

## **Task Analysis for Improving Training of Construction Equipment Operators**

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### **ABSTRACT**

We previously conducted a preliminary analysis of the tasks performed by operators of hydraulic excavators, where the excavator is stationary and the implement is controlled by joysticks operated with the left and right hands. In the present paper, we put forward a detailed comparative analysis of the tasks for a hydraulic excavator and those for a wheel loader, of which operation of the latter requires simultaneous coordination of vehicular driving and implement operation whereas operation of the former does not. These analyses, based on Hierarchical Task Analysis (HTA), illustrate the complexity of equipment operation and distinguish the skills to be acquired for each machine. By employing HTA to decompose complex tasks into a hierarchy of goals and sub-goals, a better direction may be devised for how trainees spend their practice time for both the simulator and real equipment training phases. Future phases of this research will include input from experienced operators and trainers and extension of the HTA analysis to finer levels of description, including cognitive tasks.

## INTRODUCTION

The complexity of tasks performed in the operation of construction equipment presents challenges for the study of skill development. Such tasks require intricate perceptual-motor skills that improve over many years of field experience. Although industry training programs employ established curricula that introduce equipment functions and typical task objectives, we have found no secure evidence that these curricula are informed by a systematic human-factors based analysis of the tasks performed by operators. Structured characterization of task composition can inform all stages of education and training programs, including how best to organize training conducted on a virtual reality simulator, the application emphasized for this work.

Most conventional research on acquisition of perceptual-motor skills is based on simple tasks, characterized by one or two decisions and a similar number of motions (see, e.g., Lee 2011). Simple tasks allow effects of variables to be isolated, causal influences of those variables on performance to be determined, and principles of learning and skill acquisition to be identified. However, how to apply this knowledge to training of complex skills such as operation of construction equipment is not immediately obvious because the tasks to be performed are not easily segregated (Healy and Bourne in press). Therefore, methodical examination of training principles within the context of a thorough analysis of the tasks performed by equipment operators is necessary for education and training programs to be optimized.

Benefits from applying knowledge of the task analysis potentially extend to all phases of training. Introductory sessions that are generally conducted away from the equipment may be enhanced by improving the mental models that trainees formulate before beginning to practice the tasks. The simulator training phase, which typically follows before field practice, may be improved by the design of training tasks in the highly controllable virtual environment that are more precisely focused on enhancing the fundamental skills rather than merely mimicking tasks performed in the real environment. For both the simulator and real-equipment training phases, better direction might be devised for how the trainees spend their practice time.

For the present discussion, a detailed comparative analysis of tasks for a hydraulic excavator and those for a loader is presented. This analysis illustrates the complexity of equipment operation and distinguishes the skills to be acquired for each machine. Many methods of task analyses exist (see, e.g., Diaper and Stanton 2004), but we base our analysis of equipment operation tasks on Hierarchical Task Analysis (HTA), a well accepted and developed form of task analysis (Annett 2004; Stanton 2006). HTA analyzes not only the sequences of actions involved in

executing tasks, but also the task goals, and it can be extended to make explicit the cognitive demands and design requirements (Phipps et al. 2011).

## **BACKGROUND ON HIERARCHICAL TASK ANALYSIS**

HTA was developed in response to the need for a systematic basis for understanding the component skills required in complex non-repetitive operator tasks, especially process control tasks found in industrial work practices (Annett and Duncan 1967). HTA has since been extended to depict many other types of tasks, for example, preparation for and delivery of anesthesia (Phipps et al. 2008). As noted by Phipps et al. (2011), “It is particularly useful as a general task analysis method because it provides a flexible, exhaustive and systematic means of identifying the behaviours that occur during a task (Patrick 1992)” (p. 741).

HTA begins by decomposing complex tasks into a hierarchy of goals and sub-goals. The way in which a goal can be achieved is conceived of as an operation, and an operation includes the actions that can lead to goal fulfillment, conditions that will activate the goal, and conditions that will fulfill the goal. The analysis is intended to consider both how the task should be performed and how it is actually carried out by operators (Annett 1996). Because the task is decomposed into sub-goals, performance can be analyzed at a number of different levels (Stanton 2006).

Annett et al. (1971, p. 4) described three principles on which task analysis is based:

- 1. At the highest level we choose to consider a task as consisting of an operation and the operation is defined in terms of its goal. The goal implies the objective of the system in some real terms of production units, quality or other criteria.*
- 2. The operation can be broken down into suboperations each defined by a sub-goal again measured in real terms by its contribution to overall system output or goal, and therefore measurable in terms of performance standards and criteria.*
- 3. The important relationship between operations and sub-operations is really one of inclusion; it is a hierarchical relationship. Although tasks are often proceduralised, that is the sub-goals have to be attained in a sequence, this is by no means always the case.*

These principles can be summarized as indicating that the ultimate goal is a function of system objectives, achievement of sub-goals as well as the overall system goal can be evaluated in terms of objective performance measures, and whether subtasks must be performed as sequences or have contingencies needs to be taken into

consideration (Hoffman and Militello 2009).

Although HTA was devised initially to focus mainly on the overt actions involved in achieving task goals, extensions to make the cognitive task requirements more explicit have been developed. Phipps et al. (2011) identify two such extensions, those of sub-goal template (SGT) and skills-rules-knowledge (SRK) behavior modes. For the former, after initial task decomposition, the SGT provides a way to further analyze subtasks that require an interaction between the user and a system into the types of interactions that occur (Shepherd 1993). Ormerod and Shepherd (2004) identify four templates (act; exchange; navigate; monitor), each of which seems to map onto tasks performed by equipment operators and consists of multiple task elements. From the SGT analysis, it is possible to determine the data or information that should be presented to the user. For the SRK framework, whether a particular subtask involves skill-, rule-, or knowledge-based behavior is determined. According to Rasmussen (1983), skill-based behavior reflects a highly overlearned, automatized mode that requires little effort on the operator's part. Rule-based behavior is more effortful and requires retrieval of explicit rules that the operator was taught about what actions to take in specific circumstances. Knowledge-based behavior is the most effortful and time consuming mode, requiring diagnosis of problem situations and selection of action based on the decisions reached. The general idea with respect to hierarchical task analysis is that speed of responding and the likelihood of errors of various types for each subtask can be estimated better when the mode of behavior is taken into account. Phipps et al. (2011) concluded that both frameworks were of value in helping to improve their understanding of the cognitive processing performed by anesthesiologists.

It is our hypothesis that HTA will provide an insightful description of the tasks involved in operating heavy construction equipment and facilitate a structured assessment of the skill requirements and their development. Delineating the hierarchy of goals and sub-goals and then extending that definition to incorporate the cognitive aspects of an operator's performance should reveal opportunities for substantive improvements in training procedures.

## **TRAINING SIMULATORS USED IN THIS STUDY**

Although the insights gained from our research have their application to all phases of operator training, our emphasis is on skill development and transfer from operator training simulators, which we reference for carrying out our HTA. The simulators used in this research were the Hydraulic Excavator Personal Simulator from Simlog and the 4WD Loader Operator Training Simulator from John Deere. Both present to the trainee a virtual scene from the perspective of a person in the cabin of a construction machine. The trainee controls the machine in the virtual

scene via some combination of actions with joystick(s), pedals, and a steering wheel (for the loader), mimicking the way in which the real construction equipment is controlled. The simulated hydraulic excavator consists of a boom, bucket and cab on a rotating platform sitting atop an undercarriage with tracks. This machine is designed for digging below the ground level on which the equipment rests. The training simulator tasks include Control Familiarization, Carrier Positioning, Bucket Placement, Trenching, Single Pass Digging, and so on. The simulated loader, however, is wheel-mounted, turns by means of a hydraulically actuated pivot point in the loader frame between the front and rear axles (i.e., articulation), and has a wide front mounted bucket connected to the end of two boom arms to scoop up loose material, such as dirt, sand or gravel, and carry it from one location to another. The tasks on the loader simulator include, among others, Control Familiarization, Driving on Jobsite, and Loading Trucks.

### **TASK REQUIREMENTS FOR EXCAVATOR AND LOADER OPERATIONS**

We previously carried out a preliminary analysis of the tasks performed by operators of hydraulic excavators, where the machine is stationary and the implement is controlled by joysticks operated with the left and right hands. A recent publication from our research group described the general task requirements for the fundamental construction operations of dozing, loading and carrying, and stationary (fixed position) excavation to illuminate the distinctive challenges for the class of simulators that have been marketed in recent years to train heavy construction equipment operators (Dunston et al. 2011). In this section, initial HTAs for two truck loading operations performed with different types of earthmoving equipment—an articulated wheel loader and a track-mounted hydraulic excavator—are illustrated and explained. These models were produced from our observation of the two operations as performed in the virtual environments presented in the two PC-based virtual reality training simulators described above for the respective equipment models. These observations were supplemented by reference to the experience of one of the authors in operating both types of equipment.

For our illustration, a specific task of loading dump trucks was selected and decomposed using HTA. This task was selected because it is one commonly performed with both the loader and excavator, but for which there are some differing performance requirements due to distinctions in machine configurations and limitations, control functions, and the material sources being loaded into the truck. We expected HTA to clarify the extent of similarity and differences between the two cases, which might in turn indicate effective common (i.e., transferable) and distinctive methods to facilitate skill development. In this dump truck loading task, the truck and the construction machines were on the same ground level. The HTAs

were drawn up through the observation of the typical execution of the construction tasks and apply to the steady state cycles of the operations, i.e., operation start-up steps are not included. Finally, since the overall objective is to move the soil from the source location to the truck bed, the HTAs primarily emphasize the handling of the buckets which the operators manipulate in contact with the soil.

The HTAs for the excavator and for the wheel loader are depicted as hierarchical diagrams in Figures 1 and 2, respectively. In these diagrams, the overall goal (0) is at the top of the hierarchy, with the main sub-goals located immediately underneath. Some of these sub-goals are decomposed into a second level of sub-goals. The boxes in the diagram are numbered in an outline structure, i.e., with sub-goals inheriting the number of their parent goal plus a period and new ordinal number. Also, the 'Plan' specified in the ovals shows the conditions under which each of the sub-goals are triggered. Whether subtasks are performed sequentially or concurrently is specified by the placement of notations ">" and "+", respectively, between the numbers of the subtasks. This method of notation was adopted from Annett et al. (2000).

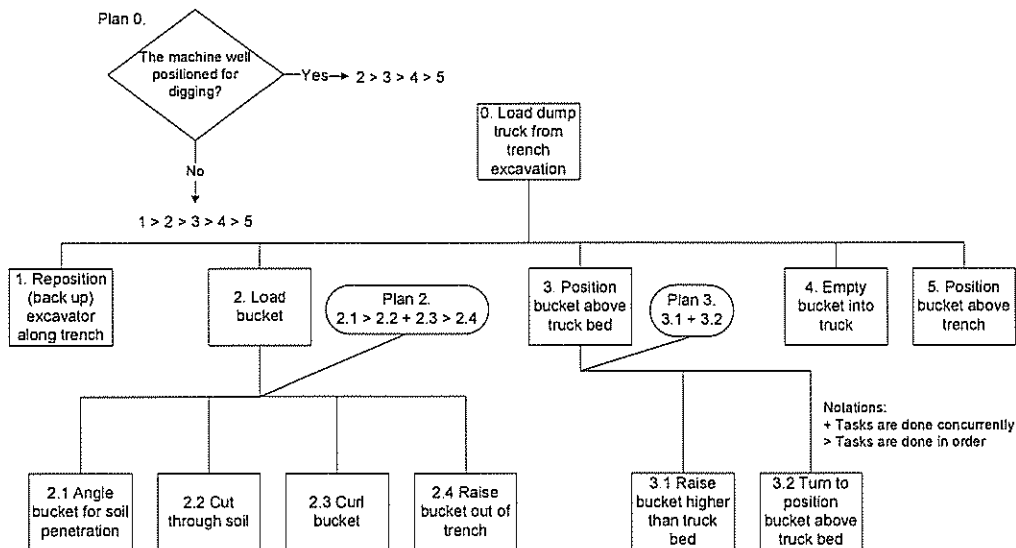


Figure 1. Goal hierarchy for excavator digging a trench and loading a truck

### HTA for Hydraulic Excavator

In the excavator scenario analyzed for Figure 1, soil is obtained from the construction of a trench and dumped into the bed of a dump truck. From a parked position in line with the trench, the operator loads the bucket by extending and angling the bucket for executing a smooth pass (cut) through the soil. While this cutting is done, the bucket is also curled toward the machine to ensure that the soil is

contained when the bucket is lifted out of the trench and swung over to the truck bed. Because the excavator and truck are on the same ground level, the bucket must be raised to an appropriate height to clear the sides of the truck bed. Once over the truck bed, the bucket is uncurled to release the soil before the machine is rotated back to place the bucket above the trench for the next digging pass. The decision point illustrated in the diamond for “Plan 0” refers to the periodic requirement that the excavator back up along the trench line to maintain an optimal reach for digging the trench.

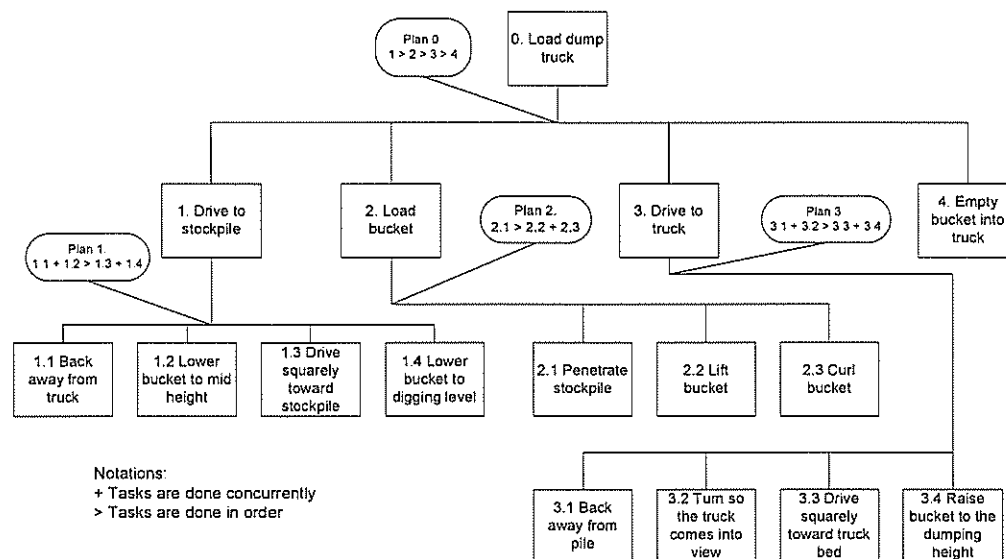


Figure 2. Goal hierarchy for loader transferring soil from stockpile to truck

### HTA for Articulated Wheel Loader

In the loader scenario analyzed for Figure 2, soil is obtained from a stockpile from, which the loader with its full bucket is backed away and then driven over to the dump truck. The operator commences to load the bucket by driving squarely towards the stockpile while lowering the bucket to ground level for cutting from the base of the stockpile. Then the operator drives the bucket into the stockpile and next simultaneously lifts and curls the bucket upward to contain the soil. With the bucket full and positioned below eye level for travel visibility, the operator backs the loader away from the stockpile while turning to bring the truck into view. Next the loader is driven over to the truck, lining up and raising the bucket to dump over the side of the truck bed. After emptying the bucket, the cycle is then completed with backing away from the truck while lowering the bucket once again to travel height. We determined that the HTA description worked best by defining the two driving segments by both backing away from one location and driving toward the other.

### **Observations from the HTA Diagrams**

Generally speaking, these analyses of the goal hierarchies for the dump truck loading task performed with an excavator and with a loader suggest that HTA is a useful tool for modeling the tasks in the form of goals and sub-goals. The structure of subtasks involved in operating each piece of equipment suggests specific skills that need to be taught, for example, the proper alignment of the loader on its approaches or the proper angling of the excavator bucket for efficient digging. The extent to which the tasks practiced in current training programs match the component skills that need to be mastered can be evaluated. The analysis also suggests that skill at subtasks in common between the excavator and loader may transfer from one machine to the other (e.g., “Empty bucket into truck”), whereas subtasks that are distinct (e.g., those for “Load bucket”) likely will not.

As for complexity, comparison of Figures 1 and 2 shows that the HTA for loading the dump truck using the loader has more sub-goals than does that of the excavator. This difference in sub-goals is because performing the task with the loader involves driving to move from the stockpile to the truck bed each cycle, whereas performing it with the excavator does not. Rather, the excavator is stationary and only requires being driven when the trenching position is no longer optimal to fill the bucket. However, the excavator has higher degrees of freedom because the bucket location is controlled by both stick and boom, whereas the loader is only controlled by the boom. To control the bucket movement efficiently, an excavator operator needs to move the boom, stick and bucket concurrently. The functions of these components are not captured in the HTA because of our focus on the bucket. Extending the HTA to further levels of sub-goals would begin to reveal these complexities. Thus, by simply comparing these specific dump truck loading HTAs for the two pieces of equipment and comparing the different control configurations, it is not possible to say which machine is more difficult to operate. Indeed, further decomposition of the tasks and the extension to include cognitive task requirements will be needed. Mental workload measurement as well as objective performance on the tasks should also indicate the relative difficulty of the tasks.

Although the same HTA diagram may characterize the goal structure for both novices and experts, it is possible that some of the subtasks performed sequentially by novices may become proceduralized in experts to allow them to perform the tasks concurrently. Such changes would be associated with the smooth control that characterizes experienced operators (Dunston et al. 2011). Quantifying the degree to which this blending of sub-task performance occurs would facilitate skill measurement. The analyses reported in this paper are based on the authors’ analyses



of the dump truck loading task. The next step is to refine these analyses by having expert heavy equipment operators evaluate the analyses and provide feedback as to modifications that need to be made to capture the task structure more accurately. Input from trainers of equipment operators can also be used to validate and revise the hierarchies, with specific emphasis on evaluating implications for training. Finally, as noted, HTA allows the tasks to be decomposed further into the fundamental information-processing steps required of operators for execution of each subtask. It is this level of analysis, which we have yet to perform, that should be of most value for evaluating training issues.

## CONCLUSION

This research on skill development, specifically as it applies to operator training for two specific types of construction equipment, will continue to aim at using HTA to decompose the complexity of equipment operation and distinguish the skills to be acquired for each machine. Identification of the skill elements not only allows training to be targeted toward those elements, but it can be used to identify elements that tasks have in common, suggesting where benefits of training are likely to transfer. Although our initial HTA comparison did not reveal definitively which equipment type is more difficult to learn and operate, we argue that extending the HTA to include basic control functions and cognitive tasks should reveal such relative distinctions. These extensions will be accomplished with input from experienced operators and/or trainers. The future findings of this research are expected to provide evidence as to how the trainees should best spend their practice time.

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