performance of each alternative on cost KPIs (log scale)

Thus, the actual cost savings between all alternatives are largely influenced by the operating cost of the road transport system to both stakeholder groups: *government agencies* and *users*. The initial acquisition cost of AV-based public transport buses is 1.7 times ($220,000/vehicle) higher than the conventional buses. However, as noted by Ongel et al. (2019), this difference is expected to drop with the reductions in autonomous vehicle technology, vehicle body and chassis. Nonetheless, it is assumed constant for the purpose of this study to provide confidence over the study results in terms of fluctuating acquisition cost. The share of the PT acquisition cost in the overall vehicle operational cost for AV-based PT service is higher than the PT services utilising conventional buses. However, overall results showed that the increased revenue generated by passenger uptake of the PT is projected to offset the high initial capital investments (Figure 9.5). This finding is contrary to the general misconception that the high acquisition cost of AVs may be a hinderance to its application for mass transit services, as also highlighted by other researchers (Ongel et al., 2019).

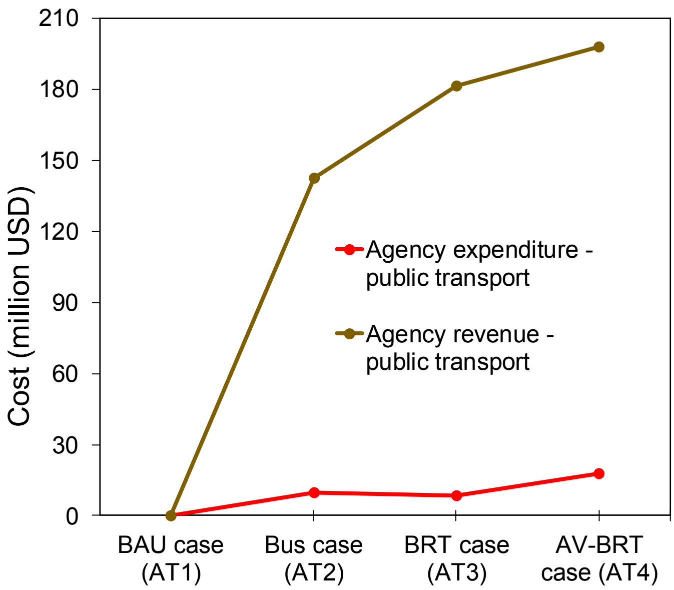


Figure 9.5 Comparison of the projected lifecycle expenditure and revenue of the public transit agency (*reported values are only related to public transport service*)

Similalry, the operating and fuel costs of autonomous bus vehicles incurred by the service-operating government agency (ADDoT) is $9.51 million (53.2%) higher than conventional bus vehicles. However, the overall savings in user time ($578.94 million or 26.37%) and private vehicle cleaning, maintenance, depreciation ($308.96 million or 26.14%) and fuel ($292.41 million or 28.57%) costs overshadow these investments (initial acquisition, fuel and operational costs) in favour of public benefit. Additionally, the difference between the projected revenue ($25.98 million or 12.03%) to the public transport operating agency gained through the bus fares paid by the users is higher than the investment cost difference between conventional vehicle-based BRT and AV-based BRT vehicles, as shown in Figure 9.5 above. These results further confirm the findings from the existing literature on the use of AVs for public transport and on-demand mobility, as covered in Section 3.5 earlier.

After applying LCCA, it can be deduced that the "*AR1, AT1*" is the most cost-ineffective option followed by "*AR2, AT1*" with a difference of only $6.21 million (0.09%) between both alternatives. Conversely, "*AR2, AT4*" followed by "*AR1, AT4*" are the most cost-effective alternatives with a difference of 0.18% between both of these options. All of these lifecycle costing results are illustrated in Figure 9.4 earlier.

9.5.2 Performance of alternatives across KPIs related to pollutant emissions

This study applied the ReCiPe midpoint method using SimaPro 8.5.2 LCA software (PRé Consultants, 2018) for roadworks and micro-simulation modeller (Vissim with EnViVer) for traffic fleet to calculate the environmental burdens of the eight alternatives across the KPIs related to pollutant emissions. Out of the three available perspectives in ReCiPe for environmental impact assessment, named *egalitarian* (E), *hierarchist* (H) and *individualist* (I), the hierarchist perspective is used in the current study based on the general scientific consensus (Vidal et al., 2013). The performance results of the eight alternatives across the expert-suggested pollutant emissions-related KPIs are presented in Table 9.3.

In general, the pollutant emissions results followed the trend exhibited by the LCCA evaluation results for the alternatives considered to achieve sustainability performance optimisation on the case study road transport system. As such, pollutants from the vehicles in the traffic fleet formed the largest share of the whole lifecycle emissions. Nonetheless, recycled material usage also resulted in significant performance improvement across all emissions-related KPIs. Alternative "*AR2, AT1*" has the same traffic fleet composition as the virgin materials-based "*AR1, AT1*" baseline alternative, however, the asphalt concrete road contains recycled materials in pavement courses and concrete works. The highest saving between "*AR1, AT1*" and "*AR2, AT1*" was noted for the ozone formation KPI measured by NO_xeq. emissions with a 15.50%

burden reduction. Next, the PM formation decreased by 13.37%, followed by the 13.28% reduction in GWP and 12.60% drop in the acidification value.

Table 9.3 LCA results for performance evaluation of each alternative on the pollutant emissions KPIs

Alternatives	**Key performance indicator (KPI) category**						
	Climate change (GWP) – *Road* (*ktonne $CO_2eq.$*)	Ozone formation – *Road* (*tonne $NO_xeq.$*)	Particulate matter formation – *Road* (*tonne PMeq.*)	Acidification – *Road* (*tonne $SO_2eq.$*)	Climate change (GWP) – *Vehicles* (*ktonne $CO_2eq.$*)	Ozone formation – *Vehicles* (*tonne $NO_xeq.$*)	Particulate matter formation – *Vehicles* (*tonne PMeq.*)
AR1, AT1	55.72	191.19	28.35	76.77	9520.14	11876.43	571.43
AR1, AT2	55.72	191.19	28.35	76.77	7262.49	8467.02	467.12
AR1, AT3	55.72	191.19	28.35	76.77	6220.55	6539.56	456.44
AR1, AT4	55.72	191.19	28.35	76.77	4307.26	5909.67	430.50
AR2, AT1	48.32	161.56	24.56	67.10	9520.14	11876.43	571.43
AR2, AT2	48.32	161.56	24.56	67.10	7262.49	8467.02	467.12
AR2, AT3	48.32	161.56	24.56	67.10	6220.55	6539.56	456.44
AR2, AT4	48.32	161.56	24.56	67.10	4307.26	5909.67	430.50

The excessively large contribution from vehicles in traffic fleet (Table 9.3) is due to high emissions from a significant percentage of older Euro III vehicles, petrol, and diesel as the primary vehicle fuel source and excessive reliance on passenger traffic on private cars. According to the results in Table 9.3 above, the highest reduction was noted for the alternatives using AV-BRT as per LCA results. In the AV-BRT based "*AR1, AT4*" and "*AR2, AT4*" alternatives, the best sustainability performance improvement was noted for the GWP-related KPI with a 54.76% reduction. The BRT

("*AR1, AT3*" and "*AR2, AT3*") and bus ("*AR1, AT2*" and "*AR2, AT2*") alternatives reduced the GWP by 34.66% and 23.71%, respectively. Reduced reliance on private vehicles for passenger transport, specifically during peak hours, is the key reason for this drop in the tailpipe emissions. Petrol is the prime source of fuel used in the passenger vehicles and contributed approximately 73% to the whole lifecycle GHG emissions from vehicles in the alternatives without any public transport service.

The fluctuations in the time-acceleration-deceleration profile of the traffic fleet due to traffic congestion also emit noteworthy quantities of PM and NO_x emissions. After only implementing the bus service in "*AR1, AT2*" and "*AR2, AT2*" alternatives, the traffic gridlock and frequent acceleration-deceleration situations are expected to improve over the service life. Table 9.3 shows that in the 30-year lifecycle from 2015–2045, NO_x emissions reduce by 28.71%, and PM by 18.25% after implementing bus service. A further shift in passenger mode choice towards public transport was modelled by BRT service introduction in the "*AR1, AT3*" and "*AR2, AT3*" alternatives which resulted in the NO_x KPI to improve by of 44.94% and PM-related KPI to improve by 20.12%. However, similar to the GWP results, AV-BRT based alternatives ("*AR1, AT4*" and "*AR2, AT4*") are the best performer on these two KPIs as measured by LCA results in Table 9.3.

Overall, the sustainability performance of the KPIs related to pollutant emissions was largely dependent upon the reduction in passenger fleet on the case study carriageway. The highway network in the case study Abu Dhabi region is built to a high standard but it is already reaching its operational capacity with frequent traffic congestions and high tailpipe emissions. It is argued here that the results of the current study show the potential of public transport in reducing these adverse impacts. After accounting for both roads and vehicles, "*AR2, AT4*" is the best performing alternative based on LCA results, followed by "*AR1, AT4*" with a difference of only 0.17% between the GWP, 0.48% in NO_x and 0.83% in PM emissions. On the other hand, "*AR1, AT1*" followed by "*AR2, AT1*" were the worst performing alternatives due to recycled material usage, smoother traffic flow, less reliance on private vehicles and changes in fuel technology.

9.5.3 Performance evaluation of alternatives for the energy consumption KPI

Every stage during the life of a road transport system involves energy input/outputs (I/Os). Figure 9.6 presents the lifecycle energy consumption results of the case study road transport system under the considered alternatives. As illustrated in Figure 9.6, the embodied energy from the roadworks component constituted the smallest component of the entire system. In the baseline alternative "*AR1, AT1*", the roadworks contributed 1062.25 TJ (0.34%) of the whole-life energy consumption. After using recycled materials, alternative "*AR2, AT1*" shows that this value further reduced by 193.07 TJ.

The energy consumption reduction is mainly attributed to the lower amount of aggregates and bitumen content required after RAP addition. Shorter transport distance between the material recycling facility and construction site compared to the distance between material extraction quarries (in Fujairah) to the processing plants and construction site (in Abu Dhabi) also affected the fuel energy consumed by the transporting heavy vehicles. Additionally, a large amount of energy is consumed in kiln heating during clinker production which is used for producing OPC and thus GGBFS addition reduced the embodied energy for concrete works. Although this reduction corresponds to around an 18% reduction in embodied energy from roadworks, it only accounts for a 0.06% drop in the lifecycle energy consumption. As users are diverted from private passenger vehicles to bus service in the "*AR1, AT2*" and "*AR2, AT2*" alternatives, energy consumption reduced by approximately 24.53%. Further improvement was noted with BRT service (35.27% less consumption) in "*AR1, AT3*" and "*AR2, AT3*".

These improvements in the energy consumption LCA results are mainly caused by the reduction in passenger car traffic that accounts for more than 80% of the traffic fleet. Reduction in traffic density is expected to provide a smoother vehicle time-acceleration-deceleration profile and better vehicle platooning; which results in improved fuel economy. The AV-BRT service combines these benefits with the high calorific value of CNG fuel. The "*AR1, AT3*" and "*AR2, AT4*" thus further reduce the vehicle energy consumption by around 55.5%. Therefore, the LCA results for both energy consumption and pollutant emissions are similar to "*AR2, AT4*" as the best performing, followed by "*AR1, AT4*".

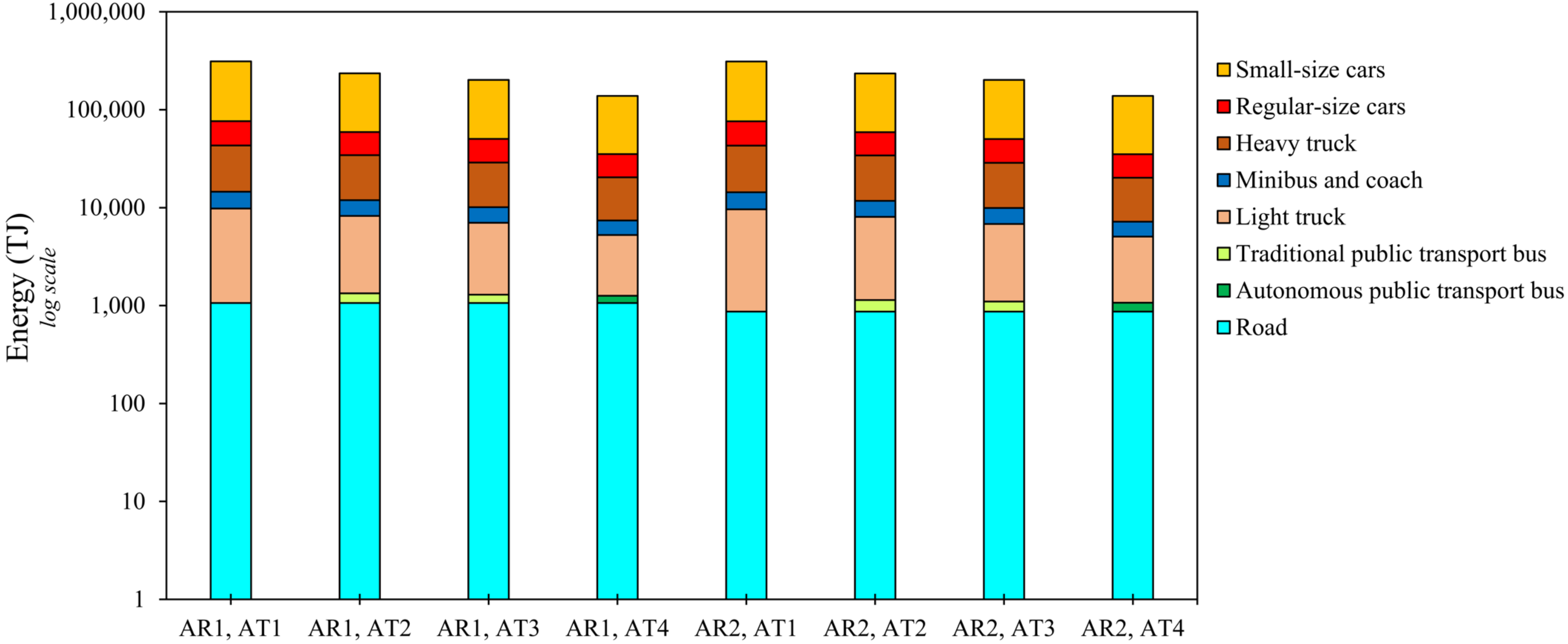


Figure 9.6 Performance results for each alternative on the energy consumption KPI (log scale)

9.5.4 MCDM results: Performance of alternatives across all KPIs

A group of five experts each, from academia, transport planners, Abu Dhabi Municipality (roadworks managing agency) and Abu Dhabi DoT (public transport agency) provided relative weights to each KPI criterion. AHP was used to perform a pairwise comparison on the relative importance of each criterion and the calculated weighting results are provided in Table 9.4. The consistency ratio value is 0.094 and confirms the validity of the AHP-TOPSIS calculations. Complete results of pairwise comparisons by each expert group are provided in Table A.2. In general, the experts assigned a higher weighting to the KPIs related to pollutant emission and energy consumption compared to the cost KPIs due to their respective perceived importance by each expert group. After applying the relative weightings for each KPI, the weighted normalised decision matrix is created using the quantitative values. The relative distances of each alternative from the ideal and negative-ideal solutions are calculated using TOPSIS methodology and the results are presented in Table 9.4.

The results show that after accounting for all of the framework KPIs, alternative "*AR2, AT4*" is the best performing, followed by "*AR1, AT4*". The baseline "*AR1, AT1*" followed by "*AR2, AT1*" is the worst-performing based on the performance across all KPIs. Although there is no disagreement between the rankings of the alternatives by the MCDM (expert priority-based), cost (LCCA-based) and the LCA results, contrary to the MCDM studies reported in literature, these results were somewhat expected and can be explained by the following reasons. Firstly, the system boundary established in this study accounts for all activities occurring within the conventional lifecycle of a road transport system while previous studies either only relied on the subjective qualitative data or ignored significant lifecycle stages. Secondly, both energy and pollutant emissions were determined as critical KPIs by the experts. Thirdly, even though the gross roadworks cost was assigned a higher rating by some of the experts, the higher quantitative value of the user time cost compared to other cost items resulted in the excessive significance of this KPI. Lastly, this may also be due to the selection of particularly usage stage-related KPIs by the experts as well as the similarity between the quantitative and qualitative (AHP weighting) values of the KPIs. Therefore, the results may change depending upon KPI selection and relative weightings of different KPIs. This will be further illustrated in the following sensitivity analysis section which assesses the impact of weighting and expert group type on the final results.

Table 9.4 MCDM framework results for sustainability performance of the alternatives across all KPIs

Key performance indicators	AHP weighting	Alternatives	TOPSIS results			Ranking			
			d_i^*	d_i^-	R_{ci}^*	All KPIs	Cost KPIs	Emissions KPIs	Enegry KPIs
Cost	0.0701								
Emissions	0.6044	AR1, AT1	0.1112	0.0075	0.0628	8	8	8	8
Energy	0.3255								
Gross road cost	0.0038	AR1, AT2	0.0617	0.0502	0.4484	6	6	6	6
PT fuel & operating cost	0.0100								
Bus fare costs – users	0.0100	AR1, AT3	0.0399	0.0727	0.6457	4	4	4	4
User time cost	0.0256								
Vehicle operating cost (maintenance, cleaning, depreciation, and fuel)	0.0208	AR1, AT4	0.0084	0.1111	0.9294	2	2	2	2
Road CO_2 emissions	0.0515								
Road NO_x emissions	0.0156	AR2, AT1	0.1111	0.0084	0.0706	7	7	7	7
Road PM emissions	0.0156								
Road SO_2 emissions	0.0210								
Vehicle CO_2 emissions	0.2842	AR2, AT2	0.0616	0.0503	0.4497	5	5	5	5
Vehicle NO_x emissions	0.1082								
Vehicle PM emissions	0.1082	AR2, AT3	0.0397	0.0729	0.6471	3	3	3	3
Energy consumption – road	0.0362								
Energy consumption – vehicles	0.2893	AR2, AT4	0.0075	0.1112	0.9372	1	1	1	1

9.5.5 Sensitivity analysis

A sensitivity analysis is performed to determine the effect of KPI weights on the results of the MCDM framework proposed in this study. The purpose of introducing *expert-controlled* KPI determination as well as *expert-proposed* relative weightings for the KPIs was to boost decision-maker confidence in the framework and enhance chances of direct applicability to solve real-world issues by establishing a degree of decision-makers' control on the framework results, without compromising the transparency of the decision process. However, this may introduce a degree of uncertainty on the final alternative rankings and the variation in ranking order is thus assessed here. The preference is given to each sustainability KPI (e.g., cost-based, emissions, energy) may be different for different expert groups. For the "academics" and "transport planners", vehicle operating cost was extremely important compared to the gross roadworks cost. Conversely, the "municipality experts" only assigned similar or slightly greater importance to the vehicle operating cost. For the "public transport operating agency experts", public transport fuel and operating costs were more or equally important as the user time cost. On the other hand, user time cost was given much higher priority by the rest of the expert groups.

For the "academics", energy consumption was much more important than cost, whereas other expert groups only assigned it a nominal priority. PM emissions from vehicles had a significantly higher priority for academics and transport operating agency compared to the GHG emission from roadworks, while municipality experts only assigned a slightly higher weighting to the vehicle PM emissions. Figure 9.7(a) illustrates the AHP-TOPSIS scores and alternatives' rankings as per the perspectives of each expert group. In general, the rankings of the considered eight alternatives for the case study transport system remained the same across all expert groups despite the variations in the relative closeness scores.

The alternative rankings are contributed by both quantitative values and qualitative importance of the KPIs. Unlike the deterministic quantitative values obtained by numerical models, the relative weights assigned to each KPI by the experts are perceived as changeable and adaptable which may influence the ranking of each alternative. Another sensitivity analysis methodology is to change the weighting of one criterion and analyse the variation in the ranking order of all alternatives (Gumus, 2009). As *cost* was generally given the lowest priority by all experts, its relative weight is gradually increased and the change in relative weights of *pollutant emissions* and *energy consumption* is determined following the approach proposed by Alinezhad and Amini (2011). The results are presented in Figure 9.7(b). In general, the sensitivity analysis shows that despite the expert controls, the MCDM framework results exhibit a strong degree of robustness.

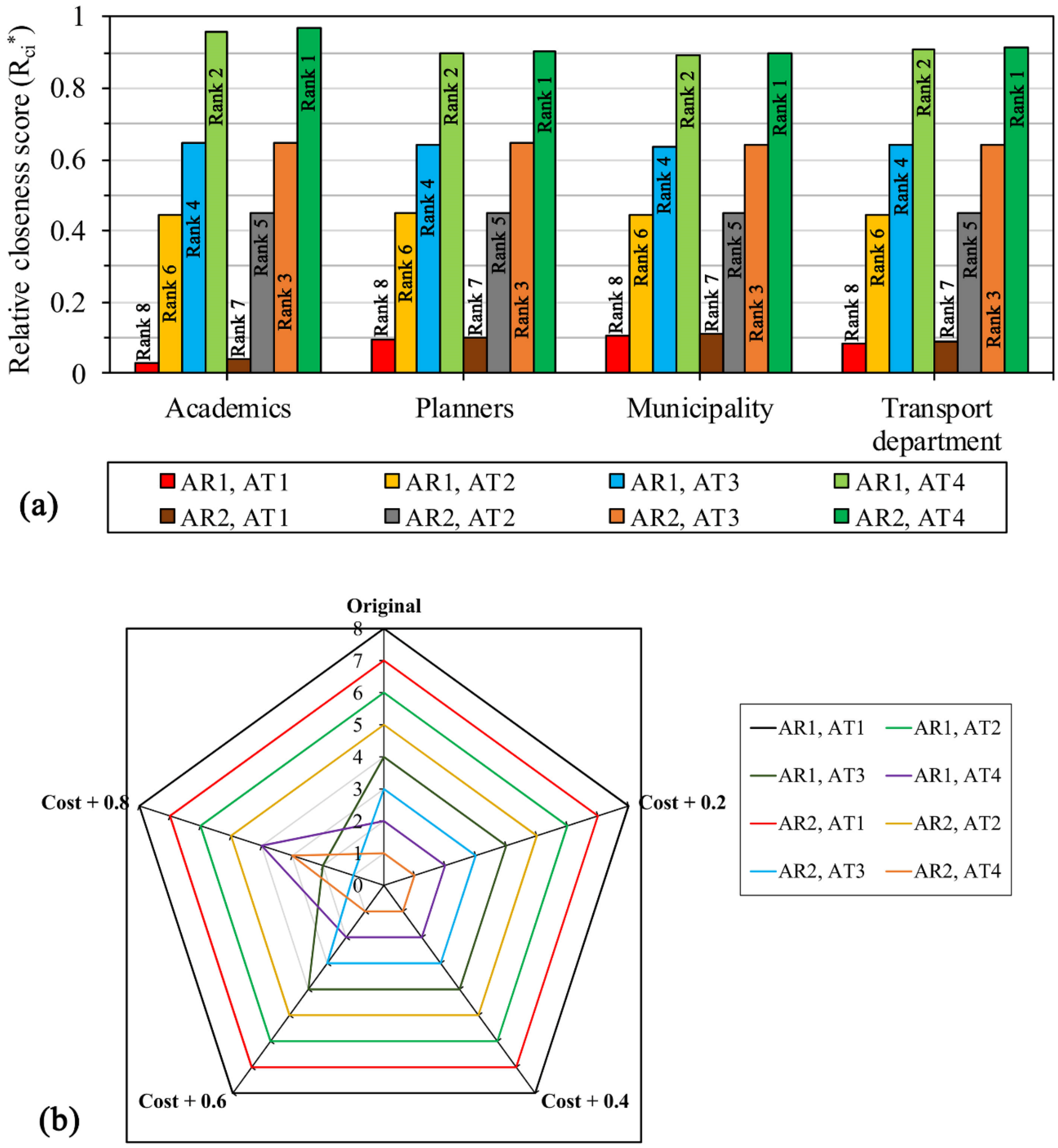


Figure 9.7 Sensitivity analysis results (a) based on expert groups, (b) varying lifecycle cost weighting

The alternative rankings display no change from the "original result" until the relative weight of *cost* is increased by "0.8". This implies that the alternative "*AR2, AT4*" using autonomous BRT service and recycled materials is the best performing option in the majority of sensitivity analysis results, whereas the baseline alternative "*AR1, AT1*" is the worst performing choice. These results show that the relative impact of numerical results from the earlier levels of the proposed framework is largely carried forward to the final results where a lower KPI value of an alternative is interpreted towards lower performance. On the other hand, in the rare cases where it is necessary to assign significantly higher importance to any particular KPI due to expert or stakeholder preferences, it may also be achieved by assigning high relative weights.

9.6 CONCLUSION

This study presents a multi-criteria decision-making framework to offer a new methodology for sustainability performance optimisation of road transport systems and fill in the gaps identified by IPCC and other international organisations on climate change, energy conservation, net-zero emissions mobility and the need of future-based autonomous transport. Sustainability triple-bottom-line cost, environmental (pollutant emissions and energy consumption) and social factors are used in this framework to estimate the road transport system performance. Stakeholders (users and government agencies) examine the existing system or new proposals in the first three levels to identify the drawbacks of the current system and "hotspots" for system improvement, by establishing clear and quantifiable KPIs. Next, traffic (microsimulation) models are constructed to empirically determine the changes in traffic flow patterns using high-resolution time-acceleration-deceleration profiles of the entire traffic fleet. Afterward, data inventories are utilised to calculate the performance of different alternatives across the established social, cost and environmental KPIs. Material quantity sheets for roadworks and microsimulation modelling outputs for vehicles/traffic fleet are used as input. This way, the framework developed in this work integrates both LCCA and LCA methodologies across all lifecycle stages.

The quantitative output data of the different alternatives are then compiled in the form of a comparison matrix. Furthermore, the priorities of different stakeholder groups, particularly, the transport system operators and relevant government agencies are also reflected. The last level of the framework developed here combines quantitative data from the comparison matrix and qualitative expert-proposed weighting for each KPI using AHP-TOPSIS methodology. The sustainability performance of each alternative is then ranked to identify the best performing alternative. A case study five-lane dual carriageway road transport system from the often congested and high traffic density Abu Dhabi highway network is used to illustrate the application of proposed framework. Stakeholder engagement results showed that users expressed a need for public transport in form of a frequent service optimised to handle peak hour traffic.

Local decision-makers and planners proposed KPIs and eight alternatives constituting different combinations of virgin and recycled materials and public bus transport service options were proposed. Relative weights of each KPI were also obtained by four expert groups: academics, transport planners, transport operating agency and municipality stakeholders. LCCA, LCA and AHP-TOPSIS results showed a general agreement where baseline "*AR1, AT1*" (virgin material and no public transport service) and "*AR2, AT4*" (recycled material and autonomous BRT service) were the worst and best alternatives, respectively. Alternative "*AR2, AT4*" is projected to save \$3.65 billion in lifecycle costs and 173.353×10^3 TJ in energy consumption. It is also expected to reduce the lifecycle GHG emissions by 5220.28 ktonnes CO_2eq., roadworks material-acidification by 9.67 tonnes SO_2eq., lifecycle PM emissions by 144.72 tonnes and lifecycle NO_x emissions by 5996.38 tonnes. Additionally, sensitivity analysis also showed the robustness of the framework results. Although the performance (relative closeness to ideal solution) scores of the alternatives varied between different expert groups, no change was observed in the ranking order.

As cost was given the lowest weightage by all expert groups, its relative weight was gradually increased to 0.8 to determine sensitivity to the relative weights. No change was noted in the majority of the cases. This shows a high degree of certainty in the framework outputs, where combining quantitative data with qualitative information produced deterministic and stable results. On the other hand, experts still have some degree of control over the best performing alternative. Thus, the framework developed by this work is not only capable of simultaneously optimising the cost-effectiveness, energy conservation, and emissions reduction potential of the road transport system, but also able to reflect the decision-maker priorities in the final outcome, while maintaining decision-maker confidence and a high degree of transparency in the decision-making process.

9.7 References

ABS, (2019). Catalog #9208.0: Survey of motor vehicle use. Retrieved (4/11/2018) from www.abs.gov.au/ausstats/abs@.nsf/mf/9208.0. Australian Bureau of Statistics.

ADB, (2017). *Peshawar sustainable bus rapid transit corridor project: Report and recommendation of the president*. Retrieved (4/11/2018) from www.adb.org/projects/documents/pak-48289-002-rrp. Manila, Philippines: Asian Development Bank.

ADM, Abu Dhabi Municipality. (1997). Standard specifications for road and bridge construction. Abu Dhabi, UAE: Abu Dhabi Municipality.

ADNOC. (2019). ADNOC fuel price distribution. Retrieved (4/11/2018) from www.adnocdistribution.ae/en.

Alessandrini, A., Campagna, A., Site, P. D., Filippi, F., & Persia, L. (2015). Automated vehicles and the rethinking of mobility and cities. *Transportation Research Procedia, 5*, 145-160. DOI: 10.1016/j.trpro.2015.01.002.

Alinezhad, A., & Amini, A. (2011). Sensitivity analysis of TOPSIS technique: The results of change in the weight of one attribute on the final ranking of alternatives. *Journal of Optimization in Industrial Engineering* (7), 23-28.

Alzard, M. H., Maraqa, M. A., Chowdhury, R., Khan, Q., Albuquerque, F. D. B., Mauga, T. I., & Aljunadi, K. N. (2019). Estimation of greenhouse gas emissions produced by road projects in Abu Dhabi, United Arab Emirates. *Sustainability, 11*(8), 2367. DOI: 10.3390/su11082367.

Andersen, O., Jensen, C. S., Torp, K., & Yang, B. (2013). *EcoTour: Reducing the environmental footprint of vehicles using eco-routes.* Paper presented at the 14th International Conference on Mobile Data Management (MDM). Milan, Italy: IEEE.

Awasthi, A., Chauhan, S. S., & Omrani, H. (2011). Application of fuzzy TOPSIS in evaluating sustainable transportation systems. *Expert Systems with Applications, 38*(10), 12270-12280. DOI: 10.1016/j.eswa.2011.04.005.

Awasthi, A., & Omrani, H. (2009). A hybrid approach based on AHP and belief theory for evaluating sustainable transportation solutions. *International Journal of Global Environmental Issues, 9*(3), 212-226.

Babashamsi, P., Md Yusoff, N. I., Ceylan, H., Md Nor, N. G., & Salarzadeh Jenatabadi, H. (2016). Evaluation of pavement life cycle cost analysis: Review and analysis. *International Journal of Pavement Research and Technology, 9*(4), 241-254. DOI: 10.1016/j.ijprt.2016.08.004.

Balaguera, A., Carvajal, G. I., Albertí, J., & Fullana-i-Palmer, P. (2018). Life cycle assessment of road construction alternative materials: A literature review. *Resources, Conservation and Recycling, 132*, 37-48. DOI: 10.1016/j.resconrec.2018.01.003.

Beinat, E. (2001). Multi-criteria analysis for environmental management. *Journal of Multi-Criteria Decision Analysis, 10*(2), 51-51.

Belgiawan, P. F., Ilahi, A., & Axhausen, K. W. (2017). Influence of pricing on mode choice decision in Jakarta: A random regret minimization model. IVT ETH Zurich.

Biswas, W. K. (2014). Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia. *The International Journal of Life Cycle Assessment, 19*(4), 732-744.

Butt, A. A., Toller, S., & Birgisson, B. (2015). Life cycle assessment for the green procurement of roads: a way forward. *Journal of Cleaner Production, 90*, 163-170. DOI: 10.1016/j.jclepro.2014.11.068.

Buzási, A., & Csete, M. (2015). Sustainability indicators in assessing urban transport systems. *Periodica Polytechnica Transportation Engineering, 43*(3), 138-145. DOI: 10.3311/PPtr.7825.

Caffieri, J. J., Love, P. E. D., Whyte, A., & Ahiaga-Dagbui, D. D. (2017). Planning for production in construction: Controlling costs in major capital projects. *Production Planning & Control, 29*(1), 41-50. DOI: 10.1080/09537287.2017.1376258.

Chen, T. D., & Kockelman, K. M. (2016). Carsharing's life-cycle impacts on energy use and greenhouse gas emissions. *Transportation Research Part D: Transport and Environment, 47*, 276-284. DOI: 10.1016/j.trd.2016.05.012.

Chesner, W. H., Collins, R. J., MacKay, M. H., & Emery, J. (2002). *User guidelines for waste and by-product materials in pavement construction*.

Chikezie, C. U., Olowosulu, A. T., & Olugbenga, S. A. (2013). Multiobjective optimization for pavement maintenance and rehabilitation programming using genetic algorithms. *Archives of Applied Science Research, 5*(4), 76-83. Retrieved (4/11/2018) from www.scholarsresearchlibrary.com/aasr-vol5-iss4/AASR-2013-5-4-76-83.pdf.

Chinery, L. E. (2010). *Modeling transportation in Abu Dhabi: A 25-year projection of emissions under alternative scenarios of the passenger vehicle fleet.* (MSc Thesis). University of North Carolina at Chapel Hill, Chapel Hill, NC. Available from UNC-Chapel Hill Carolina Digital Repository database.

Cottrill, C. D., & Derrible, S. (2015). Leveraging big data for the development of transport sustainability indicators. *Journal of Urban Technology, 22*(1), 45-64. DOI: 10.1080/10630732.2014.942094.

Currie, G., & De Gruyter, C. (2018). Exploring links between the sustainability performance of urban public transport and land use in international cities. *Journal of Transport and Land Use, 11*(1), 325–342. DOI: 10.5198/jtlu.2018.957.

D'Angelo, J., Harm, E., Bartoszek, J., Baumgardner, G., Corrigan, M., Cowsert, J., Newcomb, D. (2008). *Warm-mix asphalt: European practice*.

Dempster, A. P. (1968). A generalization of Bayesian inference. *Journal of the Royal Statistical Society. Series B (Methodological)*, 205-247.

Department of Transport Abu Dhabi. (2018). *Standard construction specifications part 1*. Abu Dhabi, UAE: Department of Transport Abu Dhabi.

DIRDC. (2019). Australian green vehicle guide. Retrieved (4/11/2018) from www.greenvehicleguide.gov.au.

Dong, J., Chi, Y., Zou, D., Fu, C., Huang, Q., & Ni, M. (2014). Energy–environment–economy assessment of waste management systems from a life cycle perspective: Model development and case study. *Applied Energy, 114*, 400-408. DOI: 10.1016/j.apenergy.2013.09.037.

ADDoT. (2009). *Surface transport master plan – A vision for connecting Abu Dhabi*. Abu Dhabi, United Arab Emirates.

Eddie, W. L. C., Heng, L., & Ling, Y. (2005). The analytic network process (ANP) approach to location selection: A shopping mall illustration. *Construction Innovation, 5*(2), 83-97. DOI: 10.1108/14714170510815195.

Environment Agency - Abu Dhabi. (2019). *Greenhouse gas inventory & projections for Abu Dhabi Emirate - Executive summary of 3rd cycle*. Retrieved (4/11/2018) from www.ead.ae/Publications/Greenhouse%20Gas%20Inventory%20For%20Abu%20Dhabi%20Emirate%202019/EAD5726_GREENHOUSE%20GAS%20INVENTORY%20REPORT_ENGLISH_FOR%20WEB.pdf. Abu Dhabi, UAE.

EPA. (2016). *Inventory of US greenhouse gas emissions and sinks: 1990-2014*. Washington, DC.

Erkul, M., Yitmen, I., & Çelik, T. (2016). Stakeholder engagement in mega transport infrastructure projects. *Procedia Engineering, 161*, 704-710. DOI: 10.1016/j.proeng.2016.08.745.

Galatioto, F., Huang, Y., Parry, T., Bird, R., & Bell, M. (2015). Traffic modelling in system boundary expansion of road pavement life cycle assessment. *Transportation Research Part D: Transport and Environment, 36*, 65-75. DOI: 10.1016/j.trd.2015.02.007.

Galí, J. (2015). *Monetary policy, inflation, and the business cycle: An introduction to the New Keynesian Framework and its applications* (2nd Ed.). New Jersey, US: Princeton University Press.

Gáspár, L., Castro-Fresno, D., Jato-Espino, D., Indacoechea-Vega, I., Paeglite, I., Pascual-Muñoz, P., Diez, J. (2016). Complex optimization of heavy duty asphalt pavement types in DURABROADS project. *Transportation Research Procedia, 14*, 3519-3526. DOI: 10.1016/j.trpro.2016.05.320.

Giani, M. I., Dotelli, G., Brandini, N., & Zampori, L. (2015). Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling. *Resources, Conservation and Recycling, 104*, 224-238. DOI: 10.1016/j.resconrec.2015.08.006.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A., Struijs, J., & Zelm, R. (2009). ReCiPe 2008, PRé consultants. *University of Leiden, Radboud University, RIVM, Nijmegen. Den Haag, the Netherlands: VROM (Dutch Ministry of Housing Spatial Planning and Environment)*.

Gumus, A. T. (2009). Evaluation of hazardous waste transportation firms by using a two-step fuzzy-AHP and TOPSIS methodology. *Expert Systems with Applications, 36*(2, Part 2), 4067-4074. DOI: 10.1016/j.eswa.2008.03.013.

Hamurcu, M., & Eren, T. (2018). An application of multicriteria decision-making for the evaluation of alternative monorail routes. *Mathematics, 7*(1). DOI: 10.3390/math7010016.

Hasan, U. (2015). *Experimental study on bentonite stabilisation using construction waste and slag.* (M.Phil. Thesis). Curtin University, Perth, Western Australia, Australia.

Hasan, U., Whyte, A., & Al Jassmi, H. (2018a). *Framework for delivering an AV-based mass mobility solution: Integrating government-consumer actors and life-cycle analysis of transportation systems.* Paper presented at the 46th European Transport Conference, Dublin, Ireland.

Hasan, U., Whyte, A., & Al Jassmi, H. (2018b). Life-cycle asset management in residential developments building on transport system critical attributes via a data-mining algorithm. *Buildings, 9*(1). DOI: 10.3390/buildings9010001.

Hasan, U., Whyte, A., & Al Jassmi, H. (2019). Critical review and methodological issues in integrated life-cycle analysis on road networks. *Journal of Cleaner Production, 206*, 541-558. DOI: 10.1016/j.jclepro.2018.09.148.

Hasan, U., Whyte, A., & Al Jassmi, H. (2020). Life-cycle assessment of roadworks in United Arab Emirates: Recycled construction waste, reclaimed asphalt pavement, warm-mix asphalt and blast furnace slag use against traditional approach. *Journal of Cleaner Prodcution, 257*, 120531. DOI: 10.1016/j.jclepro.2020.120531.

Hasan, U., Whyte, A., & Al Jassmi, H. (2019c). Microsimulation projection of current and future energy consumption and exhaust emissions from urban highway vehicles: Scenario analyses of reduction measures in Abu Dhabi. *Manuscript submitted*.

Hoque, N., Biswas, W., Mazhar, I., & Howard, I. (2019). LCSA framework for assessing sustainability of alternative fuels for transport sector. *Chemical Engineering Transactions, 72*, 103-108. DOI: 10.3303/CET1972018.

Hoque, N., Mazhar, I., & Biswas, W. (2018). Application of life cycle assessment for sustainability evaluation of transportation fuels. In *Reference Module in Materials Science and Materials Engineering* (pp. 11). Amsterdam, the Netherland: Elsevier.

Hwang, C.-L., & Yoon, K. (2012). *Multiple attribute decision making: Methods and applications a state-of-the-art survey* (Vol. 186). Berlin Heidelberg: Springer Science & Business Media.

IPCC. (2008). *Climate change 2007: The physical science basis. Contribution of working group I, II and III to the Fourth Assessment Report of the IPCC* (Core Writing Team, R. K. Pachauri, & A. Reisinger Eds.). Geneva, Switzerland: Intergovernmental Panel on Climate Change.

IRF. (2010). *World road statistics 2010*. Geneva, Switzerland.

ITF, I. T. F. (2010). *Reducing transport greenhouse gas emissions: Trends and data 2010*. Retrieved (4/11/2018) from www.itf-oecd.org/sites/default/files/docs/10ghgtrends.pdf. Paris, France.

John, I. (2018). UAE lowers petrol, diesel prices for July. *Khaleej Times*. Retrieved (4/11/2018) from www.khaleejtimes.com/business/energy/uae-lowers-petrol-diesel-prices-for-july.

Kazim, A. (2003). Introduction of PEM fuel-cell vehicles in the transportation sector of the United Arab Emirates. *Applied Energy, 74*(1), 125-133. DOI: 10.1016/S0306-2619(02)00138-1.

Kazmi, A. (2014, 1st June). Temperature nears 50 degrees in UAE. *Gulf News*.

Kuschel, G., Cooper, A., & Metcalfe, J. (2017). *Evaluating bus emissions: What colour, how big and how much is that elephant in the window?* Paper presented at the 39th Australasian Transport Research Forum (ATRF), Auckland, New Zealand.

Lee, E.-B., Thomas, D., & Alleman, D. (2018). Incorporating road user costs into integrated life-cycle cost analyses for infrastructure sustainability: A case study on Sr-91 corridor improvement project (Ca). *Sustainability, 10*(1), 179 DOI: 10.3390/su10010179.

Leyden, K. M., Slevin, A., Grey, T., Hynes, M., Frisbaek, F., & Silke, R. (2017). Public and stakeholder engagement and the built environment: A review. *Current Environmental Health Reports, 4*(3), 267-277.

Litman, T. (2019). *Evaluating public transit benefits and costs*. Victoria, BC.

Litman, T. A. (2017). Transportation cost and benefit analysis techniques, estimates and implications. Victoria, BC, Canada: Victoria Transport Policy Institute.

Litman, T. A. (2019). Evaluating public transit benefits and costs. Victoria, BC, Canada: Victoria Transport Policy Institute.

Mattson, J. W. (2008). *Effects of rising gas prices on bus ridership for small urban and rural transit systems*. Fargo, North Dakota: North Dakota State University.

Mazumder, M., Sriraman, V., Kim, H. H., & Lee, S.-J. (2016). Quantifying the environmental burdens of the hot mix asphalt (HMA) pavements and the production of warm mix asphalt (WMA). *International Journal of Pavement Research and Technology, 9*(3), 190-201. DOI: 10.1016/j.ijprt.2016.06.001.

Miranda, H. d. F., & Rodrigues da Silva, A. N. (2012). Benchmarking sustainable urban mobility: The case of Curitiba, Brazil. *Transport Policy, 21*, 141-151. DOI: 10.1016/j.tranpol.2012.03.009.

MOEI. (2018). Gasoline and diesel domestic prices 2018. Retrieved (4/11/2018) from www.moei.gov.ae/en/open-data.aspx#page=1. UAE Ministry of Energy and Industry.

Munoz, J. C., de Dios Ortúzar, J., & Gschwender, A. (2009). Transantiago: The fall and rise of a radical public transport intervention. In G. Sammer & W. Saleh (Eds.), *Travel Demand Management and Road User Pricing: Success, Failure and Feasibility* (pp. 268). Surrey, England: Ashgate Publishing Limited.

Nanaki, E. A., Koroneos, C. J., Roset, J., Susca, T., Christensen, T. H., De Gregorio Hurtado, S., López-Jiménez, P. A. (2017). Environmental assessment of 9 European public bus transportation systems. *Sustainable Cities and Society, 28*, 42-52. DOI: 10.1016/j.scs.2016.08.025.

O'Faircheallaigh, C. (2010). Public participation and environmental impact assessment: Purposes, implications, and lessons for public policy making. *Environmental Impact Assessment Review, 30*(1), 19-27. DOI: 10.1016/j.eiar.2009.05.001.

Ongel, A., Loewer, E., Roemer, F., Sethuraman, G., Chang, F., & Lienkamp, M. (2019). Economic assessment of autonomous electric microtransit vehicles. *Sustainability, 11*(3), 648. DOI: 10.3390/su11030648.

Peng, B., Du, H., Ma, S., Fan, Y., & Broadstock, D. C. (2015). Urban passenger transport energy saving and emission reduction potential: A case study for Tianjin, China. *Energy Conversion and Management, 102*, 4-16. DOI: 10.1016/j.enconman.2015.01.017.

Praticò, F. G. (2017). Metrics for management of asphalt plant sustainability. *Journal of Construction Engineering and Management, 143*(4), 04016116. DOI: 10.1061/(ASCE)CO.1943-7862.0001253.

PRé Consultants. (2018). SimaPro database manual – Methods library. San Francisco, California: PRé Consultants.

Pryn, M. R., Cornet, Y., & Salling, K. B. (2015). Applying sustainability theory to transport infrastructure assessment using a multiplicative AHP decision support model. *Transport, 30*(3), 330-341. DOI: 10.3846/16484142.2015.1081281.

Quaassdorff, C., Borge, R., Pérez, J., Lumbreras, J., de la Paz, D., & de Andrés, J. M. (2016). Microscale traffic simulation and emission estimation in a heavily trafficked roundabout in Madrid (Spain). *Science of the Total Environment, 566-567*, 416-427. DOI: 10.1016/j.scitotenv.2016.05.051.

Rabello Quadros, S. G., & Nassi, C. D. (2015). An evaluation on the criteria to prioritize transportation infrastructure investments in Brazil. *Transport Policy, 40*, 8-16. DOI: 10.1016/j.tranpol.2015.02.002.

RAD International Road Construction L.L.C. (2013). Asphalt production. Retrieved (4/11/2018) from rad.ae/site/index.php/en/asphalt-factory/asphaltproduction.

Raeside, J. (2015). Middle East emissions legislation. Retrieved (4/11/2018) from www.integer-research.com/industry-insight/emissions-legislation/middle-east

Rahman, S. (2013). UAE's per capita energy consumption among the highest. *Gulf News*. Retrieved (4/11/2018) from www.gulfnews.com/business/uaes-per-capita-energy-consumption-among-the-highest-1.1171313.

Redman, L., Friman, M., Gärling, T., & Hartig, T. (2013). Quality attributes of public transport that attract car users: A research review. *Transport Policy, 25*(Supplement C), 119-127. DOI: 10.1016/j.tranpol.2012.11.005.

Rode, P., Floater, G., Thomopoulos, N., Docherty, J., Schwinger, P., Mahendra, A., & Fang, W. (2017). Accessibility in cities: Transport and urban form. In G. Meyer & S. Shaheen (Eds.), *Disrupting Mobility: Impacts of Sharing Economy and Innovative Transportation on Cities* (pp. 239-273). Cham: Springer International Publishing.

Romilly, P. (1999). Substitution of bus for car travel in urban Britain: An economic evaluation of bus and car exhaust emission and other costs. *Transportation*

Research Part D: Transport and Environment, 4(2), 109-125. DOI: 10.1016/S1361-9209(98)00028-5.

Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research, 48*(1), 9-26.

Santos, J., Thyagarajan, S., Keijzer, E., Flores, R. F., & Flintsch, G. (2017). Comparison of life-cycle assessment tools for road pavement infrastructure. *Transportation Research Record: Journal of the Transportation Research Board, 2646*, 28-38. DOI: 10.3141/2646-04.

SCAD. (2014). *Statistical yearbook of Abu Dhabi*. Retrieved (4/11/2018) from www.scad.ae/Release%20Documents/SYB-2014_V1.1_EN.pdf. Abu Dhabi, United Arab Emirates: Statistics Centre - Abu Dhabi (SCAD).

Sgouridis, S., Abdullah, A., Griffiths, S., Saygin, D., Wagner, N., Gielen, D., McQueen, D. (2016). Re-mapping the UAE's energy transition: An economy-wide assessment of renewable energy options and their policy implications. *Renewable and Sustainable Energy Reviews, 55*, 1166-1180. DOI: 10.1016/j.rser.2015.05.039.

Sgouridis, S., Helmers, E., & Al Hadhrami, M. (2018). Light-duty electric vehicles in the gulf? Techno-economic assessment and policy implications. *International Journal of Sustainable Transportation, 12*(2), 92-106. DOI: 10.1080/15568318.2017.1332256.

Shladover, S., Su, D., & Lu, X.-Y. (2012). Impacts of cooperative adaptive cruise control on freeway traffic flow. *Transportation Research Record: Journal of the Transportation Research Board, 2324*, 63-70. DOI: 10.3141/2324-08.

Simons, A. (2016). Road transport: New life cycle inventories for fossil-fuelled passenger cars and non-exhaust emissions in Ecoinvent v3. *The International Journal of Life Cycle Assessment, 21*(9), 1299-1313. DOI: 10.1007/s11367-013-0642-9.

Smokers, R., & Rensma, K. (2006). *Geographically specific transport emission inventories: Review of feasibility for road and rail transport*. Delft, Netherlands.

Staff Report. (2015). 5.2 years: Average age of cars in UAE. *Emirates 24/7*. Retrieved (4/11/2018) from www.emirates247.com/news/emirates/5-2-years-average-age-of-cars-in-uae-2015-08-15-1.600360.

Stephan, A., & Stephan, L. (2016). Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. *Applied Energy, 161*, 445-464. DOI: 10.1016/j.apenergy.2015.10.023.

Tayyeb, H., Abd El Halim, A. E. H. O., & Easa, S. (2017). A life cycle cost analysis model of goods movement for the Gulf Cooperation Council region *International Journal of Service Science, Management and Engineering, 4*(2), 6-16. Retrieved (4/11/2018) from www.openscienceonline.com/author/download?paperId=3646&stateId=8000&fileType=3.

Treyer, K., & Bauer, C. (2016). The environmental footprint of UAE′s electricity sector: Combining life cycle assessment and scenario modeling. *Renewable* *and Sustainable Energy Reviews, 55*, 1234-1247. DOI: 10.1016/j.rser.2015.04.016.

Turk, J., Mauko Pranjić, A., Mladenovič, A., Cotič, Z., & Jurjavčič, P. (2016). Environmental comparison of two alternative road pavement rehabilitation techniques: cold-in-place-recycling versus traditional reconstruction. *Journal of Cleaner Production, 121*, 45-55. DOI: 10.1016/j.jclepro.2016.02.040.

Upham, P., Virkamäki, V., Kivimaa, P., Hildén, M., & Wadud, Z. (2015). Socio-technical transition governance and public opinion: The case of passenger transport in Finland. *Journal of Transport Geography, 46*, 210-219. DOI: 10.1016/j.jtrangeo.2015.06.024.

Ventura, A., Monéron, P., & Jullien, A. (2008). Environmental impact of a binding course pavement section, with asphalt recycled at varying rates. *Road Materials and Pavement Design, 9*(sup1), 319-338. DOI: 10.1080/14680629.2008.9690172.

Vidal, R., Moliner, E., Martínez, G., & Rubio, M. C. (2013). Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. *Resources, Conservation and Recycling, 74*, 101-114. DOI: 10.1016/j.resconrec.2013.02.018.

Vieira, C. S., & Pereira, P. M. (2015). Use of recycled construction and demolition materials in geotechnical applications: A review. *Resources, Conservation and Recycling, 103*, 192-204. DOI: 10.1016/j.resconrec.2015.07.023.

Waheed, U., Hudson, W. R., & Ralph, H. (2013). Life-cycle cost and benefit analysis. in *public infrastructure asset management* (2nd Ed.). Retrieved (4/11/2018) from www.accessengineeringlibrary.com/browse/public-infrastructure-asset-management-second-edition/c9780071820110ch14.

Wang, A., Ge, Y., Tan, J., Fu, M., Shah, A. N., Ding, Y., Liang, B. (2011). On-road pollutant emission and fuel consumption characteristics of buses in Beijing. *Journal of Environmental Sciences, 23*(3), 419-426. DOI: 10.1016/S1001-0742(10)60426-3.

Wennström, J., & Karlsson, R. (2016). Possibilities to reduce pavement rehabilitation cost of a collision-free road investment using an LCCA design procedure. *International Journal of Pavement Engineering, 17*(4), 331-342.

Whyte, A. (2015). *Life-cycle cost analysis of built assets-LCCA framework* (1st Ed.). Saarbrücken, Germany: Verlag Dr Müller (VDM).

Wu, C.-S., Lin, C.-T., & Lee, C. (2010). Optimal marketing strategy: A decision-making with ANP and TOPSIS. *International Journal of Production Economics, 127*(1), 190-196.

Wu, Z., Flintsch, G., Ferreira, A., & Picado-Santos, L. (2012). Framework for multiobjective optimization of physical highway assets investments. *Journal of Transportation Engineering, 138*(12), 1411-1421. DOI: 10.1061/(ASCE)TE.1943-5436.0000458.

Yang, C.-H., Lee, K.-C., & Chen, H.-C. (2016). Incorporating carbon footprint with activity-based costing constraints into sustainable public transport infrastructure project decisions. *Journal of Cleaner Production, 133*, 1154-1166. DOI: 10.1016/j.jclepro.2016.06.014.

Yedla, S., & Shrestha, R. M. (2003). Multi-criteria approach for the selection of alternative options for environmentally sustainable transport system in Delhi. *Transportation Research Part A: Policy and Practice, 37*(8), 717-729. DOI: 10.1016/S0965-8564(03)00027-2.

Yu, B., & Lu, Q. (2012). Life cycle assessment of pavement: Methodology and case study. *Transportation Research Part D: Transport and Environment, 17*(5), 380-388. DOI: 10.1016/j.trd.2012.03.004.

Yu, B., Lu, Q., & Xu, J. (2013). An improved pavement maintenance optimization methodology: Integrating LCA and LCCA. *Transportation Research Part A: Policy and Practice, 55*, 1-11. DOI: 10.1016/j.tra.2013.07.004.

Zaki, Y. (2019). Dubai: Should you buy, rent or hail a car? *Gulf News*. Retrieved (4/11/2018) from www.gulfnews.com/how-to/dubai-should-you-buy-rent-or-hail-a-car-1.2182260.

Zanni, A. M., & Bristow, A. L. (2010). Emissions of CO_2 from road freight transport in London: Trends and policies for long run reductions. *Energy Policy, 38*(4), 1774-1786. DOI: 10.1016/j.enpol.2009.11.053.

CHAPTER 10

CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

10.1 INTRODUCTION

The design, operation, maintenance and rehabilitation of road transport systems require holistic environmental, energy and monetary action across roadworks and traffic fleet management. Sustainable roads and transit solutions depend on public authorities' influence over user-adoptability. New technically advanced automated vehicles (AVs) and alternate fuels require consideration by decision-makers, where such transportation systems are increasingly charged to be efficient, reliable, interconnected traffic pathways marked by in-out nodes able to direct people effectively. Chapter 1 describes this overview of the existing road and transport literature (Section 1.1) and the significance (Section 1.3) of this thesis. To assess the lifecycle impact of investments in new or existing road transport systems, a new research project is presented in this thesis that proposes a framework consisting of:

1. Performing a feasibility study by establishing a case study zone or area where the road transport system requires sustainability-based optimisation, i.e., need identification, defining objectives and resource outlining. It is performed by a detailed literature review of decision-making in the field (Page 1 and Page 77) followed by consultation with local government agencies to pinpoint the appropriate case study issues.
2. Consultation with experts and decision-making stakeholders (Section 4.2 and Section 9.3.2) to identify the key performance indicators or KPIs (Pages 237-239) necessary for improving the sustainability performance of any particular road transport system.
3. An analysis of traffic flow patterns in the case study region (Page 193), addressing the suitability of any preferred alternative (Page 195-200) for direct real-world applications alongside user-opinion (Page 81). The users are thus consulted to identify the hotspots (Pages 141-144) in the existing system and collect suggestions for performance improvement (Page 216).

4. The lifecycle cost (Page 82 and Page 255) and environmental (Page 83 and Page 258-260) in/out-flows for any proposed holistic road and traffic management alternative(s) (Page 240) assessed against existing systems.
5. Stakeholder expert-opinion involvement through a multi-criteria decision-making (MCDM) framework assigning weights to cost, energy and emissions (Page 263).

This thesis is, therefore, developed as a collection of a series of research works (Page 8) to tackle each aspect of the framework. The status of the WBS methodology regarding the achievement of each research objective is tabulated in Table 10.1. The significant findings and outcome of the research study are provided in Section 10.2, based upon detailed research analysis of each component of the framework across the four subsequent levels, as also illustrated in Figures 10.1 and 10.2.

Table 10.1 Research outcome from the methodology work breakdown structure (WBS)

WBS ID	**Task description**	**Targeted objective**	**Achievement status**	**Outcome sections**
WBS task 1	- Conduct a literature review. - Identify the methodological issues in decision-making tools to mitigate lifecycle impacts from the different components of road transport system.	Objective 1	Completed	2.3, 2.3.7, 2.4, 2.4.6, and 2.5.
WBS task 2	Literature review on identifying the applicability of advances in vehicle technology and alternate fuels.	Objective 2	Completed	3.4 and 3.6
WBS task 3	Identify the KPIs for sustainability optimisation.	Objective 3	Completed	4.2.1.1, 4.2.1.2, 4.2.1.3, 4.2.1.4, 9.3.2, 9.3.3, and 9.3.4
WBS task 4	- Gathering of input information required for the regression sub-model required to compute the user travel choice preferences. - Identifying influence of public transport through surveys and information existing in the local government databases.	Objective 4	Completed	5.4.1and 5.6.3
WBS task 5	Performing data mining of travel surveys to establish user preferences for improving the existing road transport system.	Objective 4	Completed	6.3.2, 6.5.2, 6.5.3, and 6.5.3.3
WBS task 6	- Development of data inventory after information collection from local agencies, suppliers and contractors regarding the unit energy consumption and emission data for the materials required.	Objective 5	Completed	7.4 and 7.5

	- Compute the total energy consumption and emissions for the required quantity of materials in complete roadworks using a case study road transport system.			
WBS task 7	Using existing lifecycle assessment databases (e.g., Ecoinvent), local resources and any reported peer-reviewed studies, calculate the energy consumption and pollutant emission reduction potential of recycled materials across the lifecycle stages of roadworks.	Objective 6	Completed	7.5.1, 7.5.2, 7.5.3, 7.5.4, 7.5.5, 7.5.6, and 7.5.7
WBS task 8	- Coordinate with the relevant local government agencies to determine the initial agency costs for both approaches (virgin and recycled materials) including the cost of initial designs, rental of equipment and vehicles for site work and labour costs. - Calculate lifecycle agency costs of electricity for traffic lighting and signals, M&R and other operational costs	Objectives 7 and 8	Completed	9.5.1, 9.5.2, and 9.5.3
WBS task 9	Analyse and use micro-simulation models (e.g., Vissim) to calculate the additional fuel consumption, user time and vehicle operation costs, and pollutant emissions during the usage stage after establishing local vehicle inventory through a market survey	Objectives 9 – 11	Completed	8.4.4, 8.4.5, 8.4.6, 8.4.7, and 8.4.8
WBS task 10	- Calculation of quantitative performance of alternatives across all KPIs. - Using AHP-TOPSIS, couple quantitative data and qualitative weightage for sustainability KPIs from local decision-makers using surveys	Objectives 12 and 13	Completed	9.5.4, 9.5.1, 9.5.2, and 9.5.3
WBS task 11	Validate the proposed framework by determining performance of greener alternatives and find the alternative with optimum performance across all KPIs for a case study road transport system	Objective 14	Completed	9.5.3

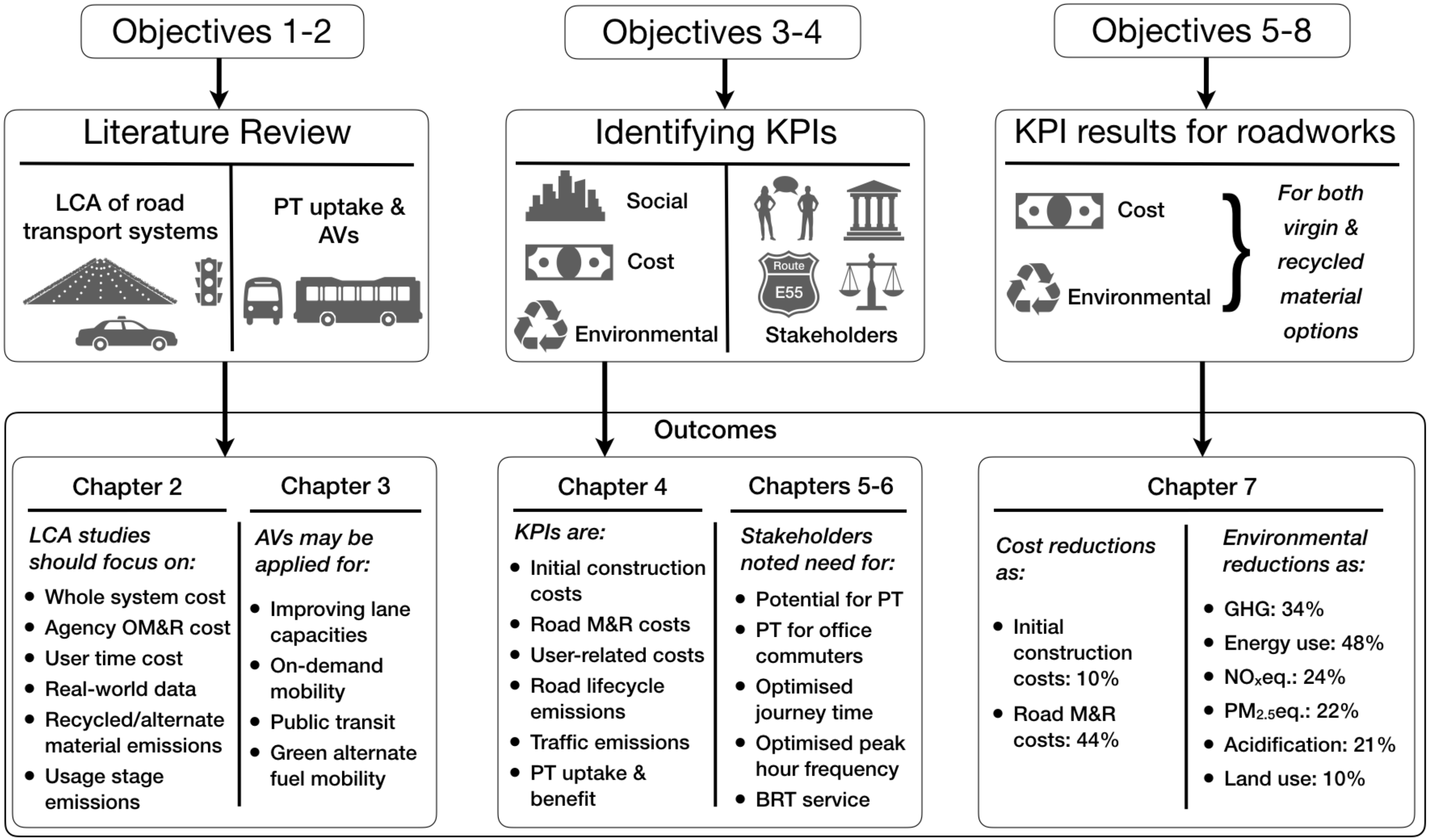


Figure 10.1 Diagram of the thesis layout, outlining relationship between thesis objectives (*Objectives 1 – 8*) and outcomes from each chapter (*Chapter 1 – 7*)

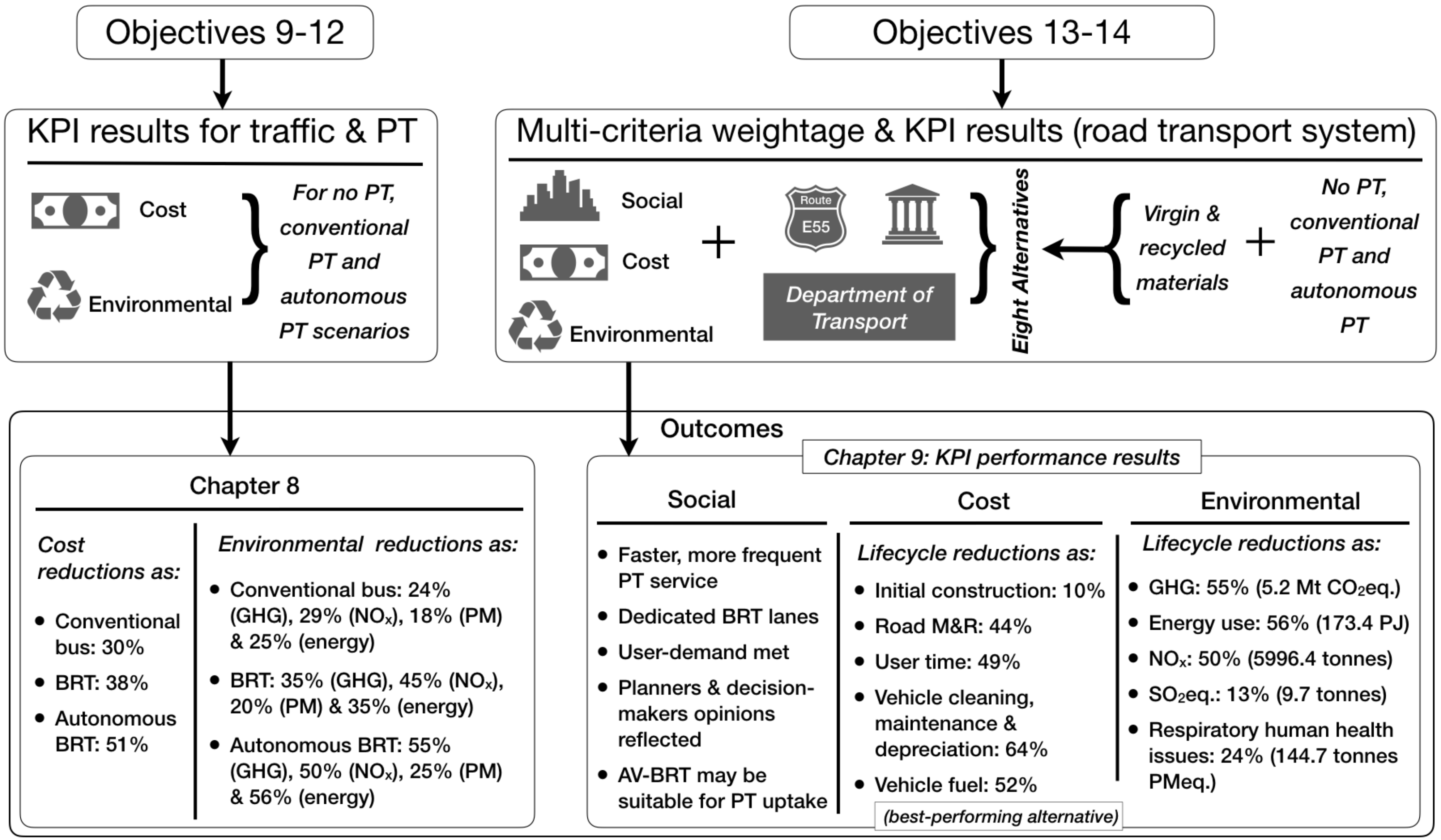


Figure 10.2 Diagram of the thesis layout, outlining relationship between thesis objectives (*Objectives 9 – 12*) and outcomes from each chapter (*Chapter 8 – 9*)

10.2 RESEARCH FINDINGS

The major findings of this thesis are explained below. Figures 10.1 and 10.2 above show the layout of this thesis outlining the relationship between the objectives of this thesis and the outcomes from each chapter.

10.2.1 Methodological issues in current LCA-LCCA decision making

Before proposing the benefits of the MCDM framework developed in this thesis, the methodological issues in the current decision-making tools and LCA-LCCA frameworks applied to road transport systems must be (and were here) identified to establish the need and objectives for the new framework. It is also significant to outline the resources that may be required to improve the existing system or select an optimum alternative for the new system by building upon the existing body of literature.

In order to identify the gaps in research and industrial applicability of lifecycle approaches to optimise the cost, social and environmental performance of road transport systems, Chapter 2 focuses on a critical literature review of the LCCA and LCA research published in the last decade. The main findings for the research gaps and probable industrial applicability of the existing LCCA and LCA frameworks are presented in Section 2.3.7 and Section 2.4.6, respectively. Overall, this review found out that the total costs occurring over the whole lifecycle of the road transport system should be assessed, and thus particular focus must be placed upon agency-based OM&R costs, user-based vehicle operating, time delays, fuel, and other administrative costs. The use of recycled materials, base/sub-base stabilisers, and asphalt binder replacement has the potential of energy saving (≥ 34% or 3.1 TJ), mitigating landfill disposal issues, and pollutant emissions reduction (≥ 34.5% CDE). Lack of "real world" LCCA-LCA application, data and stakeholder prejudice against recycled material usage are addressable (and were addressed here) by better stakeholder (decision-makers and road users) engagement via a social component (Page 43). The usage stage of a road transport system also provides a particular opportunity to reduce the system-wide cost and environmental burdens, yet, excessive private vehicle use (e.g., in the UAE region, Page 205) is a major deterrent towards the optimisation of this stage.

10.2.2 Opportunities and gaps in real-world applicability of artificial intelligence and autonomous vehicle technologies

Chapter 3 reviews the literature on advancements in autonomous vehicle and artificial intelligence (AI) technologies towards sustainability performance improvement of today's road transport systems. Section 3.2 observes that autonomous vehicle-based mobility is a step forward in the edifice of existing infrastructure norms that essentially supports green transport and shared vehicles. Temporal and legislative constraints of shared transport space demand that AVs are equipped with the ability to obey traffic rules, handle blocked routes and perform complex manoeuvres. Travellers are already experiencing a glimpse of artificial intelligence application for road transport systems in the form of on-demand mobility solutions (Section 3.3.1), SAVs (Section 3.3.2), ITS-based traffic surveillance and adaptive lane control (Section 3.3.4). Traffic engineers may design AI and AV-based road systems that can change lane configurations and speed limits to relieve traffic congestion (Section 3.3.5) as better vehicle-to-vehicle and vehicle-to-infrastructure communication becomes a reality, e.g., the Innovate UK project with a commitment of $311.7 million in autonomous and artificial intelligence-based mobility[9] and around $6.78 million investment in autonomous vehicle trials by the Government of New South Wales in Australia[10].

A review of the existing transport literature showed that the stakeholders generally expressed a predisposition towards autonomous vehicles unless they are operated on dedicated bus lanes (Section 3.4). However, AV-based mass transit system provides the added benefit of improved lane occupancy as the rapid vehicle-to-vehicle information exchange allows the vehicles to operate closer to each other (e.g., 2m for regular-size passenger cars). The safe distance between vehicles can be customised and the transport service operators may be operating fully autonomous bus shuttle services that are a hybrid between light rail transits and conventional buses, specifically if the fuel energy requirements are met by alternate fuel technologies such as CNG, hybrid (electric and CNG), electric and biofuels, etc. This may results in less

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[9] UK Research and Innovation. (n.d.). Industry challenge fund: self-driving cars. Retrieved (10/09/2019) from https://www.ukri.org/innovation/industrial-strategy-challenge-fund/self-driving-cars/.

[10] Transport for NSW. (2019). Connected and Automated Vehicles Plan. Retrieved (21/09/19) from https://www.future.transport.nsw.gov.au/sites/default/files/media/documents/2019/Connected_and_Automated_Vehicles_Plan.pdf. Sydney, NSW.

fuel energy consumption due to cooperative breaking and smoother acceleration-deceleration of vehicles which may also generate reduction in tailpipe emissions (Section 3.4.1).

10.2.3 Development of MCDM framework and identifying the KPIs for sustainable road transport systems

Chapter 4 identified that the current research on decision-making tools (LCA, LCCA, etc.) for road transport systems was somewhat lacking in that it either focused on material type (e.g., asphalt versus concrete roads) or only pavement courses, disregarding the whole structure that also constitutes roadside concrete kerbs, concrete barriers for carriageways and traffic signals and lighting works (*which was addressed in this study by including it in the scope of roadworks, Page 7.5.6*). Traffic management strategies are usually applied much later in the lifecycle of the road transport system which contributes to cost and environmental impact overruns and only offers a minimal degree of control on modifying the road transport system (Section 4.2). Technological advancements (particularly artificially intelligent transit gateways, autonomous vehicles, electric, CNG, hybrid, and biofuels) are also rapidly changing the construction practices and transport paradigm, with a significant concern on overall system sustainability (Page 3.4).

The design and management of road transportation systems is a multiple criteria problem, where the integrated parameters of *stakeholder-related social KPIs* namely across an integration of user satisfaction and adaption rate of any particular transport mode (Section 4.2.1.1); *cost KPIs* related to the agency and user costs over the service life (Section 4.2.1.2); *environment KPIs* such as GHG generation, pollutant emissions to the atmosphere and energy consumption (Section 4.2.1.3); and exogenous *decision-maker priorities* are assessed, each of which is subjected to uncertainty.

Past research analysed earlier (Sections 2.3.7, 2.4.6 and 4.2) also exposes the need for establishing comprehensive plans based on the “entire” lifecycle of a product, instead of simply the initial costs and benefits. Hence, it is not be sufficient to constrain the debate to material type or pavement courses while defining goal and scope of asset investment for such projects, and a multi-criteria approach must be (*as demonstrated by this thesis’ more integrated approach*) utilised for optimising the road transport systems across “all” KPIs (Pages 77 and 237).

10.2.4 Synthesis of data mining, consumer research and travel behavioural analysis to identify hotspots in transport system: User-based social component

Chapter 5 analysed user-preference data collected from transport system users for a (defined and selected) case-study region in Abu Dhabi city. Data analysis showed that the majority (83%) of passengers are full-time workers (Section 5.6.1). The results in Section 5.6.3 suggest that the traffic management strategies to reduce excessive private vehicle use may attract more users towards sustainable transport modes based on improving service quality. Chapter 6 performed an in-depth follow-up study of the passenger preference surveys to develop traffic management strategies towards increasing user uptake of sustainable transport modes such as public bus services. In this way the environmental impact generated by pollution from increased dependence on private automobiles may be reduced. The results presented in Sections 6.5.4.2 and 6.5.4.3 show that the notion of reduced fare levels and increased network coverage was not homogenously supported by users. Thus it is argued that decision-makers need to target "work commutes", supported by innovative solutions to enhance "user-experience", by reducing journey time and fluctuating service frequency around office hours. It is suggested that regional public transit adaptability may be resolved if "bus rapid transit services" are provided (Page 144). However, any such traffic management alternatives should build upon lifecycle impact assessments integrated directly into decision analyses across both components (roads and traffic fleet), specifically since rapid bus lanes may require an extension of existing roads and/or variation in the existing daily traffic flow.

10.2.5 Lifecycle assessment of recycled and alternate material usage for improving KPI performance of roadworks

The proposed MCDM framework postulates that sustainability optimisation needs to be performed for both roadworks and traffic fleet components of the system. Chapter 7 applied lifecycle methodology to calculate the environmental impacts of a 3.5km-long dual carriageway case study in Abu Dhabi across earthworks, pavement courses, concrete traffic barriers, concrete kerbs and parapets, and concrete foundation works for traffic signals and lighting with a 30-years' service life. A comprehensive analysis of environmental impact reduction was performed using recycled construction waste, reclaimed asphalt pavement, warm-mix asphalt and slag as alternate material and production options. The results are described below.

Actual field data for the road section (Section 7.3.1) using virgin materials and traditional asphalt production mix for pavement works and Portland cement concrete for the complete concrete works were used as the baseline case. Section 7.5.1 results showed that 26% of CO_2eq. impacts for complete roadworks are generated by earthworks which reduced by around 16% after using RCW for backfilling. Section 7.5.2 showed that after replacing 25% of sub-base and 80% of unbound-base by RCW, the energy consumption reduced by 0.06 TJ, NO_xeq. emissions by 35.3kg and GHG emissions by 4.93 tonnes CO_2eq. After coupling these environmental benefits with the partial use of RAP and WMA for the asphalt concrete courses and GGBFS for the concrete works, Section 7.5.7 showed that significant reductions in environmental impacts can be observed; namely, the GHG emissions reduced by 34%, followed by energy consumption (48%), photochemical ozone formation (NO_xeq.) by 24%, $PM_{2.5}$eq. decreased by 22%, acidification by 21%, and land use by 10%. These reductions in the environmental impacts are comparatively higher than those reported in literature and highlight the need for the project-based lifecycle assessment for each road transport system project, as proposed in the levels 1-3 of the MCDM framework in this thesis. These results were also confirmed to a confidence interval of 95% by Monte Carlo simulations to show that the probability of "alternate pavement materials" impacts being lower than the baseline case is in the 90% – 100% range for the majority of indicators (Section 7.7).

10.2.6 Microsimulation and lifecycle modelling of traffic fleet: Energy-emission paradigm

Chapter 8 tackles the sustainability optimisation issue for the traffic component of this work's case study dual-carriageway system in Abu Dhabi city for the same service life period from 2015 – 2045. High-resolution traffic microsimulation models were developed using actual traffic counts for a representative week, vehicle exhaust emissions and fuel consumption data (Section 8.3.3). All of the existing vehicle types in the case study area were modelled using detailed inventory data, traffic growth models, and advancements in fuel and vehicle technologies (Section 8.3.4). Four scenarios: baseline, bus-based and bus rapid transit-based cases were analysed.

The benefits of vehicle-to-vehicle communication and increased lane capacity offered by autonomous vehicles were modelled as the future-projected case, to further address the "frequent public BRT service" proposed by the users. The results in Section 8.4.2 that due to excessive reliance on private vehicles, traffic continued to grow in the UAE (case study) region resulting in high environmental burdens, unless public transport service can be provided (Page 207). Section 8.4.8 showed that implementing a conventional bus service will result in a 25% reduction in energy consumption, followed by 24% in CO_2 emissions, 29% in NO_x and 18% in PM exhaust emissions. The BRT scenario examined here reduced 35%, 35%, 45% and 20% of the accumulative vehicle energy consumption, CO_2, NO_x, and PM exhaust emissions. AV-BRT resulted in the highest reduction in energy consumption (56%), CO_2 (55%), NO_x (50%) and PM (25%) exhaust emissions. These significant reductions can help the local municipal and transport authorities in meeting the long-term energy conservation and pollution-control, which can be also useful for meeting similar government-led environmental targets in other regions.

10.2.7 Integration of cost-energy-emissions-social burdens from a road transport system: Identifying optimum alternative for a case study

Chapter 9 applied the proposed MCDM framework to integrate the social, cost, energy and pollutant emissions results of Chapters 5 – 8, using detailed lifecycle inventory across eight alternatives, with variations of virgin and recycled materials, and, private vehicle, bus, BRT and AV-BRT based traffic management strategies. The framework application results in the (case study) Abu Dhabi highway section argue that decision-making frameworks, if they are to be successfully implemented, must allow ongoing feedback loops. The lifecycle cost performance results in Section 9.5.1 using a discount rate of 5% showed that the user-related costs were the highest among all cost KPIs. For the baseline case, fuel costs contributed 21%, vehicle operating costs 34% and user time costs 45% of the total lifecycle costs. These high cost values were generated by traffic congestion and excessive breaking-deceleration of vehicles and were only marginally contributed by the use of virgin materials for roadworks.

The alternative coupling recycled materials for roadworks ($3.2 million less) and AV-BRT for traffic management was the best performing option among above eight alternatives. The results showed that although the acquisition and operating cost of autonomous bus vehicles is projected to be approximately 53% ($9.5 million) higher than conventional buses, yet, the cost saving in fuel (29%), vehicle operating (26%) and user time (26%) may provide an incentive to the operating agency in favour of public benefit. The exhaust pollutant emissions results in Section 9.5.2 and traffic energy consumption results in Section 9.5.3 showed that both impacts (*of energy consumption and emissions*) have a direct relationship. Both energy consumption and exhaust emission rate are dependent upon traffic volume and the traffic flow rate factors, i.e., vehicle speed-time curves, acceleration-deceleration, and braking rate. In general, the energy and emission results followed the trend exhibited by cost KPI results. The optimum alternative proposed by the framework application is projected to reduce photochemical ozone formation by 5996.4 tonnes NO_xeq., acidification by 9.7 tonnes SO_2eq., impact to respiratory and human health issues (in terms of PM emissions) by 144.7 tonnes, GHG emissions by 5220.3 ktonnes CO_2eq., energy consumption by 173.4×10^3 TJ and cost by $3.7 billion when accounting for all user-related costs. The cost savings drop to $2.1 billion and $0.6 billion if the user time; and vehicle cleaning, maintenance and depreciation costs; are respectively disregarded. After excluding all of the user-related costs, the cost savings actually transform into a cost deficit of approximately $11.7 million, mainly due to operation cost of the public transport service (if the public transport revenue of $204.3 million from "bus fares" is also diregarded).

Pairwise comparison results in Section 9.5.4 showed that the experts assigned a higher weightage to the energy consumption and pollutant emissions than the cost values. The expert group comprised of stakeholders from the agency responsible for the *road component* assigned slightly higher importance to the cost of roadworks, yet due to the coupling of quantitative and qualitative data, the higher quantitative values of user-related lifecycle costs caused the "bus rapid transit service-based" alternatives to overshadow the costs associated with construction and OM&R of the extra lane for the operation of BRT and AV-BRT services (Page 258). This introduces a robustness in the results of the developed framework as the choice of an optimum alternative for any sustainable road transport system is not easily susceptible to change with slight changes in expert preferences, yet, it still offers a degree of control to the decision-makers across the following two stages. Firstly, the choice of KPIs is dependent upon the policy objectives of the participating stakeholders. Secondly, the experts can still assign an excessively high priority to certain criteria or KPIs depending upon project-specific objectives, e.g., political promises to extend a road project, connecting far-off settlements with the road arterial network, as shown in Section 9.5.5. However, due to the use of detailed lifecycle inventory and high-resolution data modelling in the framework, such objectives are transparent and decision-making biases are thus easy to identify.

10.3 CONTRIBUTION TO KNOWLEDGE: ACADEMIC AND INDUSTRIAL APPLICABILITY

Research on the sustainability triple-bottom-line optimisation of different components of road transport systems is found to be currently focused on individual components (pavement courses, kerbs and parapets, lighting systems, private vehicle traffic, public transport service, and user behavioural surveys) with integrated system-wide optimisation considered difficult to achieve. Noting that the long-term implications of materials selected for roadworks and feedback loops from each component are also critical for selecting the optimum alternative for any project evaluation. Meanwhile, the sensibility of applying high initial capital to achieve green road construction and management from the standpoint of municipal authorities are not being addressed. This study addresses these gaps and is able to itemise nine specific contributions:

1. Decision-making across whole lifecycle cost.
2. Application of traffic microsimulation modelling for estimating vehicle costs, emissions and energy consumption.
3. Establishing a detailed inventory for all stages in lifecycle of roadworks.
4. Extending the system boundary of lifecycle assessment of road transport systems to include both *vehicle (traffic fleet-related)* and *roadworks* emissions.
5. Integration of LCCA and LCA to optimise system-wide cost and environmental impacts.
6. Integrating the preferences of stakeholders through both quantitative and qualitative data in the decision-making process.
7. Establishing a process framework to interlink user needs with the design of project proposals for road transport systems.

8. Establishing a precedence in the UAE and Middle East region by conducting the first detailed lifecycle assessment study on road transport systems in Abu Dhabi city.
9. Establishing a detailed regional inventory and process in/out-flow profile that can be used by future studies.

These nine contributions are now detailed below.

Contribution 1. A limitation of current decision-making on road transport systems is that the currently existing traffic management strategies rarely quantify the resulting impacts using detailed prediction modelling over the whole lifecycle. The extensive literature review conducted in this thesis also argued that the application of a cost-efficient analysis for investment decisions is not limited to the initial design and must be extended to the management, operation, maintenance and other stages of a road transport systems' lifecycle to achieve true optimisation across all cost-related KPIs. This new work presented in this thesis contributes to the research literature by establishing "empirical models" to predict the thus far uncertain user time and vehicle operating costs over the long-term (Page 255).

Contribution 2. Another significant contribution of this thesis is the utilisation of the advantages offered by high-resolution vehicle microsimulation models. For example, the ability to predict acceleration-deceleration and vehicle fuel consumption behaviour of individual vehicles. In this way, detailed traffic flow models are developed that can be used for long-term impact assessment across cost, energy, and emission-related KPIs. This thesis also shows the potential of industry-wide used commercial software such as Vissim, Aimsun and Sidra Intersection in modelling and predicting traffic flow over entire lifecycle instead of the currently-practiced industry focus on modelling the short-term traffic profile. The cost improvement results due to smoother traffic flow not only offer a plausible accuracy of estimates but also offer industry confidence due to the existing familiarity of industry practitioners with microsimulation modelling techniques adopted in this thesis. Furthermore, the established estimation methodology (Pages 201-202) is easily transferrable to industry as it does not require additional training of the transport strategy and planning staff.

Contribution 3. Due to the fragmented nature of existing LCA research on roadworks, the environmental benefits of recycled material use in different components of roadworks including earthworks, pavement courses, and concrete works have thus far not been compared for the same functional unit. Typically the environmental impacts of concrete works associated with road carriageway barriers, kerbs, foundations for traffic lights and signs are not modelled in road and pavement LCA studies. Environmental emissions from diesel fuel consumed during equipment (such as wheel loaders, dump trucks, air compressors, compactors, and track-type tractors, etc.) transport by road to site were not traditionally calculated by existing LCA literature. However, this work argued that it is an essential part of the real-world roadworks tendering and construction process and may influence the ability of local decision-makers to estimate the environmental impact of the entire construction process. Thus this thesis contributes by establishing a detailed inventory for this stage of the construction process (Pages 163-166), which may be used as a sample for future studies, specially targeted at conveying the results to the government agency decision-makers.

Contribution 4. The energy consumption and tailpipe emissions from vehicles in the road transport system have thus far generally been disregarded due to the traditionally uncertain nature of their inclusion in the overall system boundary. Furthermore, the trade-off between the construction of additional lane for dedicated transit service and the environmental benefits of operating uninterrupted transit service over long-term was not typically modelled by literature studies. This thesis contributes to the research literature and industrial applicability by performing a comprehensive comparison of the environmental benefits from alternatives using recycled materials for roadworks across all components and public transport for traffic load reduction. This may directly affect the interpretability and applicability of LCA research for real-world case applications by industry practitioners. Particularly for conveying the results to stakeholders who may be unfamiliar with the principles of the LCA approach.

Contribution 5. Integration of cost, environment and energy analysis approaches to road transport projects have, to date, received limited exposure in literature and had been researched independently. The operation and usage stage of a road transport system's lifecycle is also only recently received attention. Due to the often conflicting nature of both ideals, direct comparison and a simple integration is difficult to achieve in the research literature and is often incomprehensible to the industry practitioners. Many international initiatives aim to provide the practitioners, planners, and decision-makers with environmentally sensitive methodologies that can rank the annual operating capital costs and environmental load reducing potential of different road materials, design and construction techniques; e.g., Infrastructure Sustainability Council of Australia rating, Ecopoints, Greenroads and Civil Engineering Environmental Quality guidelines. However, this thesis fills the current gap with a new quantitative analysis based on real-world data over the whole lifecycle instead of only relying qualitative data or the initial and maintenance stages of the road transport system to compare the different recycling strategies, material mixing techniques, and design proposals (Pages 255-260). This thesis recommends lifecycle implications on system-wide capital requirements, energy savings, pollution generations and user mobility trends using the same functional unit which offers easy comparison between the cost, energy and emission impacts.

Contribution 6. Care should be taken in acknowledging the decision-maker priorities and other social factors related to the system users, municipal authority and transport operating agency due to their potential critical nature to the stakeholders. MCDM approaches are used in the research literature to achieve integration of these factors, however, these studies (to date) only rely on qualitative data. This thesis contributes to industrial applicability by engaging all stakeholders in a multilevel approach that acknowledges user demands, traffic growth trends, and mode use preferences of users, agency sustainability optimisation goals and project-specific priorities of the decision-makers in a transparent and quantifiable method (Page 264). This thesis contributes to the existing research literature by developing updated dynamic flexibility in ranking the different road design, construction and rehabilitation alternatives after assigning project and environmental goal-specific weightings in order to achieve cost, environmental and social sustainability.

Contribution 7. LCA research literature on road projects has not yet been translated into real-world project handling and strategy making on the scale of widespread industrial applicability. LCA tools based on the ISO 14040 (2006) guidelines presented in the existing research works are generally found to be assessing different alternatives, frameworks, system boundaries, data sources, and road transport components. This thesis contributes to LCA research by reviewing the diverse literature resources, degree of uncertainty and transparency and consistency (Page 40); which may aid in improving the real-world implementation and sustainability problem-solving capabilities of LCA frameworks. This thesis contributes to increased understanding by addressing all variables and suggesting a process framework (Page 85) interlinked with user needs and embedded functionality issues to compare the design alternatives of road project proposals.

Contribution 8. The new proposed decision-making framework developed in this thesis can increase LCA/LCCA attraction to policy-makers, planners, and users and ultimately ensure a more sustainable asset. Many past studies focused on road projects from the United States and European regions. The "existing" literature is already extensive enough to promote several industrial practices utilising at least some degree of sustainable designs in these regions. Despite the emphasis on new constructions, urban population density and heavy reliance on fossil fuel, virgin materials and lack of traffic management strategies, very few research studies have been conducted for the climatically distinct Middle East and UAE regions. This thesis contributes towards filling this gap with an estimate of the environmental impact reduction opportunities in complete roadworks and traffic fleet management using Abu Dhabi city as a model case study. This study noted higher environmental benefits than reported in roadworks literature due to material choices, asphalt production options and traffic fleet composition in the region.

Contribution 9. Currently, different sources exist for the lifecycle inventory and weighting factors to the different environmental impact categories in different regions. This thesis contributes to an original body of knowledge by establishing a detailed regional inventory, resource production, and consumption processes and the technological and trade (resource import/export) profile of the case study region. A detailed inventory of the vehicle fleet composition, fuel and engine technology is also developed (Pages 203 and 252). These data inventories can be utilised for decision analysis on other road transport system projects in the region.

10.4 RECOMMENDATIONS AND FUTURE WORK OUTLOOK

This thesis developed a multi-criteria decision-making framework utilising priorities and preferences of government and user stakeholder groups, traffic microsimulation models, LCA and LCCA methodologies for selecting an optimum road transport system, assessed against sustainability criteria set. Detailed investigation of user travel behaviour from quasi-structured surveys, composite recycled material use for complete road works and high-resolution individual vehicle flow modelling under smooth and congested conditions were performed in this thesis. In general, the recycled material use and public transport promotion is assessed as the most effective and easy-to-implement cost, energy and emission reduction strategy.

Future works may develop the research conducted in this thesis to address some of the issues outside the current scope and seeking further applicability in other aspects of (construction and project management of) infrastructure and building projects:

- Costs based on issues arising from external economic factors, such as changes in the market and government fiscal policies which may influence inflation and interest rates in the foreseeable future. An additional cost model may be added to the newly-developed framework here to include these cost variations and fluctuations modelling.
- The advent of production-line style construction practices with *Construction 4.0*[11] offers resource optimisation through a "modular-based" approach. A management system for infrastructure and road transport projects using this approach may be integrated into the decision-analysis system for future studies.
- The traffic management alternatives developed in this study were primarily targeted at meeting public demand for a *frequent* and *rapid* public transit service. As such, the study integrated vehicle microsimulation modelling tool in the framework to assess performance of alternate vehicle transport modes to meet the stakeholder demands over the long-term. However, in regions where climate, cultural and journey duration factors may promote bicycling and walking as the preferred travel modes, additional tools capable of modelling pedestrian traffic (e.g., Viswalk) is a further area to enhance the current study.
- It was observed that a majority of the HGV vehicles in the case study region are Euro II, an opportunity for environmental impact reduction by an overall vehicle policy changes may be investigated in future studies.

[11] This term is now increasingly being used to define the digitisation of the construction industry and includes underlying innovative concepts such as; Building Information Modelling (BIM), robots for construction process, drones for surveying, virtual reality, 3D printing of building components, automation, and, prefabrication.

- This research utilised in-plant recycling of reclaimed asphalt pavement for the periodic rehabilitation every five years, however, on-site recycling through cold in-place techniques may further aid in reducing the overall environmental impacts by reducing the contribution of material transport sub-stage within the M&R stage.
- Past research has shown that the vehicle flow performance and wear-and-tear may be also dependent upon the interaction between vehicle tyres and pavement surface. Due to the lack of vehicle-surface models in the UAE, this factor was outside the scope here and was not investigated in this research. Additional work to investigate the vehicle performance due to rolling resistance of the pavement surface, as well as the effect of pavement albedo and heat energy emittance to enhance the current study.
- For the region-specific context of the UAE region, due to a lack of performance data, the current practice of milling the wearing course every five years is modelled. Future work may assess the lifecycle cost and environmental benefit of longer durations between subsequent rehabilitations after detailed tests in the laboratory are performed on transverse evenness and surface deflection of the case study pavement samples.
- The proposed MCDM framework presents concise results for sustainability performances of each alternative, future work may use product declaration sheets containing performance results for each KPI category across the lifecycle stages of the road transport system.

APPENDIX A

SUPPLEMENTARY DATA

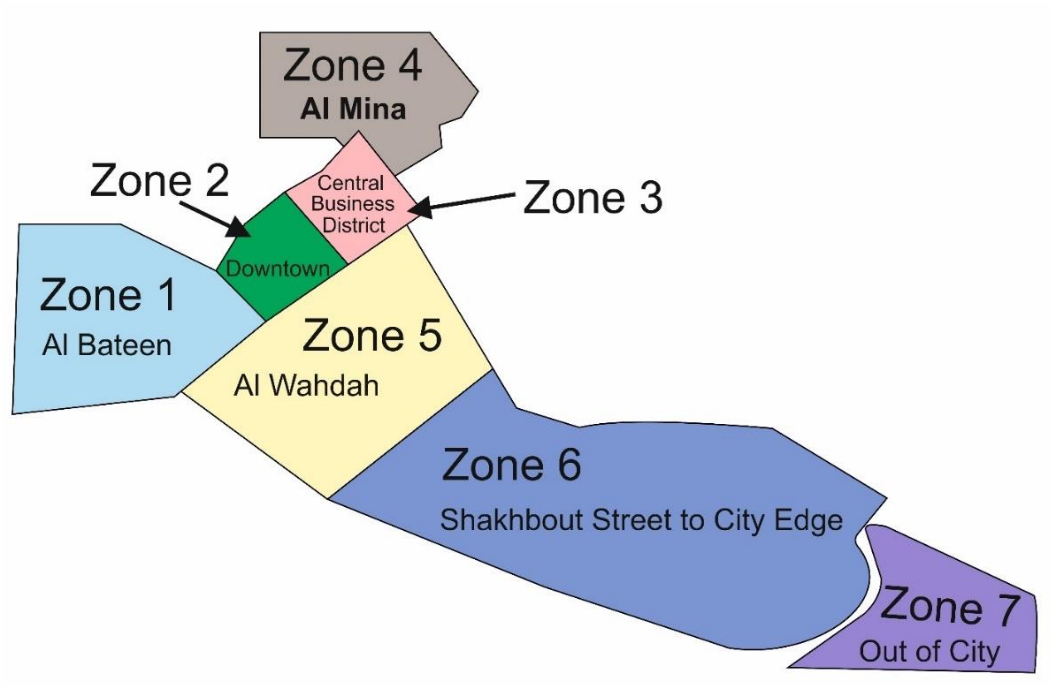

Figure A.1 Zonal distribution of the Abu Dhabi city

Table A.1 Questionnaire sample (English version) used for this study

No.	Questions	Responses (*please circle as appropriate*)						
MU	***Mode use variables***							
MU1	How often do you travel by bus?	**1.** First time	**2.** Less often	**3.** 1–3 times/month	**4.** Once a week	**5.** 2–4 times/week	**6.** Over 5 times/week	**7.** Never
MU2	How often do you travel by private car or taxi?	**1.** First time	**2.** Less often	**3.** 1–3 times/month	**4.** Once a week	**5.** 2–4 times/week	**6.** Over 5 times/week	**7.** Never
LoS	***Level of service variables***							
LoS1	How satisfied are you with current frequency of buses on this route?	**1.** Very dissatisfied	**2.** Dissatisfied	**3.** Neutral	**4.** Satisfied	**5.** Very satisfied		
LoS2	How satisfied are you with current level of network coverage on this route?	**1.** Very dissatisfied	**2.** Dissatisfied	**3.** Neutral	**4.** Satisfied	**5.** Very satisfied		
VfM	***Value for money variables***							
VfM1	How satisfied are you with current quality of ride on buses on this route?	**1.** Very dissatisfied	**2.** Dissatisfied	**3.** Neutral	**4.** Satisfied	**5.** Very satisfied		
VfM2	How satisfied are you with current level of fare of buses on this route?	**1.** Very dissatisfied	**2.** Dissatisfied	**3.** Neutral	**4.** Satisfied	**5.** Very satisfied		
ST	***Travel Bias (Structural-type Constraints Questions)***							
ST1	Your accommodation type?	**1.** Villa	**2.** Apartment	**3.** Hotel	**4.** Labour camp	**5.** Other		
ST2	What is your employment status?	**1.** Retired/Other	**2.** Visitor	**3.** Student	**4.** Unemployed	**5.** Work part-time	**6.** Work full-time	
ST3	What is your annual rent? (AED)	**1.** Under 10,000	**2.** 10,000–20,000	**3.** 20,001–40,000	**4.** 40,001–60,000	**5.** 60,001–100,000	**6.** Over 100,000	
SP	***Travel Bias (Spatial-type Constraints Questions)***							

SP1	Where do you live?	**1.** Al-Bateen	**2.** Downtown	**3.** CBD	**4.** Al-Mina	**5.** Al-Wahdah	**6.** Shakhbout St to city edge	**7.** Out of city
SP2	Where did you start this journey?	**1.** Al-Bateen	**2.** Downtown	**3.** CBD	**4.** Al-Mina	**5.** Al-Wahdah	**6.** Shakhbout St to city edge	**7.** Out of city
SP3	Where are you travelling to?	**1.** Al-Bateen	**2.** Downtown	**3.** CBD	**4.** Al-Mina	**5.** Al-Wahdah	**6.** Shakhbout St to city edge	**7.** Out of city
SP4	Purpose of your journey today?	**1.** Work	**2.** Study	**3.** Business	**4.** Personal reason	**5.** Shopping	**6.** Leisure	
SP5	Type of ticket you purchased today?	**1.** Cash	**2.** Daily pass	**3.** Monthly pass	**4.** Seniors pass	**5.** Disability pass		
SD	***Travel Bias (Socio-demographic Constraints Questions)***							
SD1	Age (years)	**1.** Under 16	**2.** 16 – 24	**3.** 25 – 34	**4.** 35 – 44	**5.** 45 – 64	**6.** Over 65	
SD2	Number of cars in household	**1.** No cars	**2.** 1 to 2 cars	**3.** 3 to 5 cars	**4.** Over 5 cars			
SD3	Do you hold a UAE driving license?	**1.** Yes	**2.** No					
SD4	Ethnicity/Nationality	**1.** UAE	**2.** Caucasian	**3.** Middle Eastern	**4.** African	**5.** South Asian	**6.** Southeast Asia	**7.** Other
SD5	Gender	**1.** Male	**2.** Female					
SD6	Your gross monthly income in AED	**1.** Under 10,000	**2.** 1,000–3,000	**3.** 3,001–5,000	**4.** 5,001–10,000	**5.** 10,001–20,000	**6.** Over 20,000	
SQ	***Perceived Service Quality Questions***							
SQ1	I am satisfied with journey time	**1.** Strongly disagree	**2.** Disagree	**3.** Neutral	**4.** Agree	**5.** Strongly agree		
SQ2	The buses are too crowded	**1.** Strongly disagree	**2.** Disagree	**3.** Neutral	**4.** Agree	**5.** Strongly agree		
SQ3	Bus travel is the easiest way for me	**1.** Strongly disagree	**2.** Disagree	**3.** Neutral	**4.** Agree	**5.** Strongly agree		

SQ4	I am satisfied with the bus-stops	**1.** Strongly disagree	**2.** Disagree	**3.** Neutral	**4.** Agree	**5.** Strongly agree
SQ5	Travel by car or taxi is expensive	**1.** Strongly disagree	**2.** Disagree	**3.** Neutral	**4.** Agree	**5.** Strongly agree
SQ6	Traffic congestion delays my journey	**1.** Strongly disagree	**2.** Disagree	**3.** Neutral	**4.** Agree	**5.** Strongly agree
SQ7	I chose to live further from work (i.e. near family and friends) and longer commute time is insignificant to me	**1.** Strongly disagree	**2.** Disagree	**3.** Neutral	**4.** Agree	**5.** Strongly agree
SQ8	I chose to live closer to work as shorter commute time is significant to me	**1.** Strongly disagree	**2.** Disagree	**3.** Neutral	**4.** Agree	**5.** Strongly agree
SQ9	Willing to pay more for bus travel if I always had a seat	**1.** Strongly disagree	**2.** Disagree	**3.** Neutral	**4.** Agree	**5.** Strongly agree
SQ10	I am satisfied with the existing distribution of bus-stops on the current travel route (Today it took me longer/many minutes to get to bus-stop)	**1.** Strongly disagree (over 25 min)	**2.** Disagree (16 to 25 min)	**3.** Neutral (10 to 15 min)	**4.** Agree (5 to 10 min)	**5.** Strongly agree (under 5 min)

Table A.2 Pairwise comparison results for each KPI based on expert opinions

Key performance indicators	Academics					Transport planners					Municipality					Transport department					Geometric mean
	A1	A2	A3	A4	A5	P1	P2	P3	P4	P5	M1	M2	M3	M4	M5	T1	T2	T3	T4	T5	
Cost → Energy	1/7	1/8	1/9	1/7	1/7	1/5	1/4	1/5	1/6	1/8	1	1/3	1/5	1/2	1/3	1/5	1/7	1/4	1/5	1/8	1/5
Cost → Emissions	1/9	1/8	1/9	1/8	1/8	1/7	1/8	1/7	1/8	1/8	1/6	1/6	1/8	1/6	1/7	1/8	1/8	1/7	1/7	1/9	1/8
Emissions → Energy	2	3	3	2	2	2	2	1	2	3	2	1	2	2	3	1	2	2	1	3	2
Cost items																					
Gross road cost → Vehicle operating cost	1/7	1/8	1/9	1/6	1/8	1/6	1/5	1/4	1/7	1/8	1	1/2	1/4	1/3	1/2	1/4	1/6	1/4	1/6	1/7	1/5
Gross road cost → User time cost	1/6	1/7	1/9	1/6	1/8	1/4	1/3	1/2	1/4	1/5	2	1/2	1/3	1	1/2	1	1/4	1/3	1/3	1/6	1/3
Gross road cost → PT fuel & operating cost	1/5	1/6	1/8	1/4	1/6	1/5	1/4	1/3	1/6	1/6	1	1/2	1/3	1/3	1/4	1/9	1/8	1/7	1/8	1/9	1/5
Gross road cost → User bus fare cost	1/5	1/6	1/7	1/7	1/5	1/4	1/4	1/3	1/5	1/5	1/2	1/3	1/4	1/3	1/3	1/6	1/7	1/6	1/7	1/8	1/5
Vehicle operating cost → User time cost	1/3	1/4	1/5	1/3	1/2	1/2	1	1	1/2	1/3	1	1	1/2	1	1	1/2	1/2	1	1/2	1/3	1/2
Vehicle operating cost → PT fuel & operating cost	6	8	9	6	7	5	3	3	5	7	2	2	3	2	2	1/2	2	1/2	1	3	3
Vehicle operating cost → User bus fare cost	3	4	5	3	3	2	2	2	3	3	2	2	3	2	3	3	5	3	4	6	3
User time cost → PT fuel & operating cost	6	7	8	6	7	5	3	4	6	8	2	2	3	2	3	1/2	2	1/2	1/2	3	3
User time cost → user bus fare cost	4	4	5	5	5	4	4	4	3	4	1	2	3	2	2	3	3	2	3	3	3
PT Fuel & Operating Cost → User Bus Fare Cost	1	1	1/2	1	1/2	1	1	1	1/2	1/2	1	1	1	1	1	2	3	1	2	4	1
Emission items																					
Road CO_2 → Road NO_x	7	7	8	6	6	5	4	4	6	7	6	5	4	6	5	7	8	6	7	8	6

Road CO_2 → Road PM	6	7	7	7	6	5	3	5	6	7	5	7	5	5	6	8	8	7	6	8	6
Road CO_2 → Road SO_2	6	6	7	6	6	4	3	4	5	6	2	2	4	2	2	4	6	3	4	6	4
Road CO_2 → Vehicle CO_2	1/9	1/9	1/9	1/8	1/9	1/7	1/6	1/6	1/8	1/8	1/5	1/7	1/8	1/6	1/7	1/8	1/9	1/7	1/8	1/9	1/8
Road CO_2 → Vehicle NO_x	1/7	1/7	1/8	1/7	1/7	1/5	1/4	1/5	1/5	1/7	1/3	1/4	1/6	1/4	1/4	1/5	1/7	1/5	1/6	1/7	1/5
Road CO_2 → Vehicle PM	1/7	1/7	1/8	1/7	1/7	1/6	1/4	1/4	1/5	1/7	1/3	1/5	1/4	1/4	1/3	1/5	1/7	1/5	1/6	1/7	1/5
Road NO_x → Road PM	1	2	2	1	1/2	1	1	1	1/2	1/2	1	1	1	1	1/2	1/2	2	2	1	2	1
Road NO_x → Road SO_2	1/2	1/2	1/3	1/2	1/2	1/2	1	1/2	1/2	1/3	1/2	1/2	1/2	1	1/2	1/3	1/3	1/2	1/3	1/4	1/2
Road NO_x → Vehicle CO_2	1/9	1/9	1/9	1/8	1/8	1/7	1/7	1/8	1/7	1/8	1/6	1/6	1/7	1/6	1/7	1/7	1/9	1/7	1/8	1/9	1/8
Road NO_x → Vehicle NO_x	1/7	1/7	1/7	1/7	1/7	1/6	1/6	1/5	1/7	1/7	1/5	1/6	1/7	1/4	1/5	1/6	1/7	1/7	1/7	1/7	1/6
Road NO_x → Vehicle PM	1/7	1/7	1/8	1/7	1/7	1/6	1/5	1/6	1/6	1/7	1/4	1/5	1/7	1/6	1/6	1/7	1/7	1/6	1/7	1/8	1/6
Road PM → Road SO_2	1/2	1/2	1/3	1/2	1/2	1	1	1	1/2	1/3	1	1/2	1/3	1	1/2	1/3	1/4	1/2	1/4	1/4	1/2
Road PM → Vehicle CO_2	1/8	1/9	1/9	1/8	1/9	1/8	1/7	1/7	1/7	1/8	1/7	1/7	1/8	1/7	1/7	1/8	1/9	1/7	1/8	1/9	1/8
Road PM → Vehicle NO_x	1/7	1/8	1/8	1/7	1/7	1/6	1/5	1/6	1/7	1/7	1/6	1/6	1/7	1/6	1/6	1/6	1/6	1/5	1/6	1/7	1/6
Road PM → Vehicle PM	1/7	1/8	1/7	1/7	1/8	1/7	1/6	1/5	1/6	1/7	1/5	1/6	1/7	1/5	1/7	1/7	1/7	1/6	1/6	1/7	1/6
Road SO_2 → Vehicle CO_2	1/9	1/9	1/9	1/9	1/9	1/8	1/9	1/8	1/8	1/8	1/9	1/8	1/9	1/9	1/8	1/8	1/9	1/8	1/8	1/9	1/9
Road SO_2 → Vehicle NO_x	1/7	1/7	1/8	1/7	1/7	1/6	1/6	1/8	1/6	1/7	1/5	1/5	1/6	1/6	1/6	1/7	1/7	1/6	1/6	1/7	1/6
Road SO_2 → Vehicle PM	1/7	1/7	1/8	1/7	1/8	1/6	1/5	1/7	1/6	1/7	1/5	1/6	1/6	1/5	1/6	1/7	1/7	1/5	1/6	1/7	1/6
Vehicle CO_2 → Vehicle NO_x	6	7	8	7	7	5	4	5	5	6	3	4	4	3	3	5	6	5	6	7	5
Vehicle CO_2 → Vehicle PM	7	7	8	7	7	5	4	5	5	6	3	4	4	3	3	5	6	4	6	7	5
Vehicle NO_x → Vehicle PM	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1
Energy items																					
Road Energy → Vehicle Energy	1/9	1/8	1/9	1/8	1/9	1/7	1/7	1/7	1/8	1/8	1/6	1/7	1/7	1/6	1/7	1/8	1/9	1/8	1/8	1/9	1/8

APPENDIX B

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Chapter 2. Article reference: **Hasan, U.**, Whyte, A., AlJassmi, H., "*Critical review and methodological issues in integrated life-cycle analysis on road networks*", **Journal of Cleaner Production**, 206 (1), 541-558, 2019.

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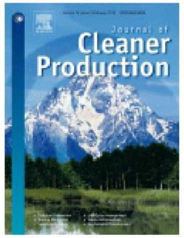

Title: Critical review and methodological issues in integrated life-cycle analysis on road networks

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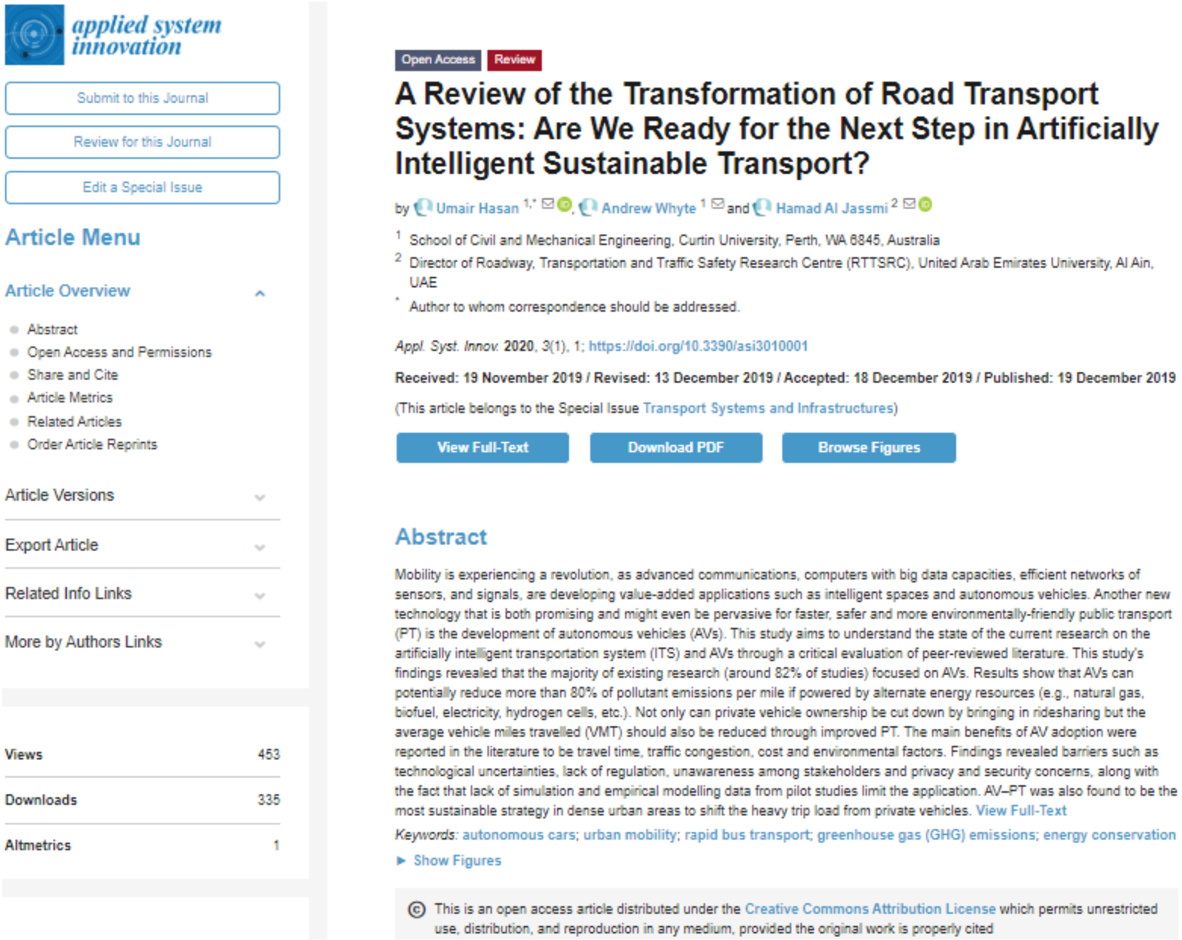

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Open Access Review

A Review of the Transformation of Road Transport Systems: Are We Ready for the Next Step in Artificially Intelligent Sustainable Transport?

by Umair Hasan [1,*], Andrew Whyte [1] and Hamad Al Jassmi [2]

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(This article belongs to the Special Issue Transport Systems and Infrastructures)

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Abstract

Mobility is experiencing a revolution, as advanced communications, computers with big data capacities, efficient networks of sensors, and signals, are developing value-added applications such as intelligent spaces and autonomous vehicles. Another new technology that is both promising and might even be pervasive for faster, safer and more environmentally-friendly public transport (PT) is the development of autonomous vehicles (AVs). This study aims to understand the state of the current research on the artificially intelligent transportation system (ITS) and AVs through a critical evaluation of peer-reviewed literature. This study's findings revealed that the majority of existing research (around 82% of studies) focused on AVs. Results show that AVs can potentially reduce more than 80% of pollutant emissions per mile if powered by alternate energy resources (e.g., natural gas, biofuel, electricity, hydrogen cells, etc.). Not only can private vehicle ownership be cut down by bringing in ridesharing but the average vehicle miles travelled (VMT) should also be reduced through improved PT. The main benefits of AV adoption were reported in the literature to be travel time, traffic congestion, cost and environmental factors. Findings revealed barriers such as technological uncertainties, lack of regulation, unawareness among stakeholders and privacy and security concerns, along with the fact that lack of simulation and empirical modelling data from pilot studies limit the application. AV–PT was also found to be the most sustainable strategy in dense urban areas to shift the heavy trip load from private vehicles. View Full-Text

Keywords: autonomous cars; urban mobility; rapid bus transport; greenhouse gas (GHG) emissions; energy conservation

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Chapter 4. Article reference: **Hasan, U.**, Whyte, A., AlJassmi, H., "*A life-cycle decision-making framework to assess the need for autonomous mobility*", **Transport Research Procedia**, 42, 32-43, 2019.

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A life-cycle decision-making framework to assess the need for autonomous mobility

Author: Umair Hasan,Andrew Whyte,Hamad Al-Jassmi

Publication: Transportation Research Procedia

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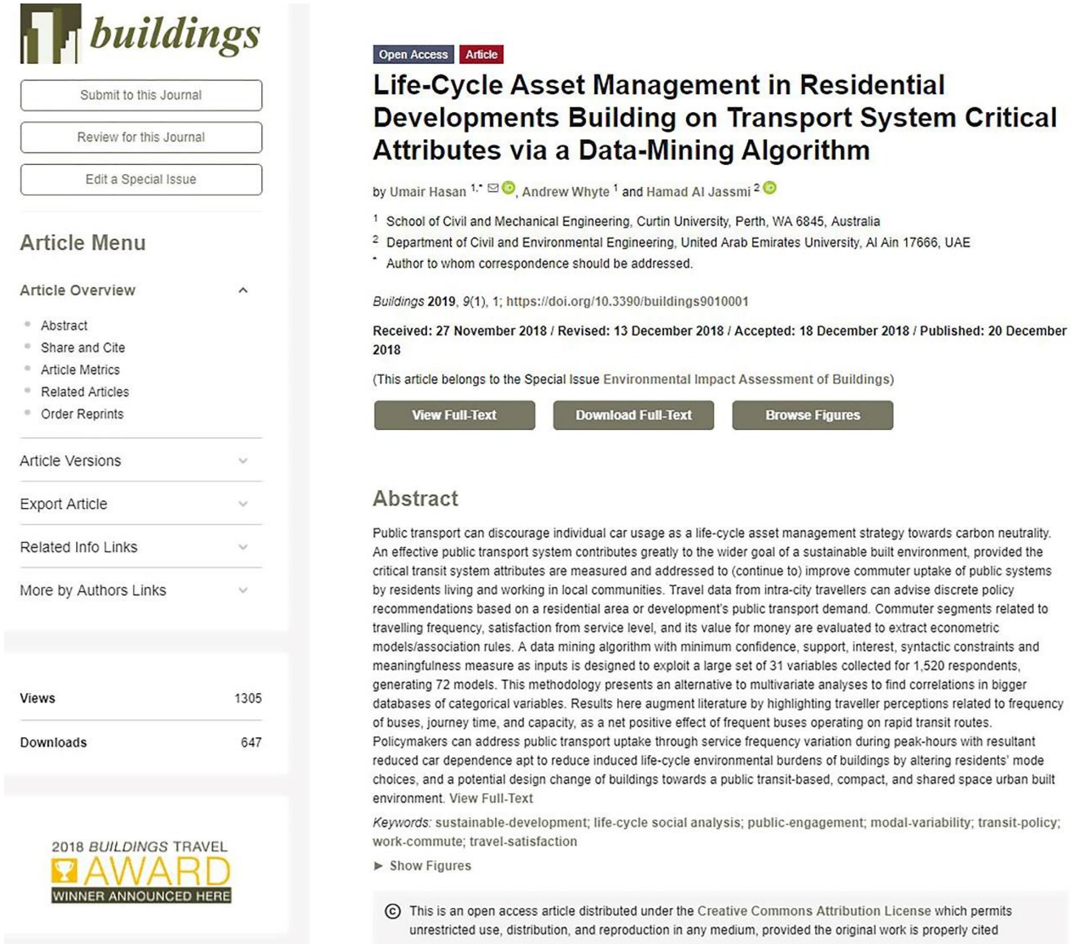

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Open Access Article

Life-Cycle Asset Management in Residential Developments Building on Transport System Critical Attributes via a Data-Mining Algorithm

by Umair Hasan [1,*], Andrew Whyte [1] and Hamad Al Jassmi [2]

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(This article belongs to the Special Issue Environmental Impact Assessment of Buildings)

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Abstract

Public transport can discourage individual car usage as a life-cycle asset management strategy towards carbon neutrality. An effective public transport system contributes greatly to the wider goal of a sustainable built environment, provided the critical transit system attributes are measured and addressed to (continue to) improve commuter uptake of public systems by residents living and working in local communities. Travel data from intra-city travellers can advise discrete policy recommendations based on a residential area or development's public transport demand. Commuter segments related to travelling frequency, satisfaction from service level, and its value for money are evaluated to extract econometric models/association rules. A data mining algorithm with minimum confidence, support, interest, syntactic constraints and meaningfulness measure as inputs is designed to exploit a large set of 31 variables collected for 1,520 respondents, generating 72 models. This methodology presents an alternative to multivariate analyses to find correlations in bigger databases of categorical variables. Results here augment literature by highlighting traveller perceptions related to frequency of buses, journey time, and capacity, as a net positive effect of frequent buses operating on rapid transit routes. Policymakers can address public transport uptake through service frequency variation during peak-hours with resultant reduced car dependence apt to reduce induced life-cycle environmental burdens of buildings by altering residents' mode choices, and a potential design change of buildings towards a public transit-based, compact, and shared space urban built environment. View Full-Text

Keywords: sustainable-development; life-cycle social analysis; public-engagement; modal-variability; transit-policy; work-commute; travel-satisfaction

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<u>Chapter 7</u>. Article reference: **Hasan, U.**, Whyte, A., AlJassmi, H., "*Life cycle assessment of roadworks in United Arab Emirates: Recycled construction waste, reclaimed asphalt pavement, warm-mix asphalt and blast furnace slag use against traditional approach*", **Journal of Cleaner Production**, 257, 120531, 2020.

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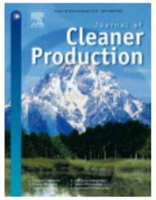

Life cycle assessment of roadworks in United Arab Emirates: Recycled construction waste, reclaimed asphalt pavement, warm-mix asphalt and blast furnace slag use against traditional approach

Author: Umair Hasan,Andrew Whyte,Hamad Al Jassmi

Publication: Journal of Cleaner Production

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APPENDIX C

STATEMENT OF ATTRIBUTION OF CO-AUTHORSHIP

To whom it may concern

Contribution to the publications listed (Papers 1 to 9) is as shown in the table below. The thesis chapters into which these papers are nominally input is described elsewhere:

Paper 1: A life-cycle decision-making framework to assess the need for autonomous mobility, *Transport Research Procedia* 2019, 42, 32-43, DOI: 10.1016/j.trpro.2019.12.004.

Paper 2: Critical review and methodological issues in integrated life-cycle analysis on road networks, *Journal of Cleaner Production* 2019, 206 (1), 541-558, DOI: 10.1016/j.jclepro.2018.09.148.

Paper 3: A review of the transformation of road transport systems: Are we ready for the next step in artificially intelligent sustainable transport?, *Applied System Innovation* 2020, 3 (1), DOI: 10.3390/asi3010001.

Paper 4: Public bus transport service satisfaction: understanding its value to urban passengers towards improved uptake, *Case Studies on Transport Policy* (manuscript under review).

Paper 5: Life-Cycle asset management in residential developments: building on transport system critical attributes via a data-mining algorithm, *Buildings* 2019, 9(1): 1-37, DOI: 10.3390/buildings9010001.

Paper 6: Life-cycle assessment of roadworks in United Arab Emirates: recycled construction waste, reclaimed asphalt pavement, warm-mix asphalt and blast furnace slag use against traditional approach, *Journal of Cleaner Production* 2020, 257, DOI: 10.1016/j.jclepro.2020.120531.

Paper 7: Microsimulation projection of current and future energy consumption and exhaust emissions from urban highway vehicles: Scenario analyses of reduction measures in Abu Dhabi, *Applied Energy* (manuscript under review).

Paper 8: A multi-criteria decision-making framework for sustainable road transport systems: Integrating stakeholder-cost-environment-energy for a highway case study in United Arab Emirates, *International Journal of Project Management* (manuscript under review).

Paper 9: Framework for delivering an AV-based mass mobility solution: integrating government-consumer actors and life-cycle analysis of transportation systems" *In Proceedings of the 46th European Transport Conference*, 10–12 October 2018; Dublin, Ireland, Association of European Transport, p. 18.

Component	Paper 1	Paper 2	Paper 3	Paper 4	Paper 5	Paper 6	Paper 7	Paper 8	Paper 9
Conception and design of the research topic	a	a, b	a	a	a	a	a	a	a
Background and literature review	a	a	a	a	a	a	a	a	a
Experimental design – content analysis	a	a	a	a	a	a	a	a	a
Experimental design – semi-structured interviews and ethics clearance	-	-	-	a, b	a, b	-	-	a, b	a, b
Acquisition of data and method	a, c	a	a	a, c	a, c	a, c	a, c	a, c	a, c
Data conditioning and manipulation	a	-	-	a, b	a	a	a	a	a
Data management, analysis, and statistical method	a, b	-	-	a	a	a	a	a	a, b
Data inventory and modelling	-	-	-	a	a	a	a	a	a
Microsimulation and lifecycle impact modelling	-	-	-	-	-	a	a	a	a
Interpretation and discussion	a, b	a, b	a, b	a	a	a	a	a	a
Paper writing and preparation	a	a	a	a	a	a	a	a	a
Paper adjustment, editing, and proofreading	a, b	a, b, c	a, b, c	a, b	a, b	a, b	a, b	a, b	a, b
Final approval	a, b, c	a, b, c	a, b, c	a, b, c	a, b, c	a, b, c	a, b, c	a, b, c	a, b, c

We, the co-authors endorse that the levels of contribution indicated above are appropriate.

Author name	Attribution key	Signature
Umair Hasan	a	[redacted]
Andrew Whyte	b	
Hamad Al Jassmi	c	