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Assessing block-level sustainable transport infrastructure development using a spatial trade-off relation model

Yongze Song [a,*], Peng Wu [a], Keith Hampson [b], Chimay Anumba [c]

[a] School of Design and the Built Environment, Curtin University, Australia
[b] Sustainable Built Environment National Research Centre, Curtin University, Australia
[c] College of Design, Construction and Planning, University of Florida, USA

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ABSTRACT

Increasing quantity and quality of roads are pathways to sustainable road infrastructure development. Understanding quantity-quality relations of road sustainability is critically required for strategic decision making. However, few knowledge are available about assessing quantity-quality relations of road sustainability from a perspective of spatial disparities. Here, we developed a Spatial Trade-Off Relation (STOR) model for assessing road quantity-quality trade-off relations at 42,425 blocks in Western Australia (WA). First, a sustainable road infrastructure index (SRII), including quantity and quality phases, was developed regarding stakeholder requirements and using multiple spatial methods to examine block-level road sustainability. Next, quantity-quality trade-off relations for road sustainability was investigated using a diminishing marginal utility approach. Further, spatial disparities of quantity-quality trade-offs were assessed through the spatial clustering based identification of hotspots and cold spots in trade-offs. Finally, contributions of the road quantity-quality interaction to economic development were estimated with the consideration of non-linear and geographically local characteristics of the associations using a generalized additive model and geographically weighted regression. We found three stages of the quantity-quality relations of road sustainability, including the increasing, marginal, and negative returns. The increasing return revealed the simultaneous growth of quantity and quality in outer and remote regions, and marginal and negative returns were primarily located in major cities. In addition, regional disparities of the trade-offs were found from the identified blocks, towns and villages, where quantity and quality were spatially clustered, for informing priorities of future strategic decisions. We also found that the contribution of road quality was about three times the contribution of quantity to resident income. This study demonstrated that efforts regarding regional quantity-quality trade-offs were required to achieve global sustainable infrastructure development goals.

1. Introduction

Road infrastructure is a fundamental public asset for global socio-economic development (Koks et al., 2019; Wang et al., 2019). The United Nations Sustainable Development Goals (SDGs), e.g, SDGs 9.1 and 11.2, highlight that building sustainable road infrastructure is one of the core actions towards sustainable development of society as a whole (Nations, 2016; Griggs et al., 2013; Song and Wu, 2021). Australia has established a series of national sustainable road infrastructure development frameworks and strategies over the past fifteen years (Sanchez and Hampson, 2012; Sanchez et al., 2013). Building sustainable road infrastructure also benefits other SDGs, and road sustainability is an approach to measure the sustainable road infrastructure development (Nilsson et al., 2016; Thacker et al., 2019; Song and Wu, 2021). Road sustainability means that the life-cycle of road construction, maintenance, and asset management will reduce burden and provide benefits for improving population accessibility to public facilities, provisioning of public services, enhancing community well-being, protecting and enhancing surrounding environment, and promoting global sustainable development (Correia et al., 2016; Torres-Machi et al., 2017; Weiss et al., 2018; Balsa-Barreiro et al., 2019).

Making decisions based on sustainable road infrastructure is typically supported by quantitative assessments of the accessibility, reliability, resilience, and quality of roads (Joyce et al., 2018; Song et al.,

* Corresponding author.
E-mail address: yongze.song@curtin.edu.au (Y. Song).

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2018). Decisions are made regarding the life cycle of road infrastructure, including investment, design, construction, maintenance, and demolition (Gajanayake et al., 2020; Ruiz and Guevara, 2020). The socio-economic development, which is affected by infrastructure performance, and social behaviours, are also essential factors affecting decisions (Pentland, 2015; Luo et al., 2021). However, as the basis of strategic sustainable road infrastructure development, accurate and reliable quantitative sustainability assessments are still limited, especially road sustainability indicators and evaluation methods (Fritz et al., 2019).

Developing indicators is essential approaches for measuring infrastructure sustainability, including road sustainability (Liu et al., 2021; Yang et al., 2021). The indicators of road sustainability are generally developed in terms of road network socio-ecological impacts and road construction project requirements (Lehtiranta et al., 2012; Kenley et al., 2014; Sanchez et al., 2015). On one hand, the primary objective of road network socio-ecological impact indicators is to analyze the associations between road infrastructure and local environment and communities (Lindenmann, 2007; Mehdi et al., 2011; Robert et al., 2017). In this case, the performance of the road itself, such as surface deterioration and defects, and its capacity to serve other transport modes, including ports, airports, and rails, are not involved in the investigation. On the other hand, road sustainability is closely associated with the resilience and quality of roads in specific road construction projects (Bocchini et al., 2014; Espinet et al., 2016). However, network-level assessments of road sustainability are still limited due to the lack of large-scale monitoring data, and multi-scale sustainability evaluation methods (Song et al., 2020). Particularly, methods are required to depict the relationship between road sustainability and practical requirements of different stakeholders.

The ultimate objective of sustainable road infrastructure development is to better satisfy stakeholder requirements (Kivila et al., 2017). The stakeholders of road infrastructure include road management agencies, residents, industrial road users, and operators of other transport modes (LLim and Yangim and Yang, 2009; Goh and Yang, 2014). To satisfy stakeholder requirements, actions should be taken to enhance the strategic road asset management abilities of road management agencies, improve road safety, and increase services and efficiency for residents to use roads, freight transportation, and other transports modes.

Increasing road quantity, improving their quality, and balancing quantity and quality in terms of regional socio-economic conditions are the primary methods for achieving sustainable road infrastructure development in road construction and management (Currie, 2004; Quddus et al., 2007). Activities related to increasing road quantity include planning and building highways and local roads and creating links to enhance road load capacity and connectivity. Building redundant roads in populated regions also may cause increased congestion, crashes, and pollution issues (Wang and Debbage, 2021). Additionally, road quality can be improved in multiple ways, such as developing regular and strategic road maintenance plans to ensure pavement performance (Gertler et al., 2016), improving the design of roads and nearby facilities, ensuring road safety, reducing traffic risks (Huang and Abdel-Aty, 2010), increasing population accessibility to public facilities and other transport modes in terms of spatial configuration of road networks (Giacomin and Levinson, 2015; Boeing, 2020; Wang et al., 2020; Wang et al., 2021). Until now, few knowledge is available for assessing the relationship between the quantity and quality dimensions of sustainable road infrastructure and their contributions to socio-economic development.

In this study, we developed a systematic and high-resolution analysis to investigate quantity-quality trade-offs of sustainable road infrastructure development. First, sustainability indicators of road quantity and quality were developed from the perspective of stakeholder requirements. The quantity dimension included road density and connectivity. The quality dimension was characterized by road surface performance, safety, accessibility to facilities, and links to other transport modes. Second, a diminishing marginal utility (DMU) was employed for assessing the quantity-quality trade-off relations of the road sustainability during infrastructure development. Third, hotspot and cold-spot neighborhoods and towns/ villages of road sustainability were respectively identified to indicate the future potentials, priorities and appropriate actions of strategic decisions. Finally, contributions of quantity and quality dimensions of road sustainability on the socio-economic development were estimated and compared using non-linear and geographically local models.

2. Study area and data

2.1. Study area

The road network in Western Australia (WA), consisting of 18,500 km of state roads and 160,000 km of local roads, represents one of the most expansive regional road infrastructure systems in the world (Fig. 1). There are 42,425 blocks in WA that the average size is 59.6 km^2 (Australian Bureau of Statistics, ABS, 2017b). In the study area, the total population is 2.45 million, and the mean block-level population is 58 people, where the population in 33.2% of the blocks is zero, such as in parks and nature reserves (Australian Bureau of Statistics, ABS, 2017b). To estimate block-level road sustainability, data about the road network, road performance, safety, accessibility and other transport modes have been collected and processed. The data used for the road sustainability estimation are presented in the following subsections.

In addition, point of interest (POI) and income data were collected in WA for the analysis. POI are accurate locations of essential infrastructures, including houses and apartments, hotels, schools and industries, sourced from open-access data of Medium Scale Topo Points of Interest (LGATE-135) (Landgate, Western Australia, 2019) and Geoscape Geocoded National Address File (G-NAF) (Department of Industry, Science, Energy and Resources, Australia, 2019). They are an effective proxy variable for human activities and residential development and are commonly used for the management of infrastructure systems (Chi et al., 2015; Song et al., 2018; Zeng et al., 2019). The mean income per person is used as a proxy indicator of socio-economic development as it can directly indicate regional development conditions (Niessen et al., 2018; Ballew et al., 2020). The data of mean income per person is sourced from the Personal Income dataset for Australia (Australian Bureau of Statistics, ABS, 2019).

2.2. Road network data

In WA, the main road (state road) network data were collected by Main Roads WA (Main Roads Western Australia, 2019b), and multi-level road network data were sourced from OpenStreetMap (OpenStreetMap, 2019). The primary function of the main road network was supporting different levels of heavy vehicle freight transportation (Song et al., 2018; Song et al., 2019), and the OpenStreetMap road network was used to characterize the density, connectivity, and accessibility of the entire network, including both state and local roads in WA.

2.3. High-resolution vehicle-based sensor data of road performance

The surface performance is a direct approach to reveal the physical quality of the road infrastructure. In this study, four road surface performance indicators with 100-m resolution, including roughness, rutting, deflection, and curvature, were collected using heavy vehicle-based LiDAR sensors across the whole road network in WA (Song et al., 2021). Roughness, or the international roughness index, demonstrates road surface deviations from the intended longitudinal profile (Song et al., 2021). The pavement roughness is closely associated with vehicle dynamics, vehicle operating costs, driving comfort, and safety and pavement loading (Song et al., 2021). Rutting indicates the maximum vertical pavement displacement in the transverse profile

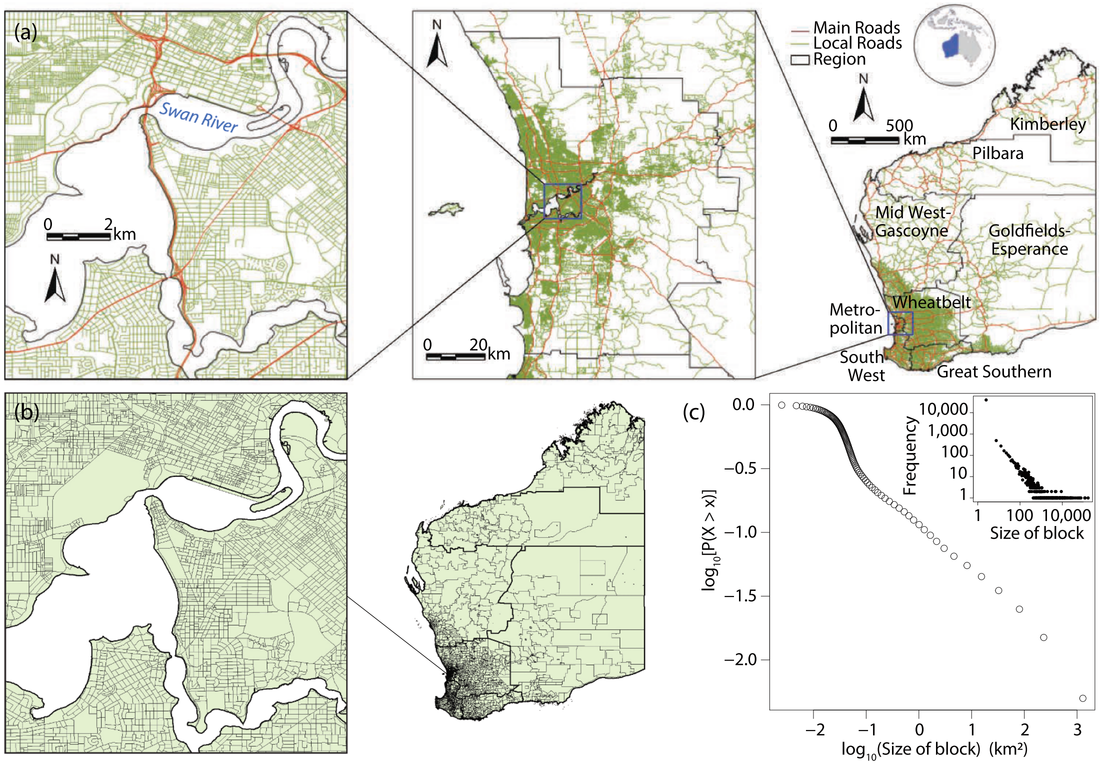

Fig. 1. Distributions of road network (a) and blocks in Western Australia (WA) (b and c). The road network includes main roads and local roads.

through a wheel path, which can cause aquaplaning (White, 2002). Deflection is a pavement strength indicator that is measured as the maximum depression of the pavement surface under a standard load (Main Roads Western Australia, 2017; Song and Wu, 2021). Curvature is an indicator of asphalt fatigue that is represented by the shape variations of the deflected pavement surface caused by loads. Roughness and rutting are monitored using a heavy vehicle-based laser scanner on a traffic speed deflectometer platform at a travel speed of 80 km/h (Western Australia Road Research and Innovation Program (WARRIP) and Australia Road Research Board (ARRB), 2017). Deflection and curvature are monitored using a Dynatest 8000 series falling weight deflectometer device and calibrated by Main Roads WA (Main Roads Western Australia, 2017). Examples of comparing spatial distributions of roughness, rutting, deflection, and curvature can be found in Song et al. (2021). The road segment-based observations of the above four indicators were then converted to block-level road performance indicators.

2.4. Road safety data

Road safety reflects the comprehensive quality of the road design and surface performance, and the surrounding environment that may disturb or affect safe driving. Road safety was estimated using the crash risk near blocks. In the study, crash records data with different levels of severities from 2015 to 2019 (Main Roads Western Australia, 2019a) and annual average daily traffic volumes (Main Roads Western Australia, 2018) were collected and processed to quantify crash risks. The crash and traffic volume data were summarized and assigned to 500-m grids covering the road network of the entire state. Then, the crash rate within each grid was calculated as the ratio of the annual total crashes to annual average traffic volume. Finally, the block-level crash risk was the spatial aggregation of the grid-level crash rates; if no roads run through the block, then the crash risk of this block was zero. The block-level crash risk ranges from 0 to 20.47, with a mean value of 0.15 crashes per 100,000 vehicles.

2.5. Facility data for assessing accessibility

Supporting access to facilities is one of the primary functions of roads. Accessibility is simultaneously affected by population needs, supplies from facilities, and the convenience of roads (Song et al., 2018; Wang et al., 2020; Wang et al., 2021). POI data of schools, hospitals, government facilities, industries, and leisure facilities (Landgate, Western Australia, 2019) were selected to quantify population accessibility to facilities.

2.6. Data of other transport modes

Road transport is a highly flexible transport mode; however, other transport modes can provide alternative solutions for human and freight movements. The links of roads to other transport modes, including ports, airports, and railways, were essential to indicate the service for the entire transport system. Thus, data of other transport modes were collected for estimating the link between road infrastructure and other transportation infrastructure (Landgate, Western Australia, 2019).

3. Methods

This study developed a spatial trade-off relation (STOR) model for quantifying the block-level quantity-quality trade-off of road sustainability. A methodological overview of the STOR model and quantity-quality trade-off analysis for the sustainable road infrastructure development is presented in Fig. 2. The method includes four steps: the definition of a block-level sustainable road infrastructure index (SRII), assessment of quantity-quality relations and trade-offs, spatial clusters identification, and estimation of SRII contributions to socio-economic development. The steps of the method are presented in the following subsections, respectively.

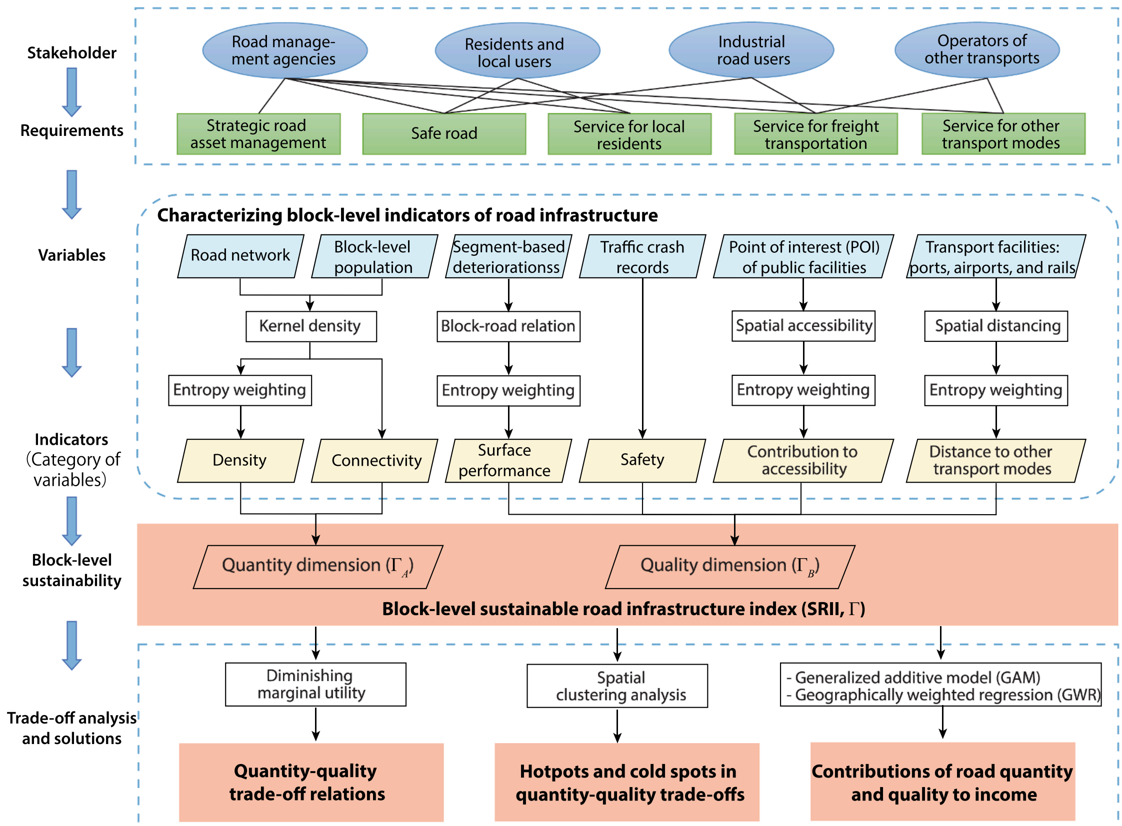

Fig. 2. Methodological overview of the quantity-quality trade-off analysis for the sustainable road infrastructure development.

3.1. Block-level sustainable road infrastructure index (SRII)

The road sustainability indexes were developed in terms of stakeholder requirements of sustainable road infrastructure development (Fig. 2). In this study, stakeholders of road infrastructure primarily include road management agencies, residents, industrial road users, and operators of other transport modes. Correspondingly, stakeholder requirements consist of strategic road asset management, safety, and services for residents, freight transportation, and other transports. To satisfy the requirements, the road sustainability was assessed using a series of indicators from quantity and quality dimensions using block-level SRIIs (Γ), where the quantity and quality dimensions were presented as Γ_A, Γ_B, respectively. Methods for computing the indicators of Γ_A and Γ_B, and the SRII definition approach are presented as follows. The indicators of Γ_A and Γ_B, and their brief descriptions were summarized in Table 1.

3.1.1. Sustainability in quantity dimension

The quantity dimension includes road density and connectivity. Road density was the average density of all the roads, and connectivity was quantified based on the road intersection density. Due to the practical strategies of road infrastructure management in WA, large area of the road network coverage, and greatly varied block sizes (Fig. 1 b and c), the road density was computed using a spatial kernel density function with a spatial resolution of 500 m. Subsequently, the block-level road density was derived from the aggregated road density map. The block-level mean main road density and mean road density were 0.34 km/km^2 and 7.82 km/km^2, respectively. The roads shared by the population were computed as the ratio of road length (mean road density in a block times block size) to residential population in a block. The block-level mean length of the roads shared by a population was 3.03 km/person. The road connectivity was the road intersection density in a block, and the block-level mean value was 3,591 intersections per block.

3.1.2. Sustainability in quality dimension

The quality dimension was characterized by road surface performance, safety, accessibility to facilities, and links to other transport modes. The indicators of road performance and safety are shown in Table 1. In addition, a spatial network analysis was applied to identify the shortest network distance between the population centroids of blocks and the three transport modes, ports, airports and railway (Table 1).

In this study, the contribution of roads to the accessibility to facilities (CRAF) was estimated to evaluate the service quality for residents and freight transportation. For a given block, the CRAF was used to assess whether the road network could provide local residents with convenient and direct solutions to access required facilities. Therefore, the CRAF was not the distance between residents and facilities but the ease of accessing these facilities. In the study, the equation of the CRAF is:

$$\mathrm{CRAF} = \frac{d_{Geometric}}{d_{Network}} \tag{1}$$

where $d_{Geometric}$ is the geometric distance and $d_{Network}$ is the distance of the shortest path on the road network between the population centroid of a block and the nearest facility. The population centroid was calculated as the population weighted central coordinate $[x_c, y_c]$ of a block using 1 km-resolution Australia Population Grid data (Australian Bureau of Statistics, ABS, 2017a). The equation of the population centroid is:

$$[x_c, y_c] = \left[\frac{\sum_{k=1}^{n} \rho_k x_k}{\sum_{k=1}^{n} \rho_k}, \frac{\sum_{k=1}^{n} \rho_k y_k}{\sum_{k=1}^{n} \rho_k} \right] \tag{2}$$

where $\rho_k, k = 1, \ldots, n$ is the population of ith grid located within a block, and $[x_k, y_k]$ is the central coordinate of the grid.

Table 1
Variables for sustainable road infrastructure index (Γ). "+" denotes a positive relationship between the indicator and Γ, and "-" denotes a negative relationship between the indicator and Γ.

Phase	Category of variables	Variables	Relation	Descriptions
Quantity	Road density	Road density (km/km^2)	+	0.178 million roads of total length 0.162 million km
		Main roads density (km/km^2)	+	10 237 main roads of total length 19 760 km
		Roads shared by population ($km/person$)	+	2.452 million population
	Connectivity	Road intersection density ($intersections/km^2$)	+	0.133 million road intersections
Quality	Road performance	Road roughness (μm)	-	Deterioration sensors data: 0.786 million observations monitored at a 200-m interval across the road network
		Road rutting (μm)	-	
		Road deflection (μm)	-	
		Road curvature (μm)	-	
	Road safety	Crash rate (crashes per million vehicles)	-	0.151 million crashes from 2015 to 2019
	Road contribution to the accessibility to facilities	Contribution to access to schools	+	813 schools
		Contribution to access to hospitals	+	533 hospitals and health care centres
		Contribution to access to government facilities	+	1083 government facilities
		Contribution to access to industries	+	1212 industrial facilities
		Contribution to access to leisure facilities	+	322 sporting and entertainment facilities
	Distance to other transport modes	Distance to ports (km)	-	14 major ports
		Distance to airports (km)	-	28 large and medium airports
		Distance to railway (km)	-	1281 railways and 8.56 thousand km

3.1.3. SRII definition

The SRII system consisted of four hierarchies. The top hierarchy was the block-level SRII, the second was Γ_A and Γ_B, the third was the six categories of variables (i.e., indicators), and the final hierarchy was the variables. The indicators were derived using the above mentioned data and methods, and then standardized to eliminate the impacts of dimension and magnitude using the following equation:

$$Y_j = \begin{cases} \dfrac{X_j - min(X_j)}{max(X_j) - min(X_j)} & \text{if} X_j \text{isapositivevariable} \\ \dfrac{max(X_j) - X_j}{max(X_j) - min(X_j)} & \text{if} X_j \text{isanegativevariable} \end{cases} \tag{3}$$

where X_j is the values of variable j, and $max()$ and $min()$ are maximum and minimum functions, respectively. The positive or negative relationships between the variables and SRIIs are listed in Table 1.

The next step was to determine weights of the variables and indicators. In this study, we assumed that the quantity and quality dimensions were equally important to SRII; hence, SRII was the sum of the equally weighted Γ_A and Γ_B. Similarly, Γ_A was the sum of the equally weighted road density and connectivity indicators, and Γ_B was the sum of the equally weighted road surface performance, facility accessibility, road safety, and links to other transport modes.

In each indicator category, variable weights were determined using the entropy weighting method to fully explore the information and variations of the variables. The information entropy of the indicator variable within each category was calculated as follows:

$$e_j = -\frac{1}{ln(m)}\sum_{i=1}^{m}\theta_{ij}ln(\theta_{ij}) \tag{4}$$

where $\theta_{ij} = \frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}}$, and y_{ij} is the standardized value in the ith ($i = 1, \ldots, m$) block of variable j. The entropy weight of variable $j (j = 1, \ldots, s)$ in a category is:

$$w_j = \frac{\varphi_j}{\sum_{j=1}^{s}\varphi_j} \tag{5}$$

where $\varphi_j = 1 - e_j$ is the entropy redundancy of variable k. The index of each category of indicators, such as road density, was the sum of the entropy weighted variables:

$$I = \sum_{j=1}^{s} w_j Y_j \tag{6}$$

3.2. Quantity-quality relations and trade-offs

The relationship between Γ_A and Γ_B could be presented as a utility function of the quality with respect to the quantity:

$$u(\Gamma_A, \Gamma_B) = f(\Gamma_A) \tag{7}$$

where the response variable observation is Γ_B. The function between Γ_A and Γ_B was fitted by a locally estimated scatterplot smoothing (LOESS) function due to the effectiveness and flexibility in local, nonparametric, and nonlinear models (Jacoby, 2000).

In the DMU assessment, the marginal utility was presented as a partial derivative of the quality function in relation to quantity:

$$\eta = \frac{\partial u(\Gamma_A, \Gamma_B)}{\partial \Gamma_A} \tag{8}$$

In the study, as the utility function $u()$ was a nonparametric function, the partial derivatives were computed using the difference quotient of the function:

$$\eta = \frac{\Delta u(\Gamma_A, \Gamma_B)}{\Delta \Gamma_A} = \frac{u(\Gamma_A + \Delta\Gamma_A, \Gamma_B) - u(\Gamma_A, \Gamma_B)}{\Delta \Gamma_A} \tag{9}$$

where the change rate in the utility Δu is associated with a small change in Γ_A ($\Delta\Gamma_A$).

The quantity-quality relationship typically consisted of three DMU stages: IR, MR, and NR. The IR stage was featured in the consistently increasing portion of the utility function u and marginal utility η, the MR stage features an increased utility function and decreased marginal utility, and the NR stage featured a consistently reduced utility function and marginal utility. Therefore, the point between IR and MR stages was at the location of an increasing $u()$ and the $max(\eta)$, and the point between MR and NR was at the location with the $max(u)$ and where $\eta = 0$.

3.3. Hotspots and cold spots identification

Spatial clusters were identified for the block-level Γ_A and Γ_B using a local indicator of spatial association (LISA) approach, a widely used local spatial autocorrelation model (Anselin, 1995; Bivand and Wong, 2018). LISA maps displayed hotspot regions (HH), cold-spot regions (LL) and other types of spatial clusters and their corresponding significances. The hotspot regions indicated that the SRII value of a block was high and that the values of its neighboring blocks were also high, and the cold-spot regions had the opposite conditions. In the study, hotspot and cold-spot regions were selected using the significance level $p < 0.05$. As a result, LISA maps were generated for both Γ_A and Γ_B. The overlapping hotspots and cold spots of block-level Γ_A and Γ_B were selected as the SRII hotspots and cold spots, and the other regions were considered non-clustered regions.

The cold-spot towns/ villages of road sustainability were identified based on the facility POI density of blocks, and population and areas of the towns/ villages (Fig. 3). Blocks with cold spots of quantity or quality were regarded as potential components of cold-spot towns/ villages. First, the cold-spot blocks with POI density higher than 34,522 POIs/ km^2, 75% quantile of POI density of all cold-spot blocks, were selected as potential blocks of towns/ villages with the assumption that towns/ villages were areas with relatively sensed facilities (Song et al., 2018). Next, the neighborhood potential blocks of towns/ villages were spatially aggregated, where blocks at different DMU stages were separated. Finally, cold-spot towns/ villages were selected from the spatially aggregated blocks according to thresholds of population and area. The selected cold-spot towns/ villages had more than 173 residents and areas larger than 0.269 km^2, which were 50% quantile values of the population and area, respectively.

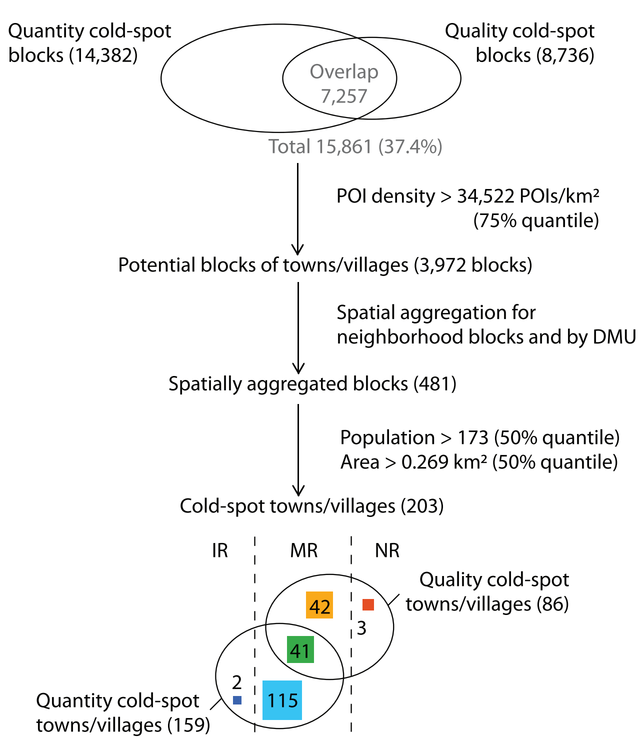

Fig. 3. Process of identifying cold-spot towns/ villages of road quantity and quality.

3.4. Contributions of SRII to resident income

The contributions of Γ_A and Γ_B to resident income were evaluated using a generalized additive model (GAM) and geographically weighted regression (GWR) model to reveal nonlinear and regional effects.

The GAM can identify nonlinear relationships between responses and explanatory variables through a set of nonparametric smoothing functions (Hastie and Tibshirani, 1990; Friedman et al., 2010). The GAM constructed in this study is given as follows:

$$z = \beta_0 + \sum_{h=1}^{2} g_h(x_h) + \epsilon \quad (10)$$

where z is the LGA-based mean income per person, β_0 is an unknown coefficient, g_h ($h = 1,2$) is a spline-based univariate smoothing function, explanatory variable x_1 is Γ_A and x_2 is Γ_B, and ϵ is a normal random error term ($\epsilon N(0,\sigma^2)$). The GAM was run using the R "mgcv" package (Wood, 2011; Wood, 2017). The smoothing function parameters were automatically determined using the generalized cross-validation criterion and an iterative process to ensure computational efficiency and accuracy (Wood, 2004).

The GWR was an essential local approach in analyzing spatially varied relationships (Fotheringham et al., 1998). The spatial instability of the regression coefficients can be measured across the entire study area using the GWR model with distance-decay weights based location-wise parameter estimations (Fotheringham et al., 2003). The GWR model built in the study is as follows:

$$z = \beta_0(\mathbf{v}) + \sum_{h=1}^{2} \beta_h(\mathbf{v})(x_h) + \epsilon \quad (11)$$

where $\beta_0(\mathbf{v})$ and $\beta_h(\mathbf{v})$ are regression coefficients at location $\mathbf{v}$. The GWR model was developed using the R "spgwr" package (Oshan et al., 2019). The bandwidth was selected using an adaptive spatial kernel density function. In the model, a distance-based spatial weight matrix was calculated to characterize the spatial relationships between nearby LGAs. The optimal number of neighbor LGAs was determined by minimizing the Akaike information criterion (AIC) for the model. In both the GAM and GWR, the contribution of each explanatory variable was calculated as the deviance that was explained by the variable.

4. Results

4.1. Estimates of road quantity and quality

Table 1 shows a summary of variables used for computing the quantity and quality dimensions of road sustainability indexes. Table 2 shows the estimated weights of variables and indicators. With the weights of indicators, the block-level Γ_A and Γ_B have been computed, respectively. Fig. 4 shows spatial distributions of block-level Γ_A and Γ_B across the state. In addition, the block-level SRII is calculated to merge the information from both quantity and quality dimensions (Fig. 5).

Fig. 5 and Table 3 show the comparisons between SRIIs and remoteness areas (Australian Bureau of Statistics, ABS, 2018), population, and POI in WA. The results indicate that the road sustainability and its quantity and quality dimensions are high in major cities and inner regions, but that is relatively low in remote areas (Fig. 5). We also found that 27.8% of the population lives in blocks of the top 20% of the SRII, which cover 24.7% of the points of interest (POI) of facilities, and 6.5% of the population lives in blocks of the bottom 20% of the SRII, which contains 9.5% of the facility POI (Table 3). Both the population and POI percentages are slightly more optimal than those of the SRII. Therefore,

Table 2
Weights of variables and indicators for sustainable road infrastructure indexes.

Phase (weight)	Category of indicators (weight)	Indicator	Weight
Quantity (0.5)	Road density (0.5)	Road density	0.049
		Main roads density	0.131
		Roads shared by population	0.820
	Connectivity (0.5)	Road intersection density	1.000
Quality (0.5)	Road performance (0.25)	Road roughness	0.404
		Road rutting	0.262
		Road deflection	0.163
		Road curvature	0.172
	Road safety (0.25)	Crash rate	1.000
	Road contribution to the accessibility to facilities (0.25)	Contribution to access to schools	0.154
		Contribution to access to hospitals	0.146
		Contribution to access to government facilities	0.169
		Contribution to access to industries	0.299
		Contribution to access to leisure facilities	0.232
	Distance to other transport modes (0.25)	Distance to ports	0.163
		Distance to airports	0.367
		Distance to railway	0.470

from the perspective of sustainable development, the road infrastructure can satisfy stakeholder requirements in both urban and rural areas in WA.

4.2. Quantity-quality trade-off relations

The quantity and quality dimensions of sustainable road infrastructure development are unequally distributed across the study area. Dense roads are helpful for improving overall road quantity, but they do not always indicate high road quality. Additionally, high-quality sustainable road infrastructure can also come from reasonably instead of extremely dense roads. In the study, the quantity-quality trade-offs are quantified with a utility function and a marginal utility function, where the marginal utility is presented as a partial derivative of the quality function of the quantity. Fig. 6 shows the DMU-based analysis of the quantity-quality trade-off relations of road sustainability. The quantity-quality relationship encompasses all three stages of DMU, including increasing return (IR), marginal return (MR), and negative return (NR). The IR stage is featured in the consistently increasing portion of the utility function and marginal utility, the MR stage features an increased utility function and decreased marginal utility, and the NR stage features a consistently reduced utility function and marginal utility. To further understand the varied Γ_A-Γ_B relation at different DMU stages, Fig. 7 shows a summary of indicators of the SRII at DMU stages and spatial distributions of DMU stages. In general, SRII indicators have high values in the NR stage and low values in the IR stage (Fig. 6 a and Fig. 7). The estimated dividing lines of the three stages are 0.072 and 0.585 of Γ_A (Fig. 6 b), corresponding to 0.092 and 0.697 km/km^2 of road density, and 0.051 and 0.559 intersections/km^2 of road connectivity (Fig. 6 c and

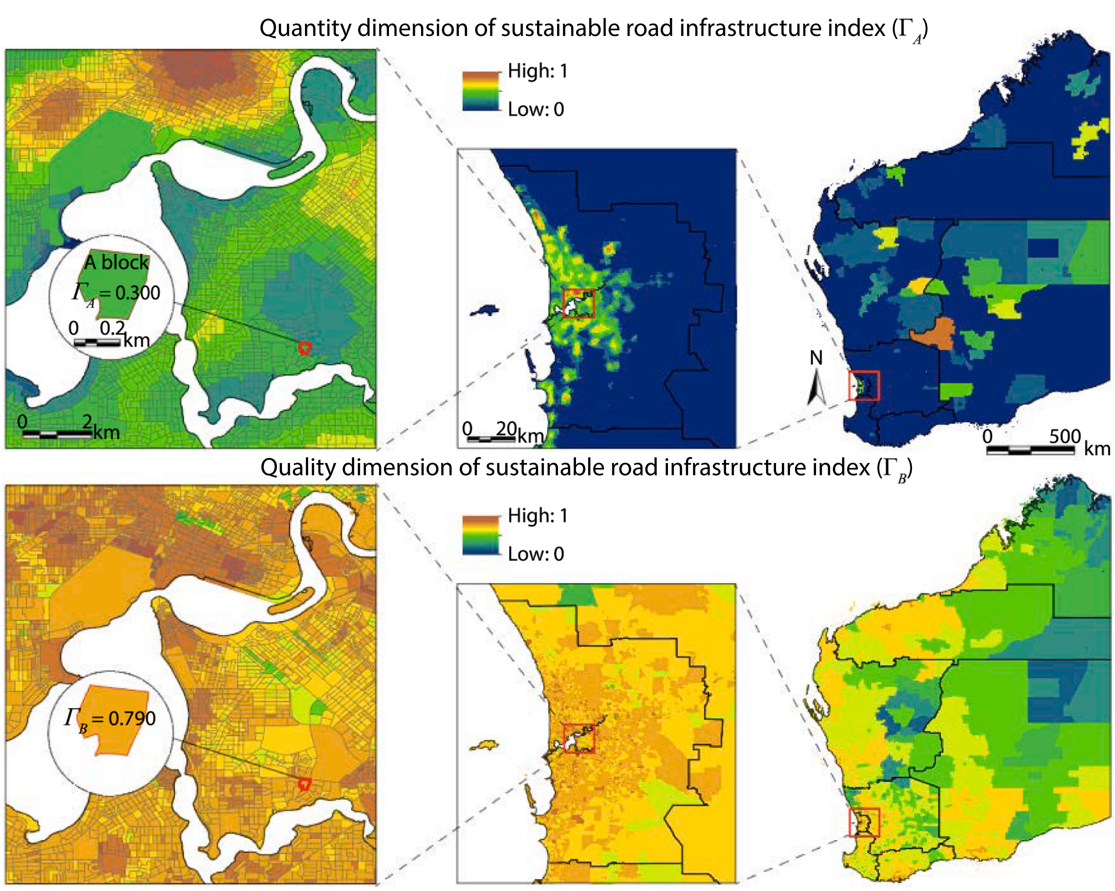

Fig. 4. Spatial distributions of block-level quantity (a) and quality (b) dimensions of the sustainable road infrastructure index (SRII, Γ) in Western Australia. The quantity dimension of SRII (Γ_A) is computed with indicators of road density and connectivity, and the quality dimension of SRII (Γ_B) is estimated with indicators of road surface performance, road safety, road contribution to the accessibly to facilities, and distance to other transport modes.

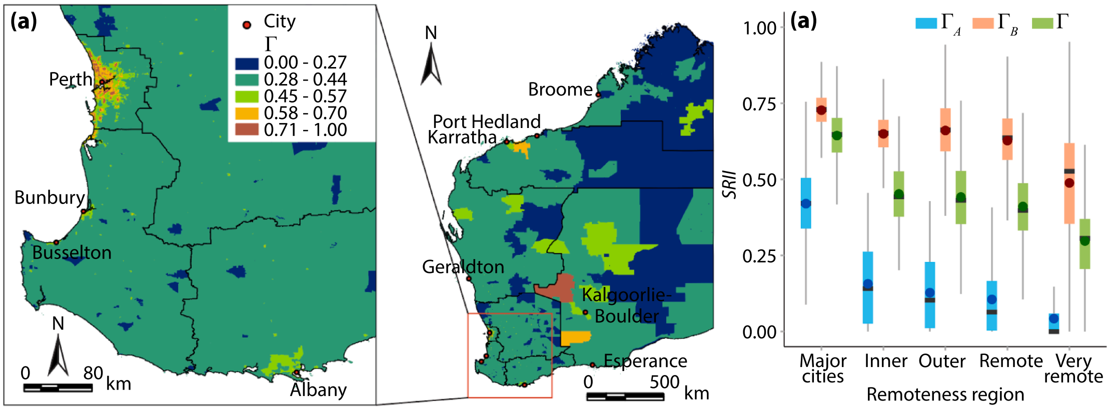

Fig. 5. Spatial distribution of the block-level SRII. Relationships of SRII, population and remoteness regions. (a) Relationship between SRII and Remoteness regions, (b) Population percentages within five SRII quantiles, and (c) Population within five SRII quantiles and remoteness regions.

Table 3
Statistical summary of population and points of interests (POIs) of facilities in quantiles of SRII.

SRII Quantile	SRII Range	Percentage of population	Percentage of POI
First (lowest)	0.00–0.40	6.45%	9.49%
Second	0.41–0.53	16.64%	19.34%
Third	0.54–0.62	22.91%	22.87%
Fourth	0.63–0.68	26.20%	23.60%
Fifth (highest)	0.69–1.00	27.79%	24.70%

d).

Table 4 shows a comparison of blocks between DMU stages and remoteness areas. In the IR stage, Γ_B significantly increases with the growth of Γ_A. Blocks at the IR stage are primarily non-residential blocks, accounting for 85.8% of all blocks, such as parks and bare lands, and 74.5% of the IR-stage blocks are distributed in outer and remote regions. In the MR stage, Γ_A and Γ_B consistently increase, but the increasing rate or marginal utility of Γ_A decreases when Γ_A increases from 0.072 to 0.585. MR-stage blocks, accounting for 72.3% of the blocks in WA, are predominantly residential blocks with surrounding public facilities, such as parks and lakes. Over 80% of the WA population live in MR-stage blocks. In the NR stage, Γ_B decreases with an increase in Γ_A. Blocks of urban cores are identified in the NR stage, which account for only 1.3% of the area across the state but cover 21.2% of the blocks and 7.8% of the population.

4.3. Hotspots and cold spots in quantity-quality trade-offs

At the block level, Fig. 8 shows distributions of blocks with clustered road sustainability, including hotspots and cold spots, which have consistently high or low SRII values with neighboring blocks. In the study, SRII values in hotspots and cold spots are represented by the highest and lowest of the three types of spatial clusters: high-high (HH), low-low (LL), and other clusters. Mean quantity and quality SRII indicators in hotspots are the highest and those in cold spots are the lowest. Table 5 shows a summary of blocks, population, and areas in hotspot and cold-spot regions of road sustainability. Hotspot and cold-spot regions of Γ_A cover 24.1% and 17.1% blocks, and those of Γ_B cover 33.1% and 5.2% blocks, respectively. Hotspots are typically clustered in urban cores, and cold spots are distributed in remote and very remote areas. Fig. 9 shows comparisons of SRII, blocks, and population density between DMU and spatial clusters of road sustainability to explain the relationship between sustainable infrastructure development and spatial distributions in the quantity-quality trade-off relations. The overlap rates of spatial distributions between hotspot, other, and cold spot blocks and NR, MR, and IR stage blocks are 49.6%, 69.5%, and 64.9%, respectively. The MR stage contains all three types of spatial clusters. No blocks in the IR stage are located in hotspots, and no NR-stage blocks are located in cold spots. In the NR stage, Γ_A in hotspots is similar to that in other regions, but Γ_B in hotspots is slightly higher than that in the other regions. In the MR stage, both Γ_A and Γ_B in hotspot regions are significantly higher than those in cold-spot regions. In the IR stage, Γ_A is not critically different in the cold-spot and other regions, and it is significantly lower than that in the other DMU stages. Additionally, Γ_B in cold-spot regions is much lower than that in the other regions.

At the town or village level, Fig. 8 b shows the five groups of cold-spot towns/ villages of road sustainability identified from the cold-spot blocks for assisting future practical efforts in improving the road sustainability. The cold-spot blocks, where both the quantity and quality of road sustainability are significantly lower than those of the other regions, are characterized as exhibiting extremely low population densities, but 5.2% of the population still lives in these regions. From the perspective of decision making, increasing quantity and quality in cold-spot towns/ villages, where population and public facilities are denser than other areas, can effectively improve overall road sustainability. In total, 203 towns/ villages are identified from 15,861 neighborhood blocks using a cold-spot towns/ villages identification approach regarding facility POI density of blocks, and population and areas of towns/ villages. The cold-spot towns/ villages are classified into five categories based on the interaction of DMU stages and quantity-quality relations for strategic decisions. Among the towns/ villages, increasing quantity is the priority of sustainable road infrastructure development strategies for 57.7% towns/ villages which are featured in quantity cold spots and IR or MR DMU stages. In addition, increasing quality is the priority for 22.2% towns/ villages that are featured in quality cold spots and NR or MR DMU stages. For the 20.2% towns/ villages featured in cold spots of both quantity and quality, and in the MR DMU stage, strategic increasing both quantity and quality is required for sustainable road infrastructure development.

4.4. Contributions of road quantity and quality to income

Fig. 10 shows spatial distributions of income and the relationships between income and remoteness regions, DMU, and spatial clusters. The mean income per person is used as a direct indicator of regional socio-economic conditions. In WA, the high-income regions include Perth, the capital city of the state, and the northern and southern mining and industrial areas. The capital city is one of the major cities, and the mining and industrial areas are primarily distributed in remote regions. The high-income regions are typically located in the NR stage of DMU and in hotspots, and low-income regions are in the IR stage and cold-spot clusters.

Fig. 11 demonstrates that the Γ_A and Γ_B can significantly contribute

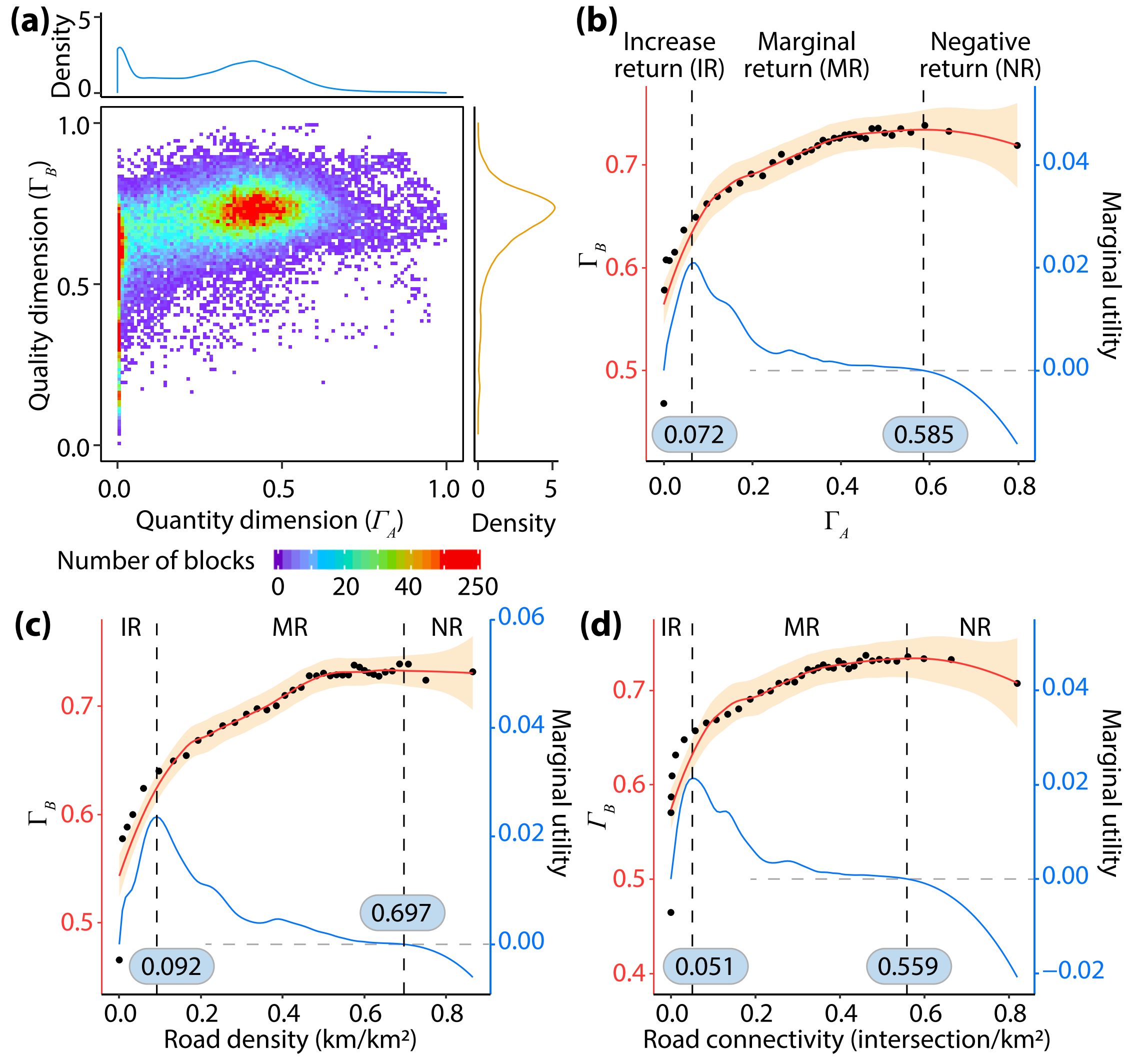

Fig. 6. Quantity-quality relations of sustainable road infrastructure and analysis of diminishing marginal utility (DMU). (a) Scatter plot of the relationship between the quantity and quality dimensions of the SRII. (b) Analysis of DMU and residential blocks in the three DMU stages, including increasing return (IR), marginal return (MR), and negative return (NR). (c) Trade-offs between road density and quality of road sustainability. (d) Trade-offs between road connectivity and quality of road sustainability.

to income, a proxy variable of socio-economic development. Features of sustainable road infrastructure contributions via nonlinear interactions and regional disparities are identified using nonlinear and spatial models, respectively. Fig. 11 a shows that the nonlinear and spatial models indicate that SRII can contribute to 22.1% of the local personal income, where Γ_A contributes to 5.9% and Γ_A contributes to 16.2%. Thus, Γ_B generally contributes to the local income at a rate 2.7 times higher than that of Γ_A. Fig. 11 b shows that although the contributions of road sustainability to personal income are significant, there are still differences in quantity and quality ranges and across regions. The nonlinear analysis in Fig. 11 c indicates that the growth rate of personal income varies within different SRII ranges. When Γ_A is lower than 0.42, personal income is substantially elevated with an increase in Γ_A, but when Γ_A is higher than 0.42, the growth rate of personal income is reduced. This means that when Γ_A is relatively low, increasing the road quantity can benefit personal income growth. In addition, there is a steeper increase in the income growth when Γ_B is higher than 0.69. This is because the road infrastructure quality is highly effective in reducing poverty and improving the availability and accessibility of public facilities (Calderon and Serven, 2004), and this effect is enhanced with the increased quality of road sustainability. Finally, from the spatial perspective, Γ_A has a high contribution to the income in outer and remote areas, blocks at the IR stage, and cold-spot regions (Fig. 11 d). In contrast, Γ_B has higher contributions in major cities and inner regions, which are primarily the blocks in the MR and NR stages and non-cold-spot regions.

5. Discussion

This study estimates road sustainability and the quantity-quality trade-off relations from the perspective of stakeholder service and requirements. It is essential to perform an analysis, make decisions, and take actions from stakeholder perspectives as they play a key role in assessing progress towards the SDG objectives and in resource allocation. The contributions and implementations of this study to practical decision making are discussed from following aspects.

First, the analysis of spatial hotspots and cold spots and contribution of SRII to resident income provide regional solutions for establishing strategies, decisions, and actions for sustainable road infrastructure development. Among the cold-spot blocks of road sustainability, the identified cold-spot towns and villages are priorities of future sustainable road development strategies. Strategic efforts are required for decisions in terms of the road quantity-quality features and DMU stages of the towns and villages. In addition, the quantity and quality dimensions

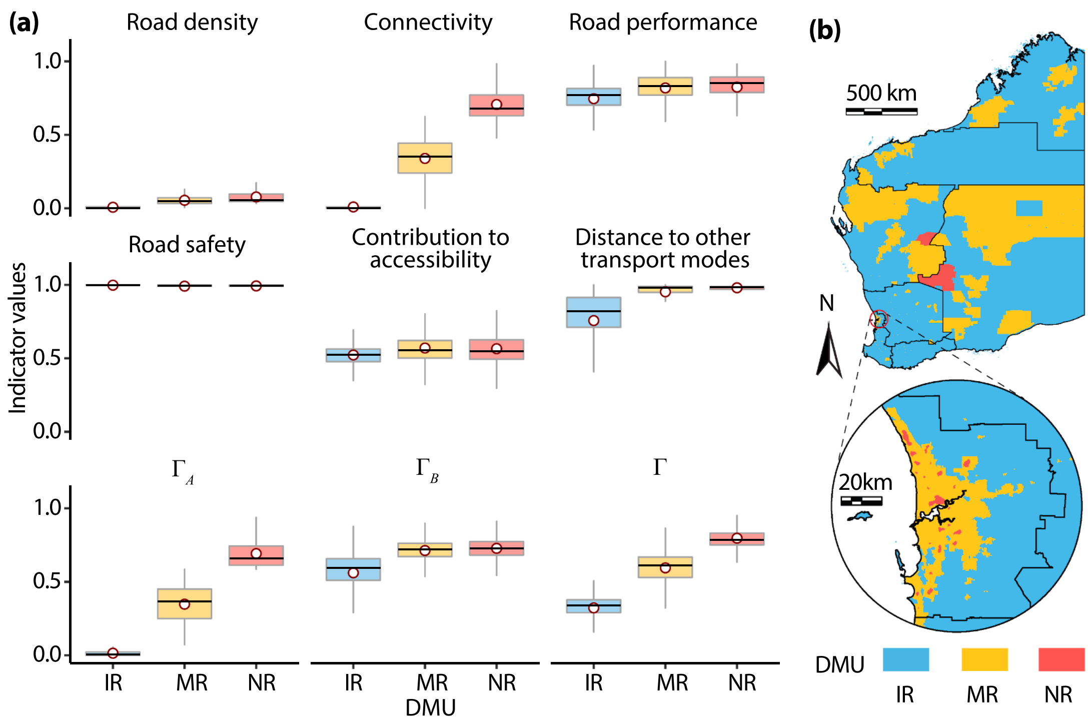

Fig. 7. Summary of indicators of the SRII at DMU stages (a) and spatial distributions of the three DMU stages (b).

Table 4
Numbers of blocks in three stages of diminishing marginal utility (DMU) and different remoteness regions.

DMU	Remoteness regions				
	Cities	Inner	Outer	Remote	Very remote
IR	538	1757	2227	1495	2980
MR	22503	2950	2912	1417	902
NR	2742	0	0	0	2

of sustainable road infrastructure can contribute 22.1% to the mean income per person. Regarding the quantity dimension, building new roads can typically provide enormous opportunities for socioeconomic development (Gibbons et al., 2019). Regarding the quality contributes 2.7 times more than the quantity dimension, this study reveals that, in general, efforts to improve the quality of road infrastructure can yield more positive returns for resident income. The quality dimension discussed in this study includes road surface performance, safety, facility accessibility, and links to other transport modes.

In addition, this study demonstrates that both the quantity and quality dimensions of sustainable road infrastructure and their contributions to socioeconomic development have significant regional disparities. Frist, due to the marginal utility of both dimensions, different road maintenance and management strategies can be proposed to handle challenges in each of the three DMU stages. The estimated dividing lines of the three DMU stages are 0.092 and 0.697 km/km^2 of road density, and 0.051 and 0.559 intersections/km^2 of road connectivity. In addition, hotspot regions of roads with clustered high SRII values are primarily identified in densely populated areas, such as major cities and inner regions, and cold spots are predominantly located in remote regions with low population densities. Approximately 5.2% of the population lives in cold-spot blocks. Although most cold-spot regions are non-residential areas, there are still 10.7% of cold-spot blocks are the blocks of towns and villages with dense population and facilities. Road construction and improving road stakeholder services in rural and remote areas are critical for eliminating SRII regional inequalities and enhancing livelihoods, livability, and wellbeing (Faiz et al., 2012). Therefore, efforts are required in the identified cold-spot regions to improve their regional sustainable road infrastructure. Establishing a long-term vision is essential for building sustainable infrastructure (Thacker et al., 2019), where regional disparities must be carefully and systematically considered in road construction, maintenance, and management.

Finally, the quantity-quality trade-off analysis driven by stakeholder requirements are significant for the strategic decisions for global sustainable road infrastructure development. The DMU analysis and spatial modelling demonstrate that strategic and long-term road maintenance activities can typically satisfy road stakeholder requirements in WA. However, the global road infrastructure network still faces numerous challenges. For instance, the SDG 9.1 targeting sustainable infrastructure highlights the quantity of infrastructure and lacks the descriptions of quality dimension due to the difficulties in the definition and data collection. The difficulties also lead to the limited local studies at a large scale, which is critically important for developing global, nation-wide and regional strategic decisions regarding the quantity-quality trade-offs with regional disparities and the requirements of cold-spot neighborhoods and local areas. The strategic decisions of investment into and construction of road infrastructure can greatly contribute to meeting the SDG 9 and other SDGs. A direct benefit of road construction and maintenance is that it improves the accessibility of public facilities and provisioning of public services, such as water, education, and healthcare, for local communities, especially in rural and poor areas. This benefit is closely associated with ending poverty (SDG 1), promoting agriculture supply and ending hunger (SDG 2), ensuring the availability of water and sanitation resources (SDG 6), and the accessibility of reliable energy (SDG 7). Building sustainable road infrastructure is also a key component of resilient and sustainable urban development (SDG 11), where road infrastructure projects should be implemented with reduced consumption and waste (SDG 12) and decreased carbon emissions (SDG 13).

There are still limitations of this study and further studies are recommended in following aspects. First, more studies about regional disparities and quantity-quality relations of road sustainability in other regions are needed due to the difference of road sustainability among

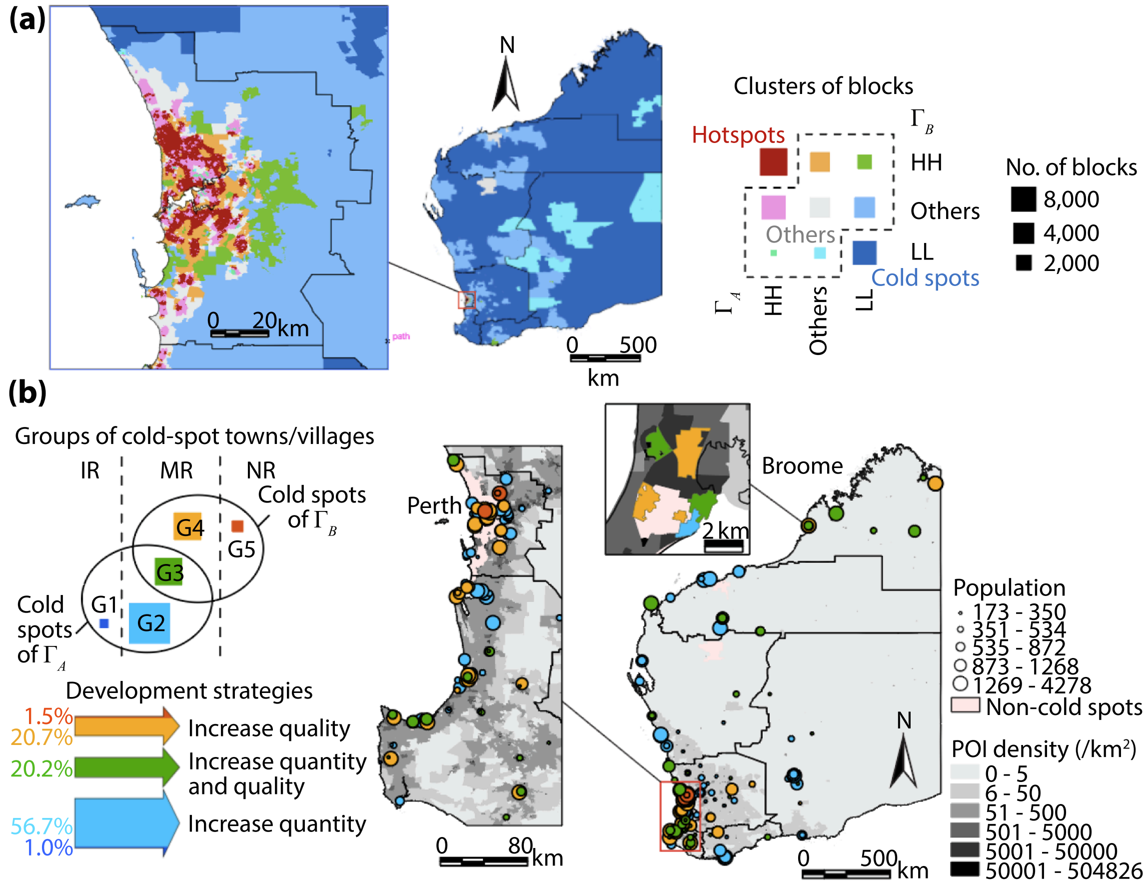

Fig. 8. Distributions of hotspots and cold spots in quantity-quality trade-offs. (a) Spatial distributions. HH: high–high cluster; LL: low–low cluster. (b) Five groups of road sustainability cold-spot towns and villages identified by the interaction between DMU and cold spots of Γ_A and Γ_B. Group 1 (G1): cold spots of Γ_A on the IR stage; Group 2 (G2): cold spots of Γ_A on the MR stage; Group 3 (G3): cold spots of both Γ_A and Γ_B on the MR stage; Group 4 (G4): cold spots of Γ_B on the MR stage; Group 5 (G5): cold spots of Γ_B on the NR stage.

Table 5
Summary of blocks, population, and areas in hotspot and cold-spot regions of road sustainability.

SRII	Percentage of blocks		Percentage of population		Percentage of areas	
	Hotspots	Cold spots	Hotspots	Cold spots	Hotspots	Cold spots
Γ_A	39.1%	20.6%	47.8%	17.1%	0.15%	87.4%
Γ_B	42.3%	33.9%	57.7%	8.8%	0.03%	79.4%
Γ	24.1%	17.1%	33.1%	5.2%	0.02%	78.6%

various regions. The spatial distribution pattern of road infrastructure in WA is different with that in other places. In addition, it is recommended to develop localized datasets of variables when methods in this study are applied in other regions. For instance, it might be difficult to collect high-resolution data of road performance in regions without historical observations.

6. Conclusions

This study provides a block-level analysis of quantity-quality trade-offs in sustainable road infrastructure at a large spatial scale. The developed SRII can be used to examine road sustainability from quantity

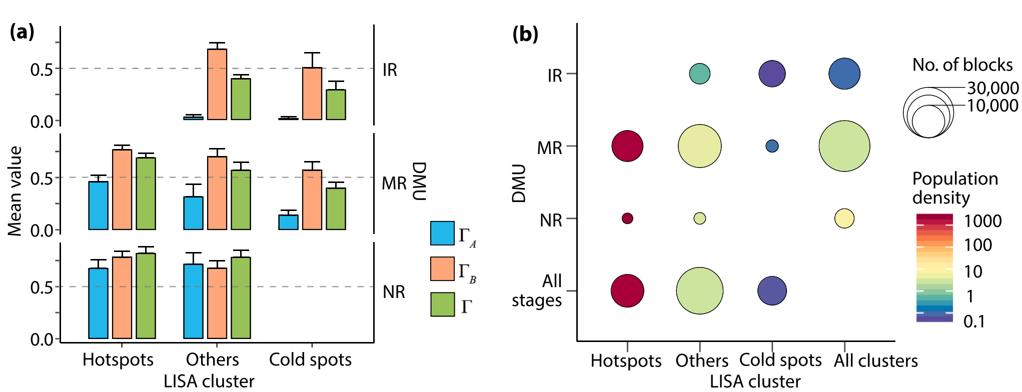

Fig. 9. Comparison of spatial clusters and DMU stages of road sustainability by (a) SRII, and (b) statistics of blocks and population density.

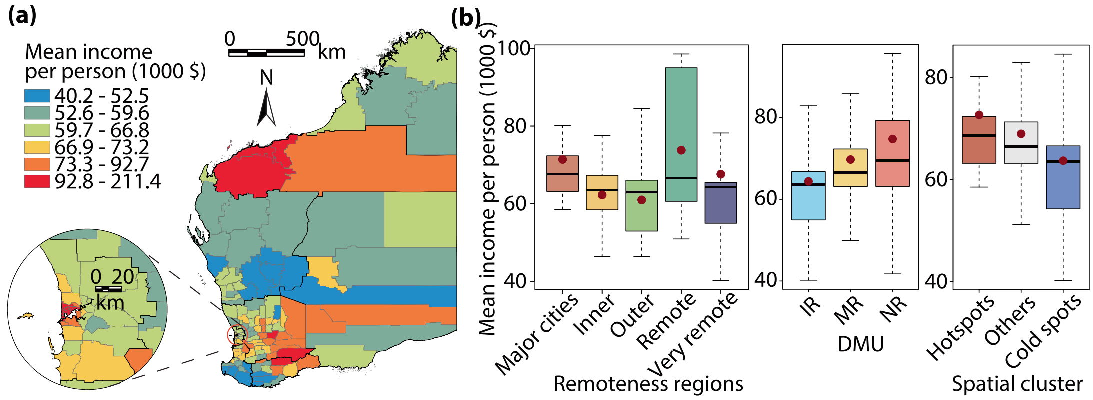

Fig. 10. Spatial distributions of mean income per person (a), and Relationships between mean income per person with remoteness regions, DMU stages and spatial clusters (b).

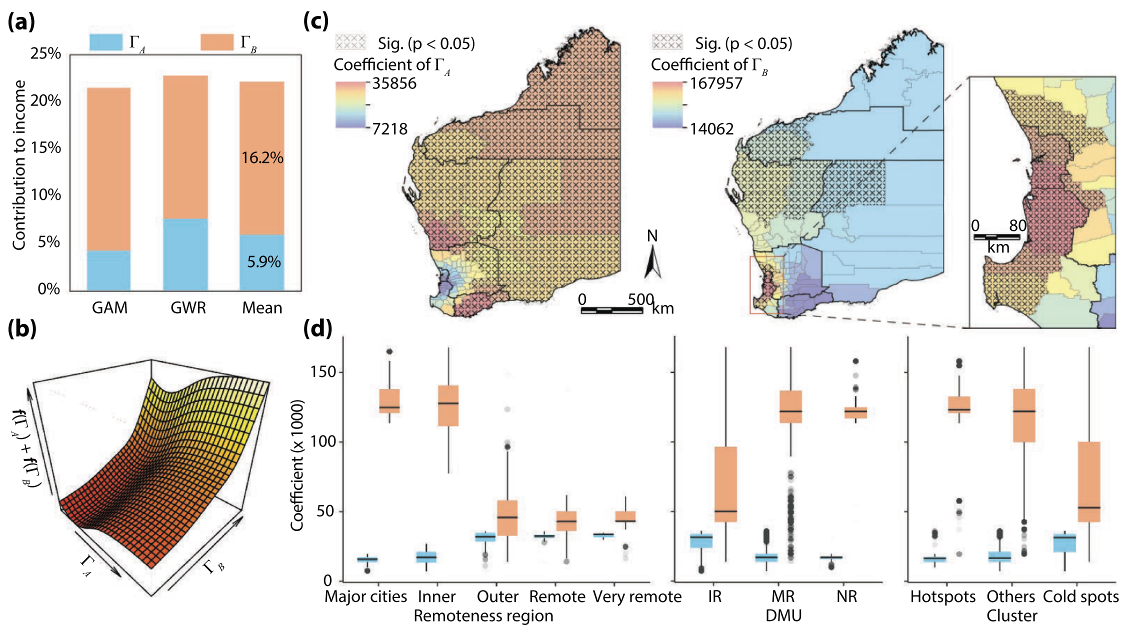

Fig. 11. Contribution of sustainable road infrastructure and quantity–quality dimensions on socio-economic development. (a) Contribution of SRII on the income explored by nonlinear and spatial models. (b) Nonlinear contributions. (c) Local contributions. (d) Regional disparities in contributions compared with region remoteness, DMU stage, and spatial cluster.

and quality perspectives, and the STOR model is effective in assessing road quantity-quality trade-off relations. This study reveals the a three-stage relation between quantity and quality dimensions of road sustainability, which informs the regional disparities of road development. To further understand the regional disparities in the quantity-quality relations, spatial methods are developed to identify regional clustering regions, towns, and villages, and quantifying contributions of the road quantity and quality to economic development. The study also finds that the contribution of road quality can contribute about three times the contribution of road quantity to residential income. Therefore, strategies with considerations of quantity-quality trade-off relations and regional disparities are required to achieve global sustainable infrastructure development goals.

CRediT authorship contribution statement

Yongze Song: Conceptualization of this study, Methodology, Formal analysis, Writing - Original Draft. **PengWu**: Conceptualization of this study, Supervision, Writing- Reviewing and Editing. **Keith Hampson**: Writing- Reviewing and Editing. **Chimay Anumba**: Writing- Reviewing and Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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