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16. ABSTRACT
The California Department of Transportation (Caltrans) needs to provide the best available training to its Maintenance personnel, particularly those operating heavy equipment. This research study evaluated the applicability and benefits of state-of-the-art heavy equipment simulators to support training efforts at the Maintenance Equipment Training Academy (META) and in Caltrans districts. Initial trainings showed that the simulators can be integrated easily into training efforts and were received positively by trainers and users. Training plan proposals were developed. The cost benefits of simulator use over real equipment were estimated. Simulators can be transported in a trailer from district to district, which was evaluated in a cost-benefit analysis as well as discussed with trailer layouts and logistics.

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# Advanced Highway Maintenance and Construction Technology Research Center


Department of Mechanical and Aerospace Engineering
University of California at Davis


## Evaluation of Heavy Equipment Simulator Systems


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Barbara S. Linke : Principal Investigator



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# California Department of Transportation

Division of Research, Innovation and System Information

# Executive Summary

The California Department of Transportation (Caltrans) needs to provide the best available training to its Maintenance personnel, particularly those operating heavy equipment. This research study evaluated the applicability and benefits of state-of-the-art heavy equipment simulators to support training efforts at the Maintenance Equipment Training Academy (META) and in Caltrans districts.

## Problem, Need, and Purpose of Research

Equipment availability for training is often limited, especially in remote areas. In addition, in the early stages of training, it may be inappropriate for trainees to operate actual heavy equipment. This research study presents an evaluation of two commercially available heavy equipment simulators with regards to their applicability and benefits for Caltrans training use. This evaluation aims to enable Caltrans to decide whether it would be valuable and efficient to incorporate heavy equipment simulators into personnel training as stationary simulators META and in a traveling training scenario whereby the equipment can be used to train Caltrans personnel across districts.

## Background

Training on heavy equipment is traditionally performed with the student operating the real equipment under the guidance of a trainer. The availability of new digital training environments and realistic simulators opens new and cost-effective options for heavy equipment training.

## Overview of the Work and Methodology

The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center procured two heavy equipment simulators and co-developed training plans to evaluate simulator use for Caltrans training. The mobility of simulators was analyzed for possible transport to other districts. Traveling training scenarios were also developed and analyzed with regards to feasibility and cost-benefits.

## Major Results and Recommendations

The major results and recommendations are:

- The Caterpillar simulator and the John Deere simulator are beneficial to be included in the training of new employees. These simulators expose trainees to heavy equipment in a safe environment.
- Training plan templates for the new employee training were developed. Training with simulators can be evaluated using trainee and trainer surveys. Trainees' performance on the simulators can be assessed with built-in metrics while performing the tasks on the simulators.
- Up to five simulators can be comfortably mounted into an existing 48-ft trailer to move them to other districts.
- A cost-benefit analysis of simulator vs. real equipment use showed much lower ownership and operating costs for the simulators. Worksheets were developed for comparing costs and training effectiveness ratios.
- A cost-benefit analysis of stationary and traveling simulator use showed that training at META with stationary simulators has the lowest cost per student if the students are local. Flying in students increases the costs significantly so that the scenarios wherein local students are trained with traveling simulators are comparatively cost-effective.

The results aim to support Caltrans in deciding whether to incorporate the systems into Caltrans' business operations. As an additional product of the research, Caltrans had the option of taking possession of the heavy equipment simulators procured as part of the research.

Deployment will benefit from the following:

- One or more dedicated Caltrans support persons for simulator maintenance and troubleshooting,
- Sufficient spacing around the simulators for trainer and trainee observation,
- Acquisition of a customized trailer if the simulators are to be transported for training, and
- Integration of the simulators into the Caltrans intranet.

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# List of Acronyms and Abbreviations

| Acronym | Definition |
|---|---|
| AHMCT | Advanced Highway Maintenance and Construction Technology |
| BEST | Basic equipment Safety Training |
| Caltrans | California Department of Transportation |
| DOE | Division of Equipment |
| DOT | Department of Transportation |
| DRISI | Division of Research, Innovation and System Information |
| GFCI | Ground fault circuit interrupter |
| HMS | Highway Maintenance Station |
| META | Maintenance Equipment Training Academy |
| OEM | Original Equipment Manufacturer |
| PC | Personal computer |
| TV | Television |
| UPS | Uninterruptible power supply |
| VR | Virtual Reality |

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# Chapter 1: Introduction

## Problem

The California Department of Transportation (Caltrans) needs to provide the best available training to its Maintenance personnel, particularly those operating heavy equipment. Equipment availability for training is often limited, especially in remote areas. In addition, in the early stages of training, it may be inappropriate for trainees to operate actual heavy equipment. As such, Caltrans would benefit from state-of-the-art heavy equipment simulators to support training efforts at their Maintenance Equipment Training Academy (META) and in the districts.

## Objectives

The primary product of this research is an evaluation of up to two commercially available heavy equipment simulators. This evaluation will enable Caltrans to decide whether it would be valuable and efficient to incorporate heavy equipment simulators into personnel training, particularly as a traveling training scenario wherein the equipment is used to train Caltrans personnel across districts.

## Scope

The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center procured two heavy equipment simulators and evaluated the applicability and benefits of these simulators for Caltrans' training purposes. Specifically, the transport and use of equipment in a traveling training scenario was analyzed. First, AHMCT co-developed training plans (e.g., how much training is needed over what time period for initial training) to evaluate simulators for Caltrans staff. Second, the mobility of simulators was analyzed for possible transport across districts. Third, traveling training scenarios were developed and analyzed with regards to feasibility and cost-benefits.

## Literature

There is a plethora of literature on the subject of virtual reality (VR) simulation training systems for a large variety of applications [1], [2]. Heavy equipment including excavators, wheel loaders, etc. constitute a small fraction of this research topic [3], [4]. Most of the literature focuses on the design of the VR training systems [3], [5], but limited literature demonstrates the effectiveness of VR training and the transfer of training. The following bullet points include results from literature on VR training for flight, snowplows, ships, cranes, dragline excavators, surgery, and heavy equipment. The results are subdivided into two groups: effects of training and training methods. Following these findings, there is a brief discussion on the types of operator tasks and metrics for evaluating skill mastery.

## *Effects of Simulator Training*

- Execution time, control errors, and mental workload decreased with simulator practice on heavy equipment [6].
- Positional accuracy and task time improved with simulator practice on heavy equipment [7].
- Operational skills could be improved with simulator practice on an excavator [8].
- Cross-training on different machines (excavator and loader tested) had no effect on performance [9].
- Operators who trained with a VR simulator and those with the real machine performed equally well after 10 hours of training (12 participants, with less than five hours prior training) on an excavator [10].
- Productivity (measured in cubic meters per hour) and machine duty (boom stress index) improved both in the short term (three out of four individuals) and long term (two out of four individuals) after simulator training on a dragline excavator [11].
- Safety training was found to be effective for both inexperienced (average of four years) and experienced (average of 12 years) operators on overhead crane simulator training [12].
- Training of short time intervals (20 minutes) demonstrated no difference in performance or anxiety in operators [13].
- Nausea was experienced by some operators on an overhead crane simulator [12].
- Accident rate and fuel efficiency was improved in a snow plow simulator over a six month training period [14].
- Fuel efficiency was improved though correct gear shifting, but no effect was found in maintenance costs in snowplow simulators [15].
- Fuel efficiency, average speed, and accident rate was improved in trained vs. untrained drivers in a snowplow simulator over in a two hour period [16].

- VR training leads to both reduced surgery time [17] and improved technical surgical skills [18].

# Simulator Training Methods

- Varying training exercises (modules/scenarios) increased skill retention when compared to single exercise training for excavator simulator training [9].
- Practice variation increased retention and transferability but decreased training efficiency [19].
- Varying training schedules (mixed practice vs. blocked practice) had no discernable effect on performance in heavy equipment simulator training [20].
- Blocked practice improved acquisition whereas mixed practice increased retention and transfer [19].
- Rest intervals and periodic refreshers are beneficial for motor skill training [19].
- Guided instruction is more effective than self-guided exploration in excavator simulator training [21].
- Using whole-body flight simulators were found to be beneficial for novice pilot training by demonstrating the effects of motion, whereas motion showed no effect on expert pilot trainings [22].
- Airplane-specific flight simulators were shown to have better skills transfer than non-specific flight simulators; non-specific flight simulators demonstrated more generic skills transfer [23].
- In ship-maneuvering simulators (e.g., container ships), trainees were able to game (defeat) the simulator by using ship-position displays that were not available in realistic settings [24].
- In team-based ship-maneuvering simulators (e.g., container ships), roleplaying is critical for team-format simulators [24].
- In team-based ship-maneuvering simulators (e.g., container ships), the team will place a higher mental workload on an individual operator [25].
- High fidelity simulators are not necessary for training collective skills. Low fidelity simulators that emphasize high fidelity psychological models are more cost effective, are more accessible, and thus provide more opportunity for practice [26].

## *Task Types*

Additionally, several authors subdivided the skill types that are used and trained during practice, highlighting what simulators are effective at training:

- Strategic-level vs. control-level vs. tactical level skills in snowplow simulator training [27].
- Cognitive-prediction tasks vs. perceptual-motor tasks in excavator simulator training [9].
- Cognitive tasks vs. perceptual-motor tasks in flight simulator training [19].

Where strategic-level tasks are the purpose of the trip and many occur before entering the vehicle (e.g., where and when to go), tactical-level tasks are the choice of maneuvers (e.g., decisions regarding speed, passing, lane selection), and control-level tasks are moment-to-moment (e.g., maintaining speed, following distance, lane centering) [27]. While cognitive tasks depend on working memory and problem-solving, perceptual-motor tasks require motor skills and precise control [19]. Cognitive tasks have greater generalizability, yet motor tasks have better retention but less transfer [19].

The findings highlight that motor tasks are better trained within a simulator. Situational awareness of the machine and its surroundings are harder to train in a virtual reality simulator. A snowplow simulator study found that "over-training" on gear shifting for operators improved their situational awareness but required a much longer training schedule (three years) [15]. This discrepancy between situational awareness and motor-procedural tasks was highlighted by Dunston et al.: novices must devote their attention to the performance of a task whereas an expert has acquired procedural knowledge that allows them to perform the task automatically [4].

## *Evaluation Metrics*

Evaluation of operator mastery should not solely rely on training time [1]. As identified by So [9], in heavy equipment, efficient handling of the "implements" (the cutting, moving, and processing ends of the machine) can be examined to evaluate operator skill [28]. Thus, heavy equipment training simulators should evaluate implement handling efficiency in addition to machine maneuvering [29].

# Overview of Research Results and Benefits

The key deliverables of this project include:

- List of must-have and nice-to-have specifications for the simulators (Chapter 2)

- One or two simulator systems installed at META and documentation on simulator software (on-site)
- Training plan information from outside sources (Chapter 1 and 3)
- Training plan templates (Chapter 3, Appendices C and D)
- Evaluation surveys for trainees and trainers (Chapter 3, Appendices A and B)
- Findings on possible design for transport (Chapter 4)
- Comparison of the training scenarios and cost-benefit analysis (Chapter 5)

The goal is to improve Caltrans' training efforts and thereby improve staff skills at operating heavy equipment by obtaining one or two heavy equipment simulators and evaluating them to determine the value and efficiency they bring to Caltrans' training efforts, specifically in a traveling training scenario across districts within current working conditions. The end products are interim reports, a final report summarizing the effort to inform Caltrans' decision-making, and one or two equipment simulators that can be transferred to Caltrans.

It is anticipated that this research will lead to safer and more effective training, resulting in safer Maintenance operations through the confirmation that heavy equipment simulators bring value and efficiency to the operator training programs. This research may lead to reduced training costs and better/faster/safer outcomes in Maintenance operations as more staff are better trained to do their jobs correctly and safely. Furthermore, environmental sustainability can be improved by bringing simulators into the different districts and reducing travel.

The research aligns with Caltrans' strategic goals for *Stewardship and Efficiency* as improved heavy equipment training will lead to more effective and efficient operators who are better able to maintain the infrastructure. The research also aligns with the strategic goal *Safety and Health* as it will lead to improved Maintenance personnel training with immediate benefits. Finally, it supports the goal *Organization Excellence* through efforts to improve Caltrans' processes to take advantage of current technology to support the Caltrans Mission, Vision, and Goals in the most efficient and safest manner possible.

# Chapter 2: Procurement and Ensuring Best Functionality and Safety

## Caltrans System Specifications

AHMCT collaborated with Caltrans to create specifications for the purchase of the two simulators. The systems should consist of a base unit with a computing system, monitors, and input controllers. The software packages might be modular and cover specific equipment, such as excavators, loaders, dozers, or backhoe, on different difficulty levels (beginner or advanced operator). Trainer software helps to assess the performance of the operator. Further services by the provider include installation, training, and maintenance. The major requirement is for the systems to be as similar as possible as to the original equipment manufacturer (OEM) piece of heavy equipment. The following lists gives additional must-have specifications.

*Must-have specifications*:

- Base unit with at least one monitor, input controllers for the minimum heavy equipment types (e.g., pedals, joystick, steering wheel), and computing unit
- Dynamic platform (operator receives motion feedback through the seat)
- True-to-life controls that are as realistic to the OEM components as possible
- Installation: one-day training and three-year maintenance
- Minimum heavy equipment types that should be simulated are
    - Excavator,
    - Wheel loader, and
    - Grader.

The additional *nice-to-have specifications* are:

- VR or Augmented Reality (AR) options
- Multiple monitors in the front and back
- Upgradeable computers
- Multiple difficulty levels in the training modules
- Training evaluation software

- Additional heavy equipment to be simulated, including:
    - Dozer,
    - Backhoe,
    - Tractor, and
    - Equipment variations of above specified list of minimum heavy equipment type.

# Procurement and Installation

AHMCT performed extensive research to investigate systems currently available to purchase. To ensure simulators purchased would meet Caltrans' needs, AHMCT obtained quotes from Papé Machinery and Simformotion, LLC. and reviewed specifications with Caltrans' personnel. Simformotion, LLC. provided the best option for a commercially available simulator that most accurately simulates both the physics and the human machine interface of Caterpilllar heavy equipment excavators, wheel loaders, and motor graders. Papé Machinery quoted a simulator that offered the key specifications of the OEM controls for John Deere excavators, wheel loaders, and graders. A leading competitor was able to offer closely equipped system but lacked the OEM controls and was unable to provide them. Both quotes were approved by the Division of Equipment (DOE) before procurement.

The procurement process of the two systems involved detailed paperwork and constant communication with the UC Davis Supply Chain, causing unforeseen delays. Once all required documentation was completed, purchase orders were sent to both vendors. Simulators were delivered and installed at META (Figure 2.1).

Part of the system installation included training from the vendors. Caterpillar provided training to AHMCT and META staff. General functionality of the system was confirmed. Initial training for the John Deere simulator was provided by CM Labs, the software provider. General functionality was also confirmed at the time of installation.

For any future simulator purchases, AHMCT recommends the following:

- Ensure quotes include detailed specifications or part numbers for different modules, controllers, year of manufacture, etc.
- Ensure quotes include any discounts for units on display, demo units, or bulk purchases.
- Determine extended warranty and maintenance contract needs. Software updates might be limited by the hardware obsolescence, which must be taken into consideration when purchasing older systems from inventory.


**Figure 2.1: Simulators installed at META**

# Set Up for Functionality and Safety

Several improvements of the set up were implemented:

- AHMCT added a modem to allow infrequent internet access to update and troubleshoot the simulators by the service departments. Steps were taken to ensure that wiring for both simulators did not become entangled and were color coded with the respective ports to allow easy reconnection (Figure 2.2).
- A long enough cable was added to the VR headset for the Caterpillar simulator and a track-ball mouse. A possible tipping hazard of the Caterpillar simulator was mitigated by additional and more prominent safety labeling on the platform (Figure 2.3). As an option against a pinching hazard, stationary sleeves can be added to the front legs. Additional measures, such as tape on the floor, were considered for the traveling scenario.
- Lastly, a log procedure to track usage was recommended, such as paper sheet with dates, names, modules, and simulators used.

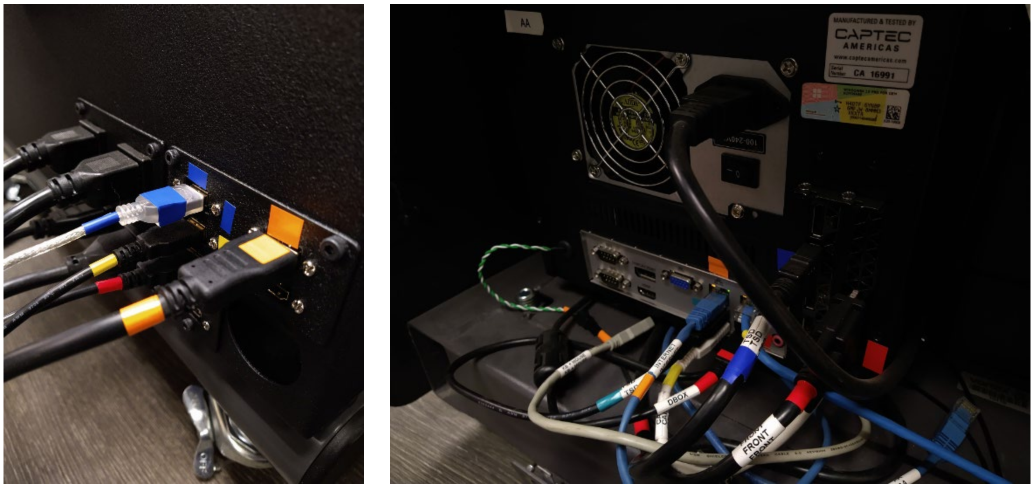


**Figure 2.2: Cable and ports are color coded**


**Figure 2.3: Safety labeling on the platform**

# Chapter 3: Training Plans and Evaluation

Training plans include the numbers of training days, trainees, training tasks, machines to learn (loader, backhoe, etc.), number of trainers, and number of simulators. It was considered how long it takes to train a person on one type of equipment (i.e., loader) and how many trainings can be done in each day, considering time demands for set-up and operator strain. For feedback on the training plans, evaluation surveys were drafted and administered by Caltrans to trainees and trainers.

## Background and Best Practices

The development of the training plan drafts was informed by three types of data:

1) Existing practices at Caltrans were reviewed and discussed with trainers at META.
2) The training modules, operational tasks, and software in the simulators at hand were explored, documented, and ranked by difficulty and estimated length.
3) Information was gathered and analyzed from outside sources, such as research literature, simulator vendors, and training facilities. The research literature was discussed in Chapter 1. Further review of training practices demonstrated that training facilities, such as community colleges and training centers that use heavy equipment simulators for training, commonly combine simulator training with field training on real equipment. Thirteen training centers (three Departments of Transportation [DOTs], six colleges, and four technical institutes) quoted their course lengths as ranging from six hours to 16 weeks in interviews and on their websites. The median training time was 40 hours per course.

## Caltrans-specific Training Plans

Two training plan scenarios for excavator and grader training were considered:

1) The novice training, called the Basic Equipment Safety Training (BEST) training class, which covers initial Caltrans safety instruction, and truck and loader training, and introductory exposure to motor grader and backhoe/excavator through use of simulator exercises, and

2) The advanced training, which covers backhoe/excavator and motor grader in more intensive detail and integrates real equipment operation training.

To develop the draft training plans, AHMCT discussed current on-iron training practices for each equipment type with trainers, who emphasized that consistency and safety are critical outcomes of the training. The draft training plan for the BEST training class was discussed multiple times with the trainers prior to implementation and subsequently improved through several iterations based on trainer feedback and anonymized trainee feedback. Several considerations were taken into account:

- Caltrans uses backhoes for regular maintenance operations. On both simulators, excavator modules were used as a stand-in for backhoes due to the similarity in operation.
- Several BEST trainings were held with groups of more than 20 employees. On two days, students in groups of three to four used the simulators for three hours per day on the excavator training modules.
- Exercise recommendations in the BEST training plan were selected to provide students with introductory exposure to each equipment type beginning with basic controls. Further exercises were selected to best reflect common uses for each equipment type within Caltrans, such as trenching with the backhoe/excavator.
- Each simulator offers basic control exercises for each equipment type. These exercises teach students how to use joysticks, pedals, control panel buttons, and steering wheels to actuate different components of the equipment. Some teach the simultaneous usage of multiple controls to perform articulated motions. New trainees will benefit from becoming familiarized with the controls in a safe virtual environment before practicing on real equipment. These exercises are included in the BEST training plan.
- Another consideration in exercise recommendations was to provide each student with sufficient training time (at least 30 minutes per equipment type across multiple exercises) while keeping seat time low enough that other students could complete the exercise(s).
- More challenging exercises were included in the recommendations to accommodate students with more advanced prior experience.
- Exercise recommendations were provided for both equipment types on both simulators (John Deere and Caterpillar) so that trainers could use either simulator for either equipment type simultaneously.

Appendix C shows the final draft of the BEST training plan. The plan provides several options for exercises the trainers can assign for each equipment type on either simulator (Figure 3.1). It also provides guidance on which exercises to use for students of different prior skill levels.

Appendix D shows a self-guided version of the BEST training plan that can be provided as a handout for students to follow on their own. The self-guided version is more linear, concise, and visual, providing the student with a quick and easy reference for each step in setting up and completing the exercise. Compared to the training plan in Appendix C, which is directed at trainers, the self-guided version excludes details about exercise selection criteria.

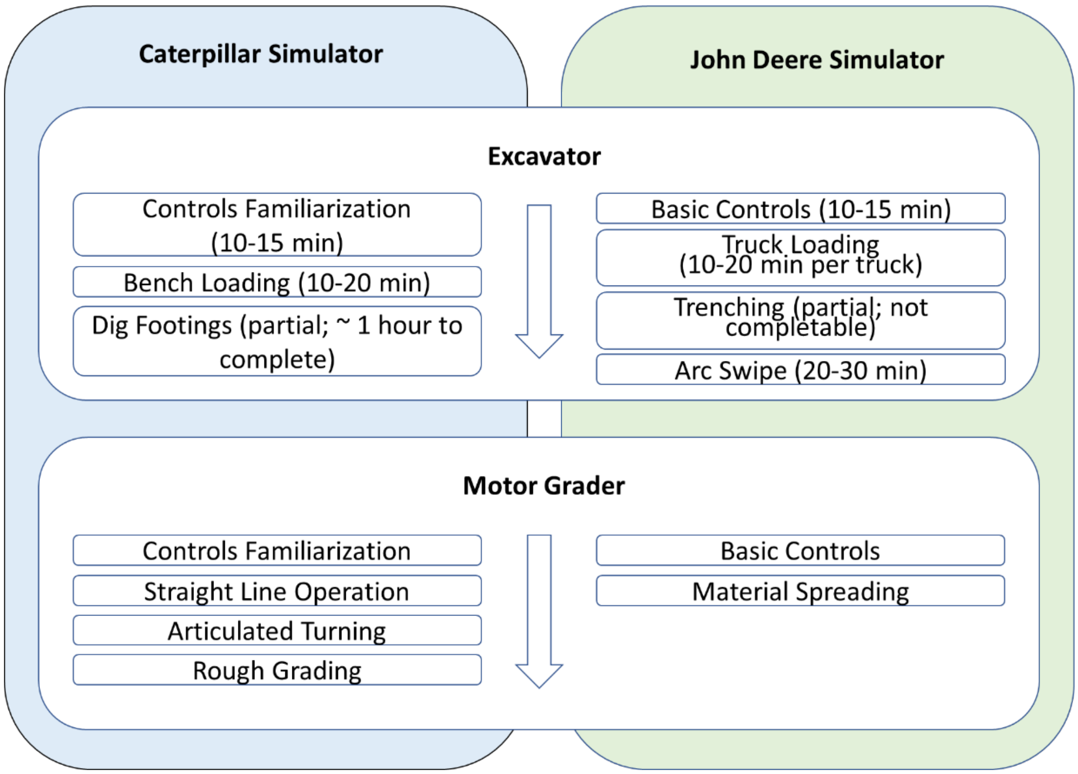


**Figure 3.1: Graphical representation of exercise selection sequence for each equipment type on each simulator.**

# *Advanced Training Plans*

Advanced trainings are week-long and focus on specific equipment. The training plan draft would incorporate simulators and integrate with practice with real equipment. Suggestions for these advanced trainings are as follows:

- Trainees could either spend part of each day on simulators and part on real equipment. Alternately, the week could be divided into simulator days and real equipment days. The availability of simulators and equipment will guide this decision. For example, if the simulators are at META but the real equipment is at a training site, it might not be feasible to work with both on the same day.

- Simulators could be used for basic familiarization with each task that is taught in the training prior to more detailed training on the real equipment.
- Advanced trainings would include walk-around exercises wherein students check the integrity of various subsystems of the equipment, such as oil levels, bolt tightness, etc. The virtual environment will show a greater and less predictable array of issues the trainee may encounter when performing an equipment walk-around.

## *Use of Metrics to Evaluate Trainees*

Both simulators are able to record performance metrics from each training session. These metrics can be used to evaluate trainee performance. The metrics are customizable and address damage or efficiency. Examples are execution time, fuel burnt, average forward speed, number of collisions, average bucket height, and volume of material moved. Some metrics address critical failures that would lead an exercise to end, such as the bucket hitting an electric pole or cable or simulated human or moving the bucket over the human. Additional challenges can be added by the trainers in the form of day and night (Caterpillar simulator) or weather conditions (John Deere simulator).

# Evaluation

AHMCT and Caltrans developed a trainee survey (Appendix A) and a trainer survey (Appendix B), which were administered by Caltrans to their employees. The anonymized data were given to AHMCT for analysis. The following results were gained:

- Trainees appreciated the realistic simulator setup as well as the chance to improve their confidence to operate the machines.
- Trainees provided short written responses to the survey. Survey responses were quantified on a 1 to 5 scale by one AHMCT researcher for analysis, where 1 represented a strongly negative response and 5 represented a strongly positive response. Results were monitored across several BEST training sessions to assess the effects of training plan revisions.
- Figure 3.2 shows the quantified results of surveys from the first three BEST trainings. Reponses were consistently positive from the first BEST training session, with all questions ranking higher than a 3 on average. Over the three training sessions, all questions improved slightly, which could likely be attributed to a more streamlined instruction process as trainers became more familiar with the simulators and the training plan was improved.

- Question 1addresses the realism of the simulator environment. Many trainees described the feeling as very similar to real equipment.
- Question 2 addresses the user-friendless of the software environment. Trainees generally found the user interface easy to navigate.
- Question 3 addresses the simulators' hardware interface, such as control modules. Many trainees said they liked that the simulators use the same hardware found in the equipment they simulate.
- Question 4 addresses the auditory, visual, and motion feedback of the simulators. Some trainees had difficulty with blind spots when machine components were not visible on-screen and a lack of depth perception.
- Question 5 addresses the trainees' self-assessed improvement in confidence to operate real equipment. Many trainees expressed that they felt prepared to operate the real equivalent; although, this sentiment was less prevalent in those who had prior experience with the equipment.
- Additional individual comments from trainers and more experienced trainees provided positive feedback on the highly realistic graphics and simulation software. It was pointed out that limited depth perception can affect some operations. The controls are very realistic, but only for electronic control systems (compared to hydraulic controls for example).

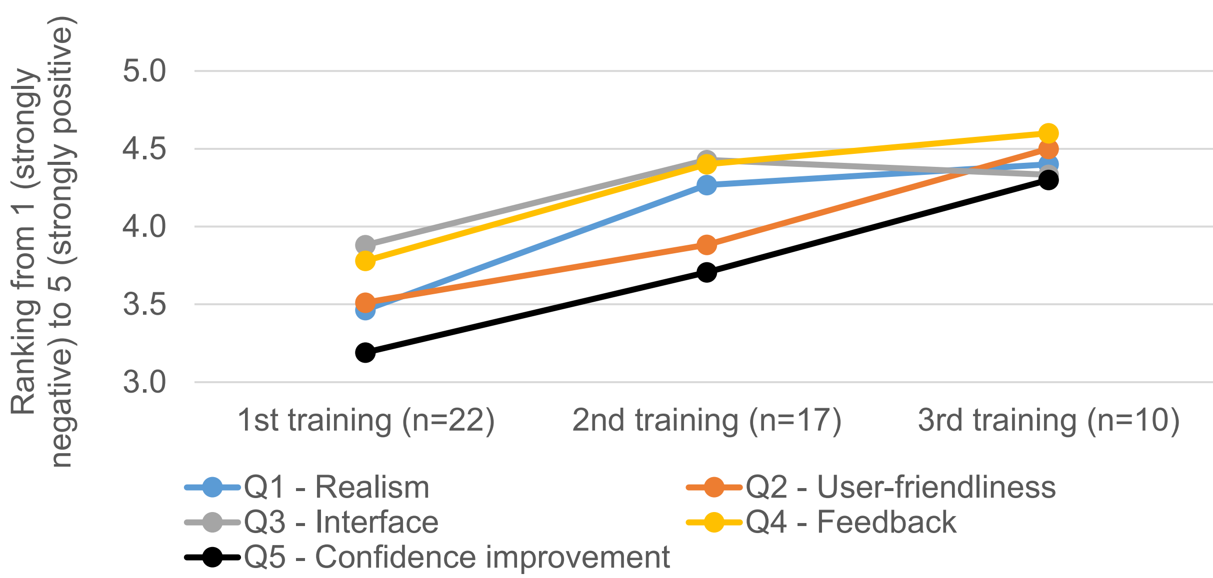


**Figure 3.2: Quantified survey responses from the first three BEST trainings (n = number of answers).**

# Chapter 4:
# Design for Possible Transport of Simulators

## Initial Simulator Installation

The setup of both simulators was studied during installation.

- John Deere simulator setup takes less than one hour and needs two people (Figures 4.1 and 4.2).
- The Caterpillar simulator arrived in a disassembled state, but setup took less than one day (Figures 4.3 and 4.4). One person was able to do most of the steps alone but was sometimes helped by a second person (such as for lifting of monitors or balancing of guard).
- The Caterpillar simulator mobility kit is installed underneath the simulator platform. A lever can be engaged and disengaged by stepping on it to lift the simulator on small caster wheels. The simulator can then be pushed to a new position, but it has yet to be confirmed how steep an incline the mobility installation supports.

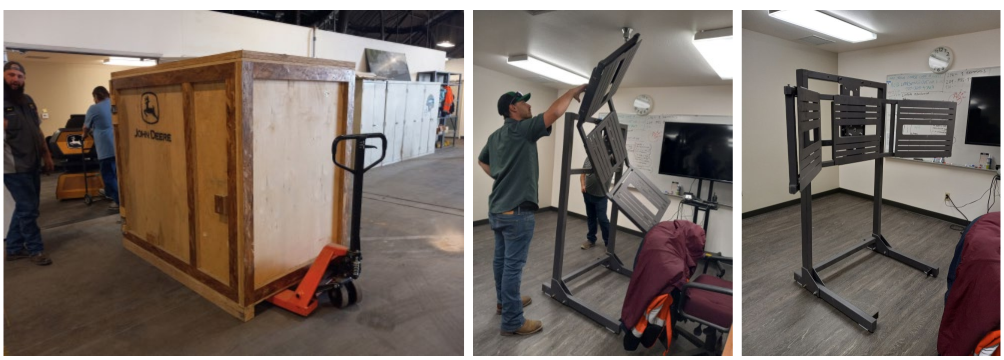

**Figure 4.1: Installation of John Deere simulator (left: transport box; middle and right: screen stand)**


**Figure 4.2: Left: exchangeable modules of John Deere simulator; right: installed John Deere simulator**

**Figure 4.3: Installation of Caterpillar simulator (left and middle: transport boxes; right: sliding of based unit)**

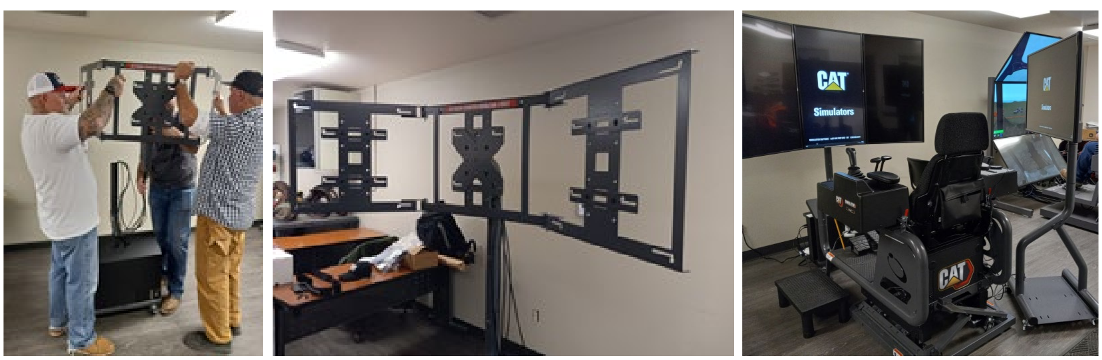


**Figure 4.4: Left and middle: Installation of Caterpillar screen stand; installed Caterpillar simulator**

# Installation Power Requirements

The simulator power requirements were examined for stationary simulator use and use in a truck in a traveling scenario.

- The 2013 Caterpillar document *Requirements & Recommendations* specifies that the simulator, monitor, and motion platform require 12 amps. Also, the simulator must not be plugged into a ground fault circuit interrupter (GFCI) outlet, because the actuators might trigger the breaker.

- John Deere support specified that the three-screen setup with motion platform was rated at about 2000 W and would need two dedicated 15 amp circuits.
- AHMCT measured power consumption of both simulators during representative training sessions with an Onset HOBO power meter (Figures 4.5 and 4.6). The power profiles show plateaus at different stages of operation, including startup, idling, and active simulation. Local peaks in the power consumption occur when computers and actuators initialize. Global power consumption peaks occur during simulations when certain simulation events cause maximum actuator acceleration.
- Power measurements of the Caterpillar simulator showed that idling with the computer and four displays drew about 300 W, idling with software SimU running and no exercise loaded about 500 W, and a running exercise drew 600 to 700 W. Peak load measured was only 800 W.
- Power measurements of the John Deere simulator showed that idling with the computer and four displays drew about 400 W. Running exercises typically drew between 500 to 600 W, with a maximum observed draw of about 650 W.

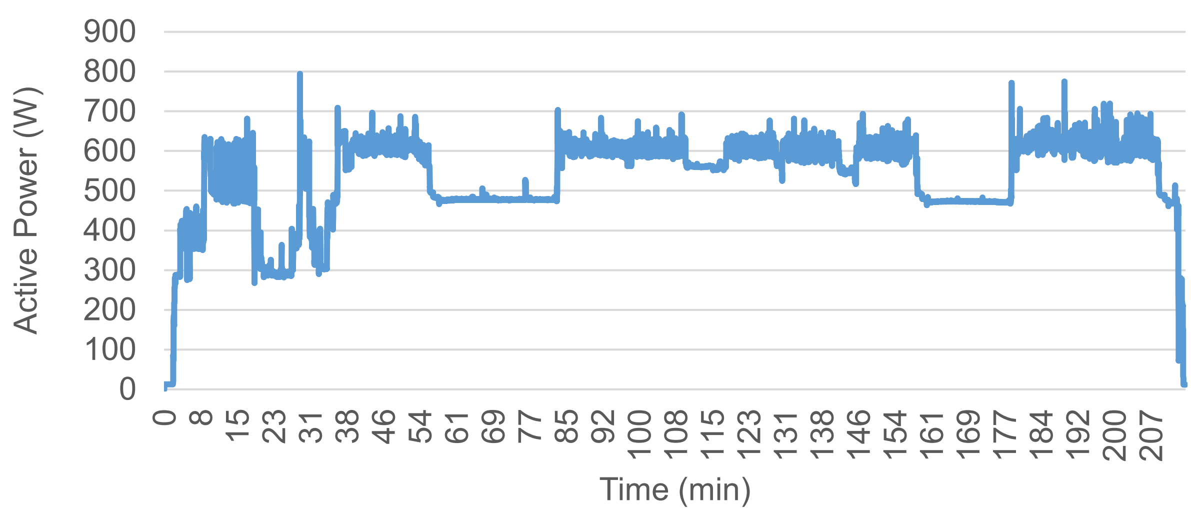


**Figure 4.5: Power consumption of Caterpillar simulator during a representative training session.**

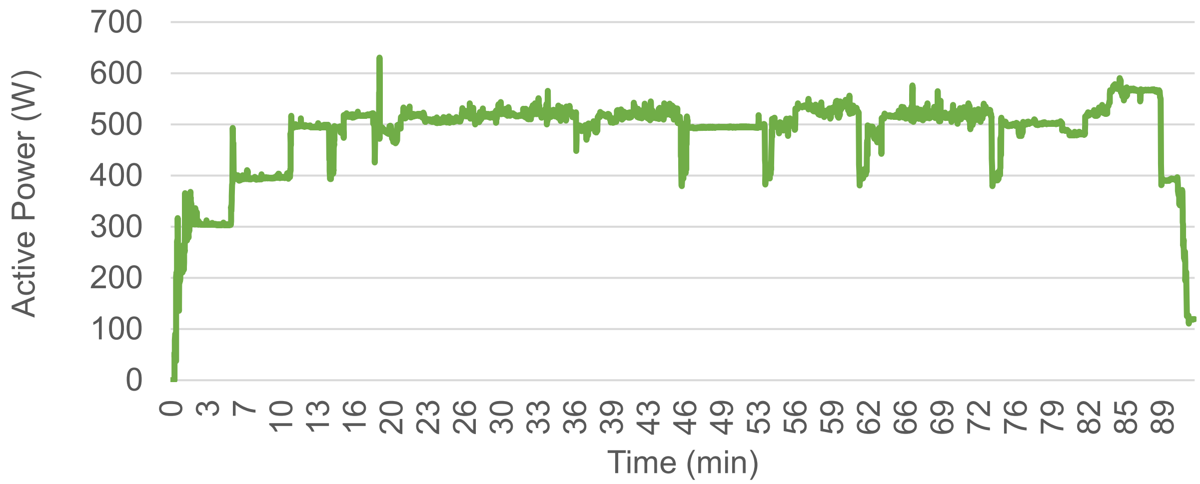


**Figure 4.6: Power consumption of John Deere simulator during a representative training session.**

# Design for Transportation and Installation of Simulators onto an Existing 48-foot Trailer Truck

Installation of the simulators in an existing 48-foot trailer truck was assessed. Simulator training would be performed in the trailer. The simulators would need to be loaded and unloaded into the trailer once per month and might be in transit 100 hours, or 4,000 miles, every year. The design should last 10 years. Preferably, the simulators should be easily maneuvered by two people. The existing trailer does not have gate lifts, so the simulators might be moved with forklifts and can potentially be set on pallets. The following factors were considered:

- Installation would need to include security against robbery, protection during transport, student fatigue over long sessions, electrical power needs, airflow, and general layout.
- The trailer might not have access to shore power from a building, so a sufficiently sized power generation system would be needed with one 15 amps circuit at 120 V per simulator.
- The John Deere simulator dimensions were used in the design because it is slightly larger (less than four inches) compared to the Caterpillar simulator. Figure 4.1 shows the top view dimensions of the simulator that was used to create the three-dimensional (3D) model of the simulator. Figure 4.2 shows the front view of the simulator and the 3D model.

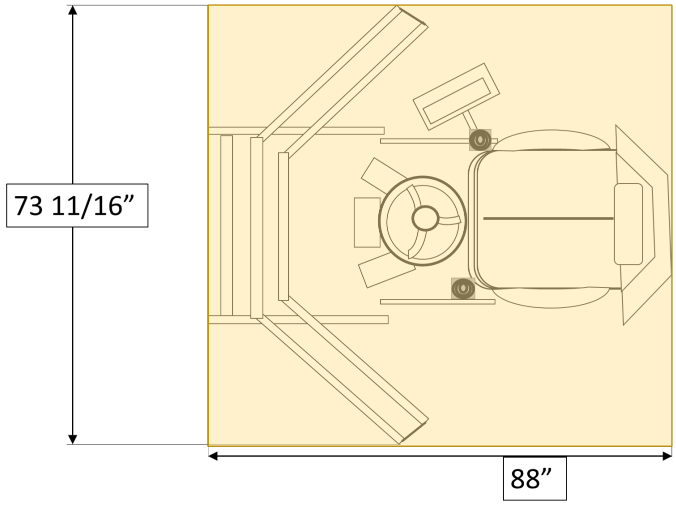


**Figure 4.1: Top view of simulator chair, TV screens and other components**

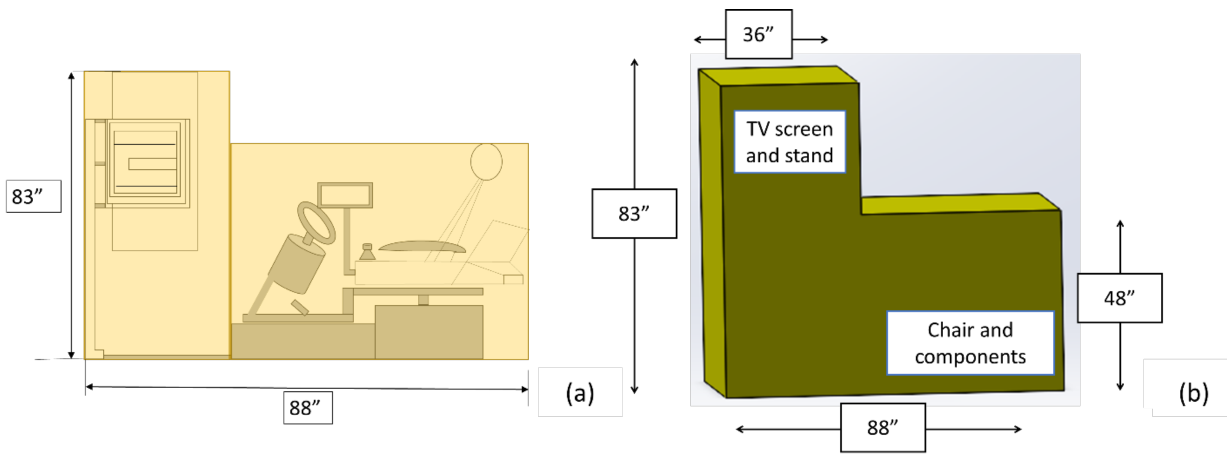


**Figure 4.2: (a) Side view of simulator chair, TV screen and components; (b) Model side view to include simulator chair, TV screen and components**

The existing 48-foot trailer truck would need to be cleaned out in order to install the simulators. Currently, it has cabinets and a training braking system installed. Some of the doors in the trailer need to be permanently closed in order to install more simulators. Several layout options were considered for installing the simulators into the trailer truck, which are discussed in the following sections.

# *Layout A – Two Simulators*

Figures 4.3 and 4.4 show the layout for installing the two current simulators. Given the amount of space available, this is a comparatively easy solution and the currently installed cabinets and the braking system can remain in the trailer. The main drawbacks are:

- For easy accessibility of the simulators, double door 3 needs to be permanently closed.
- Trainees can only access simulator 1 through door 1 or door 2.
- Simulator 2 can be accessed through the back door or by walking in between the simulator chair and TV screen of simulator 1.

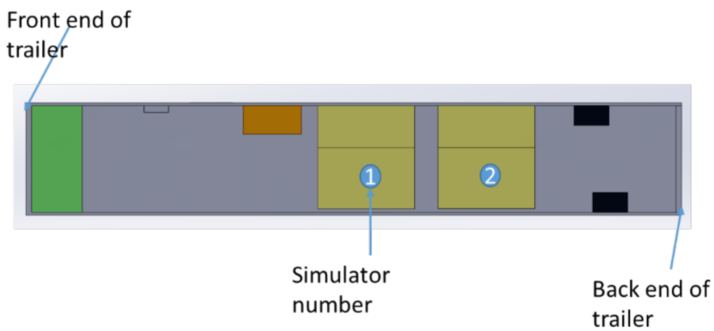


**Figure 4.3: Layout A - Top view layout**

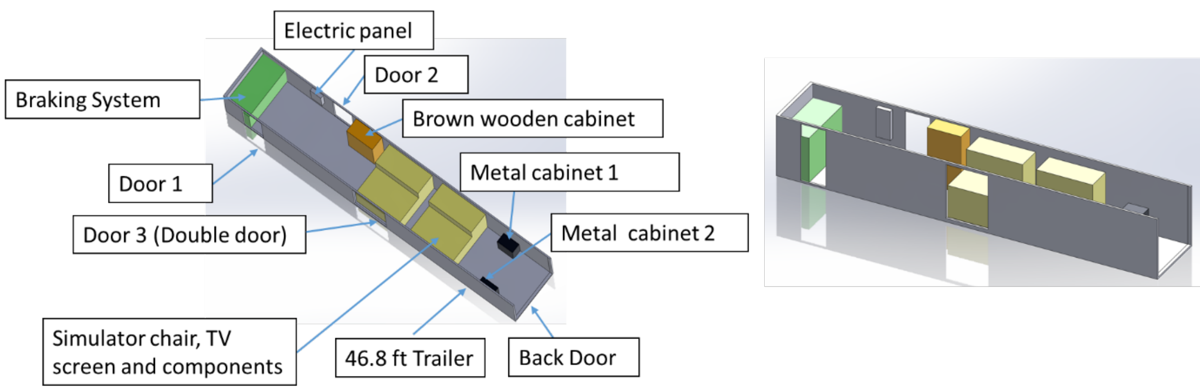


**Figure 4.4: Layout A - Isometric view layout**

## *Layout B – Five Simulators*

A layout that will fit up to five simulators requires positioning four of the five simulators with the screens along one long trailer wall (Figure 4.5). In order to do this, the following conditions need to be met:

- The existing cabinet and braking system in the trailer have to be removed.
- Doors 1 and 3 need to be permanently closed, and trainees can only enter the trailer via door 2 and the back door.
- In this configuration, simulators 3 and 4 can only be accessed if the trainees walk in between the chair and the TV screen of simulators 2 or 5 respectively. This layout might feel too enclosed to the trainees.

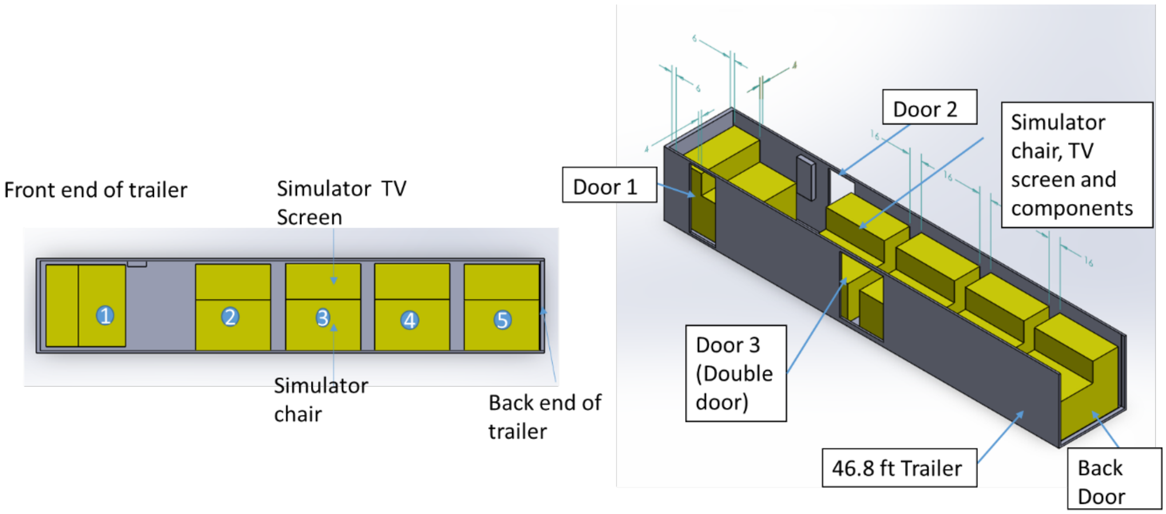


**Figure 4.5: Layout B - Top view layout and Isometric view layout**

# *Layout C – Six Simulators*

## Layout C1 - Screens Mounted on the Long Trailer Wall

The maximum number of simulators that can fit into the trailer is six. As Figure 4.6 shows, the six simulators can be installed if the TV screens are mounted on the trailer walls instead of using the screen stands. In addition, the following problems exist:

- The existing cabinet and the braking system in the trailer have to be removed.
- Door 1 must be permanently closed, and the trailer can only be entered via door 2, door 3 and the back door.
- To access simulator 5, trainees need to walk in between the chair and the TV screen of simulator 4 or 6.
- Mounting screens on the trailer wall will require customized brackets.

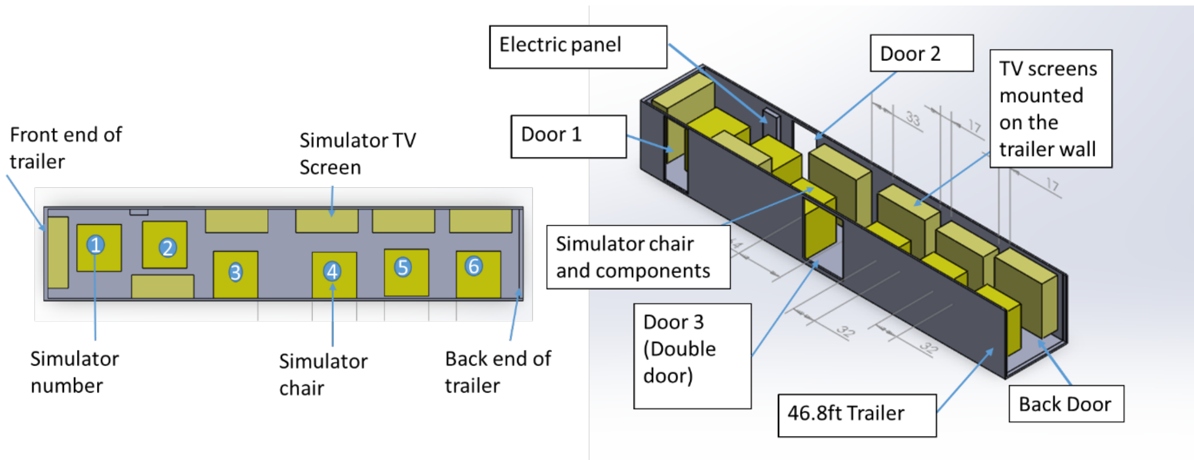


**Figure 4.6: Layout C1 - Top view layout and Isometric view layout**

## Layout C2 - Simulators Perpendicular to the Trailer Wall

Another layout that will fit up to six simulators into the trailer requires positioning the simulators with their screens perpendicular to the long trailer walls and keeping the screen stands (Figure 4.7). Issues found with this set up are:

- The existing cabinet and the braking system in the trailer have to be removed.
- Door 3 has to be permanently closed, and the trailer can only be accessed via door 1, door 2, and the back door.
- It is very difficult to access simulators 3, 4, 5, and 6 because trainees have to fit between the TV screens and the trailer wall. Interactive training with trainers or multiple students is almost impossible.
- It is a very tight fit for the six simulators but can be acceptable as a transport layout. The six simulators can then be set up at another training facility.

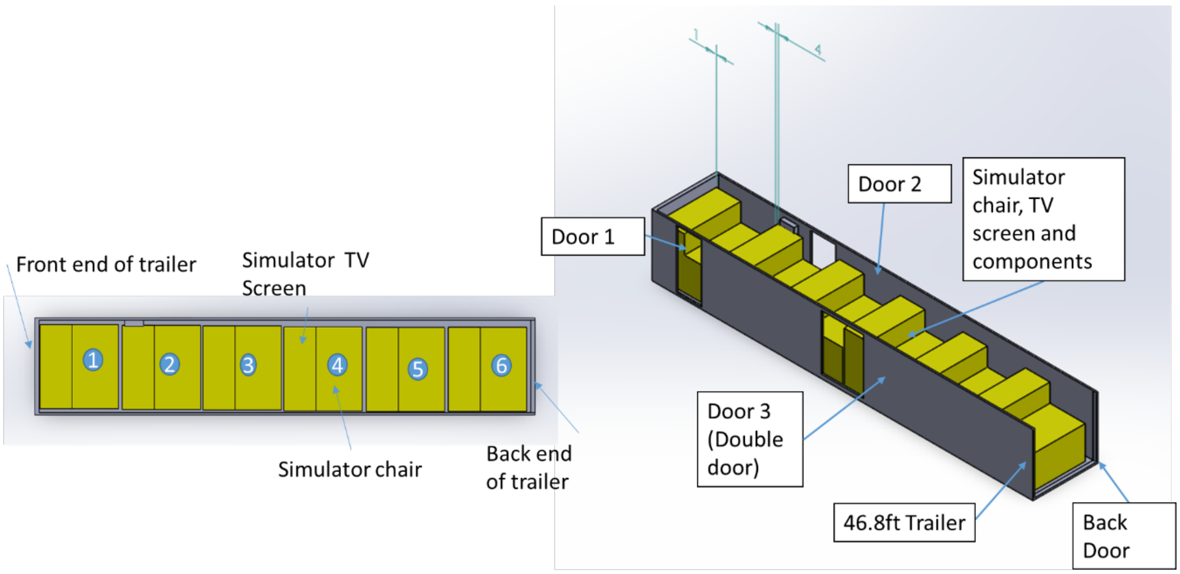


**Figure 4.7: Layout C2 -Top view layout and Isometric view layout**

## Securing the Simulators in the Trailer

In addition to the layouts outlined above, the following items should also be taken into consideration when planning secure transport of the simulators:

- Simulators can be moved by forklift onto the trailer, but a lift gate would be preferred to load and unload the simulators.
- D-ring tie-down anchors can be used to secure or tie down the simulators onto the floors of the trailer during transportation. It is recommended to use six D-rings with 1,000 lbs capacity each. One D-ring would be placed in each corner of the simulator and two D-rings on each side of the screen stand.
- Screens should be stored during transportation instead of staying mounted on the stands or the walls.
- The simulator crates provide good safety for the chair and components for movement and transportation. The screens might be stored in the original cardboard boxes.

# Chapter 5:
# Feasibility Study of Traveling Training Scenarios and Cost-Benefit Analysis

The feasibility of traveling with the simulators was evaluated from a cost-benefit perspective. Three scenarios were considered: real-life equipment training (former practices with no simulators), stationary simulator training (simulators stay at META), and different simulator traveling scenarios (simulators travel to specific districts).

## Simulator Training versus Real-life Equipment Training

### *Hourly Rates*

The hourly rates of simulators and equipment were calculated and compared to the Caltrans rates where available. The hourly rate estimation method was developed from a combination of two textbooks [30], [31]. Hourly cost estimates were calculated for the John Deere Simulator, CAT Simulator, CAT Wheel loader 983k, CAT Excavator 20 Ton 315, CAT Grader 140, and CAT Method 140 Ton Crane (example from [30], [31]). The rates are based on depreciation value, ownership costs, and operating costs. Hourly rates can be expanded to include trainee and trainer labor costs. Table 5.1 shows the inputs for the simulator calculations, and Table 5.2 shows the costs for the heavy equipment.

**Table 5.1: Inputs for simulator calculations**

| Input for simulator calculations | Value | Unit |
|---|---|---|
| Students per two-week training period | | |
| Simulator hours per student for new intro course | | |
| Estimated annual use in hours | | h |
| Total expected use in hours | | h |
| Useful life | | years |
| Sales discount | | % |
| Sales tax | | % |
| Interest | | % |
| Insurance | | % |
| Taxes | | % |
| Warranty (per year) | | $ |
| Repairs | | % |
| Mass | | lbs |
| Freight | | $/lbs |
| Power consumption of simulator (incl. Screens and PCs) | | W |
| Electricity price CA | | $/kWh |

**Table 5.2: Inputs for heavy equipment calculations**

| Inputs for heavy equipment calculations | Value | Unit |
|---|---|---|
| Equipment HP | | hp |
| Carrier HP | | hp |
| Condition of use | | |
| Students per two-week training period | | |
| Equipment hours per student for new intro course | | |
| Estimated annual use in hours | | h |
| Total expected use in hours | | h |
| Useful life | | years |
| Tires (4x) | | $ |
| Tire life | | h |
| Tire repair rate (of straight line depreciation for tires) | | % |
| Sales discount | | % |
| Sales tax | | % |
| Interest | | % |
| Insurance | | % |
| Taxes | | % |
| Storage | | % |
| Repairs rate | | % |
| Implement replacement rate (blades; bits; rips; shanks; etc.); assumed as part of maintenance costs | | |

| Inputs for heavy equipment calculations | Value | Unit |
|---|---|---|
| Fuel factor (gas) | | gal/h/hp |
| Fuel factor (diesel) | | gal/h/hp |
| Fuel cost (Diesel) | | $ |
| Servicing (FOG) factor | | % |

## Hourly Ownership Costs

The depreciation value would account for any discounts or sales taxes (Table 5.3). For the heavy equipment, the tire replacement costs need to be deducted as they will be included in the operating costs.

**Table 5.3: Depreciation value calculation for simulator or heavy equipment**

| Depreciation value components | Value | Unit |
|---|---|---|
| Delivered price (including taxes, freight, and installation) | | $ |
| List price | | $ |
| Discount at 7.5% | | $ |
| Sales tax | | $ |
| Freight | | $ |
| *Net Value for depreciation (sum of above)* | | $ |

The deprecation costs are the depreciation value amortized over the lifetime of the equipment (Figure 5.4). For the simulator, this is assumed to be 10 years as informed by the sales staff. This deprecation cost in addition to the interest, insurance, taxes, and storage sums up to the ownership costs. Interest is the lost value of the money had it been invested elsewhere. Insurance would include the insurance for the building that the simulators are housed in. Storage costs are additional fees to store the equipment.

**Table 5.4: Hourly ownership cost calculation for simulator or heavy equipment**

| Ownership cost components | Value | Unit |
|---|---|---|
| Depreciation = [net value]/[depreciation period in hours] | | $/h |
| Interest, insurance, taxes: | | |
| Interest (borrowed to purchase equipment) | | $/h |
| Insurance | | $/h |
| Taxes | | $/h |
| Storage | | $/h |
| *Total Hourly Cost of Ownership (sum of above)* | | $/h |

## Hourly Operating Costs

For the simulators, the operating costs include the electricity costs during use, unexpected repair costs (assumed with small annual repairs and a large repair every five years), and warranty and software renewal fees for the three training software packages (Table 5.5).

**Table 5.5: Operating cost calculation for simulator**

| Operating cost components | Value | Unit |
|---|---|---|
| Electricity costs | | $/h |
| Repairs [Unanticipated] | | $/h |
| Small annual repair (one per one year) | | $ |
| Small repair frequency | | years |
| Large infrequent repair (one per five years) | | $ |
| Large repair frequency | | years |
| Renewal fees (all three packages; to software keep updated) | | $/year |
| Renewal fees hourly | | $/h |
| *Total Hourly Operating Cost (sum of above costs per hour)* | | $/h |

For the heavy equipment, the operating costs include fuel, servicing (filters, oil, grease), tire wear, tire repair, and equipment repair (Table 5.6). Values for lifespans in hours depending on light-to-hard duty cycle and some usage and cost rates can be found in textbooks [30], [31] or from manufacturers. Notably, the wheel loader has four tires, the excavator has zero tires (it uses steel tracks), and the grader has six tires.

**Table 5.6: Operating cost calculation for heavy equipment**

| Operating cost components | Value | Unit |
|---|---|---|
| Fuel = Factor (hp)(fuel cost per gallon) | | $/h |
| Servicing (filters, oil, grease [FOG]) cost = (% hourly gas) | | $/h |
| Tires hourly depreciation (replacement cost/life in hours) | | $/h |
| Tires repair (repair factor * tire hourly depreciation cost) | | $/h |
| Repairs: [factor (useful life in h)(hourly depreciation rate)]/10,000h | | $/h |
| *Total Hourly Operating Cost (sum of above)* | | $/h |

## Total Ownership and Operating Costs with or without Wages

Total ownership and operating costs are the sum of hourly ownership costs and hourly operating costs. In addition, the instructor operator hourly wage or the student trainee hourly wage can be added. The calculated hourly rates for ownership and operating costs are shown in Table 5.7. These example values clearly show how much cheaper operating a simulator is compared to operating the real equipment. For simulators, the ownership costs are the major contributors: 62% or 74% of costs. For the heavy equipment, the operating costs are much larger in comparison to the ownership costs and make up 77%, 59%, or

56% of total ownership and operating costs for the wheel loader, excavator, or grader, respectively.

**Table 5.7: Total ownership and operating cost comparison (for the estimated conditions)**

| Equipment or simulator | Total ownership and operating cost |
|---|---|
| John Deere Simulator | 7.25 $/h |
| Caterpillar Simulator | 7.89 $/h |
| Wheel Loader | 54.15 $/h |
| Excavator | 53.55 $/h |
| Grader | 75.77 $/h |

# *Payback Period*

The annual cost of a simulator or piece of heavy equipment running for eight hours on five days in 52 weeks per year was estimated as product of hourly rate times use hours (8 h/d * 5 d/week * 52 weeks):

Annual cost = hourly rate [dollars/hour] ·2,080 [hours/year].

The cost savings per year for using the simulators in place of heavy equipment can be calculated as the difference of annual costs times a use percentage of the simulator. Here, an initial use percentage of using the simulators for 50% of the use hours was estimated. However, use of simulators will vary depending on training timelines and requirements and could easily vary from 0% to 100% since introduction to equipment controls and broad training can be provided using the simulators, whereas operator certification must occur with the actual equipment.

Cost savings per year = (annual cost of real equipment – annual cost of simulator) * 50%

Then, the average payback period in years for using a simulator for the use percentage in place of the real heavy equipment is calculated as simulator purchase price divided by the cost savings per year:

Average payback period = purchase price of the simulator ÷ cost savings per year.

Table 5.8 shows the average payback time for substituting training on the representative pieces of real equipment, wheel loader, excavator, and grader, by either a John Deere simulator or a Caterpillar simulator. The payback times vary between 1.8 years to 3.6 years. Training on the grader has the shortest payback time because of the high total ownership and operating costs of the grader.

**Table 5.8: Average payback period for replacing the equipment in the column by a John Deere or Caterpillar simulator (for the estimated conditions)**

| Equipment replaced | Average payback period for the John Deere simulator | Average payback period for the Caterpillar simulator |
|---|---|---|
| Wheel Loader | 2.6 yrs | 3.4 yrs |
| Excavator | 2.8 yrs | 3.6 yrs |
| Grader | 1.8 yrs | 2.3 yrs |

# Equipment Effectiveness

Training on simulators can save time and costs if the training on real equipment becomes faster. Research on flight simulators defined three ratios to analyze this situation: training effectiveness ratio (TER), cost effectiveness ratio (CER), and TER Cutoff (which is 1/CER).

- Training effectiveness ratio TER is a ratio of the learning time on the equipment between using a simulator and not.

TER = learning time on the equipment using a simulator / learning time on the equipment without a simulator

- Cost effectiveness ratio (CER) is a ratio between the simulator hourly cost rate and the equipment hourly cost rate.

CER = simulator hourly cost rate / equipment hourly cost rate.

TER Cutoff = 1 / CER

- The three ratios TER, CER, and TER cutoff are related and can be used to determine if a particular instructional task is cost effective in a simulated environment. If TER > TER Cutoff, then the simulator is cost effective, whereas if TER < TER Cutoff, then the simulator is not cost effective.
- These ratios come from research from flight simulators and the US Airforce [32], [33], [34], [35]. Taylor et al. reported that TER values can range from 0.5 to -0.11 in flight simulator training [35]. The negative value represents a reduction in performance from using the flight simulator and was uncommon. Orlansky et al. found a median value of 0.48 for flight simulators [34]. Thus, flight simulators can be very effective. A TER of 0.5 indicates that every 1 hour spent on the simulator saves 30 minutes of real equipment time.
- Research has not been undertaken to measure the TER values of construction equipment simulators.
- The TER cutoff values calculated with the values in Table 5.6 range from 0.1 to 0.15. If wages for trainers are added, these values increase

to TER cutoff = 0.36 to 0.54. This result means that simulator training is still cost-effective if we assume a TER of TER = 0.55, which means that 10 hours of training on a piece of equipment can be reduced to only 4.5 hours if additional 10 hours training are spent on a simulator. This finding does not take student wages or other costs into account.

# Comparison of Traveling and Stationary Simulator Training

A series of cases were defined and compared to determine if driving heavy equipment simulators to a Caltrans maintenance station for operator training would be cost effective as compared to flying operators into Sacramento to visit META for the training. Eight scenarios were developed that incorporated different costs associated with traveling and training operators. Costs included:

- Mileage cost reimbursement for students driving their personal vehicles more than 50 miles in a day,
- Flight cost for students flying to or from a training location,
- Per diem travel costs, which include lodging, meals, and incidentals,
- Mileage costs of trainers driving the simulator truck to a training location,
- Personnel hourly costs paid during training,
- Personnel hourly costs pair during simulator setup and pack-down, and
- Personnel hourly costs during simulator transportation.

Several cities were selected for the traveling scenarios, namely Sacramento, Redding, San Diego, and San Francisco; these cities were selected to highlight either the distance from META or the per diem costs associated with traveling to the city. Scenarios 1, 2 and 4 were designed to be the lowest cost training scenarios. Scenarios 3, 5 and 6 represent the most likely to occur scenarios. Scenarios 7 and 8 are designed to be the most expensive scenarios. Note, if a person drives their personal vehicle less than 50 miles, it is assumed that their mileage does not have to be compensated. Additional assumptions are outlined following the scenarios.

- Scenario 1: Students local to the Sacramento area, who drive less than 50 miles to META, visit META for training. The only costs incurred are the hourly personnel costs paid during training.
- Scenario 2: Students are within the Sacramento area, who drive more than 50 miles to META, visit META for training. This scenario includes personnel costs during training, and students will be compensated for their drive to META.

- Scenario 3: Students from Los Angeles visit META. This scenario includes personnel costs during training, flight costs, and per diem costs for the students.
- Scenario 4: Trainers drive the simulator truck to a Highway Maintenance Station (HMS) close to Sacramento. The trainers park the simulator truck at the HMS and drive their personal car every day to the HMS. This scenario includes mileage costs for the trainers (as opposed to the students), mileage costs for driving the truck, personnel costs for training, personnel costs to setup and pack-down of the simulators, and personnel costs during simulator transportation.
- Scenario 5: Trainers drive the simulator truck to Redding from META and stay at Redding for two weeks. This scenario includes mileage costs for the trainers to drive the simulator truck, per diem costs for the trainers, personnel costs during training, personnel costs during simulator setup and pack-down, and personnel costs during transportation. This scenario represents traveling to a HMS that is of moderate distance from META and is in a locale that is not expensive. Students are local and within 50 miles of the truck location at Redding.
- Scenario 6: Trainers drive the simulator truck to San Diego from META and stay in San Diego for two weeks. This scenario has the same costs as Scenario 5, but with a further distance to travel and a more expensive city, the costs associated with driving are higher than Scenario 5 and the per diem costs are also higher than Scenario 5. This scenario represents traveling to an HMS that is far away from META and is in a locale that is expensive. Students are local and within 50 miles of the truck location at San Diego.
- Scenario 7: Trainers drive to San Diego and train non-local students in San Diego for two weeks. This scenario includes mileage costs for students, per diem costs for students to stay in San Diego, mileage costs for the trainer to drive the truck to San Diego, per diem costs for the trainers to stay in San Diego, personnel costs for training, personnel costs to setup and pack-down the simulators on the truck, and personnel costs to drive the simulator truck.
- Scenario 8: Trainers drive to San Francisco, and students fly into San Francisco to attend training. This is the costliest scenario and provides an estimate for the upper bound of the costs using the model and assumptions. This scenario includes mileage costs for the students, flights costs for the students, per diem costs for the students, mileage costs for trainers to drive the simulator truck, per diem costs for the trainers, personnel costs during training, personnel costs during simulator setup, and personnel costs during simulator transport.

## *Traveling Costs and Personnel Costs*

Depending on the scenario, the traveling and personnel costs include the following:

- Mileage cost reimbursement for students driving their personal vehicles more than 50 miles in a day.
- Flight cost and rental car costs for students flying to or from a training location. It can be assumed that students will share rental cars at four students per car. Adjusting this number increases the costs.
- Per diem travel costs for students, which include lodging, meals, and incidentals.
- Mileage costs of trainers driving the simulator truck to a training location.
- Personnel costs paid to trainers during training, during simulator setup and pack-down, and during simulator transportation.

Appendix E shows the calculation tables. Assumptions for the scenarios include the following:

- If driving personal vehicles less than 50 miles, then mileage is not compensated.
- When driving a personal vehicle more than 50 miles, then mileage is compensated at a rate of 0.56 dollars per mile.
- Per diem meal rates were assumed at a maximum of $46 for each day from Caltrans documentation.
- Per diem lodging rates were assumed to be the maximum rates and were dependent on the county or city in which lodging would occur (per Caltrans documentation). The lowest rate was $90 per day for non-specified counties and cities, and highest was $250 per day in San Francisco.
- The hourly rate for instructors was estimated as $32/hour and for students as $20/hour.
- The tractor rental rate is set at $56.81/hour, and the trailer rental rate at $9.82/hour, both for the simulator truck.
- Simulators on the truck are assumed to take four hours to setup and four hours to pack-down with the two trainers. Setup and pack-down of the simulator truck is assumed to occur outside of the 80-hour (ten-day) training session.
- The number of students per instructor is assumed to be six students per instructor.

- In simulator-driving scenarios (Scenarios 4 to 8), two instructors drive the simulator truck to the training location; thus, an assumed total of 12 students are trained.
- In the scenarios with students traveling to META (Scenarios 1 to 3), three instructors are assumed to be available to train students; thus, an assumed total of 18 students are trained.
- For two weeks of training, ten per diem days are used.
- Flights are assumed to cost $100 per two-way flight from and to anywhere within California.
- Rental cars are assumed to cost $100 per day. Students are assumed to share rental cars with four people per car.
- Driving the simulator truck and flights are assumed to occur over the weekends.
- Instructors driving the simulator truck are assumed to be compensated for their hours, but staff are not compensated for their in-flight hours.

## *Comparison*

All costs were compared, both total costs and per-student costs (Table 5.9). For the chosen scenarios and assumed values, Scenario 8 is most expensive and provides an estimate for the upper bound of the costs using the model and assumptions. Training at META with stationary simulators has lowest cost per student for local students. Scenarios 4, 5, and 6, where local students are trained with traveling simulators, are still very cost-effective even for training in higher per diem counties, such as San Diego County.

**Table 5.9: Total and per student costs for the three stationary and five traveling training scenarios**

| Scenario | Scenario description | Total costs ($) | Costs per student ($) |
|---|---|---|---|
| Scenario 1: Students Visit META for Training from Sacramento | Lowest possible cost scenario; only train students less than 50 miles from META<br>(18 students total, 3 trainers) | 36,480 | 2,027 |
| Scenario 2: Students Visit META for Training from Close to SAC | Students need to be compensated for their drive to META, but do not require per diem<br>(18 students total, 3 trainers) | 41,621 | 2,312 |

| Scenario | Scenario description | Total costs ($) | Costs per student ($) |
|---|---|---|---|
| Scenario 3: Students Visit META for Training from LA | Students need round trip tickets from their local, need to rent cars, and will spend per diem (18 students total, 3 trainers) | **68,160** | **3,787** |
| Scenario 4: Trainers Drive to HMS Close to SAC | Trainers drive the simulator truck to a Highway Maintenance Station close to META and park it there for 2 weeks; they then drive to and from the local HMS via car (12 students total, 2 trainers) | 25,531 | 2,128 |
| Scenario 5: Trainers Drive to Redding | Trainers drive the simulator truck to Redding stay for 2 weeks (12 students total, 2 trainers) | 28,866 | 2,405 |
| Scenario 6: Trainers Drive to San Diego | Trainers drive the simulator truck to San Diego stay for 2 weeks (12 students total, 2 trainers) | 31,335 | 2,611 |
| Scenario 7: Trainers Drive to San Diego, Students come to San Diego | Trainers drive the simulator truck to San Diego stay for 2 weeks; non-local students travel to San Diego for Training (12 students total, 2 trainers) | 53,199 | 4,433 |
| Scenario 8: Trainers Drive to San Francisco, Students fly to San Francisco | Most Costly Scenario; Trainers drive the simulator truck to San Francisco stay for 2 weeks; non-local students fly into San Francisco for Training (12 students total, 2 trainers) | **73,418** | **6,118** |

# Chapter 6: Deployment and Implementation

During this evaluation period, Caltrans and AHMCT successfully integrated the simulators into the training program. The simulators were placed in a fixed location in an existing classroom. The training was an introductory course for the students. Future deployment will require additional simulators and possible installations in a mobile trailer. Continuing deployment of simulators will need to consider the following issues.

## Requirements for Continuous Technical Support

AHMCT personnel provided technical support to setup and maintain the simulators and to resolve technical issues with the manufacturers. The effort required a period of self-directed training to become familiar with the hardware and software and to develop the expertise required to support Caltrans training. Regular communication with the vendors was required. Dedicated Caltrans personnel will be required to continue the technical support.

At least one dedicated support person must be assigned to maintain the simulators. This support person will need a few days of dedicated work to become familiar with the systems. After this initial effort, the support person time will drop to an estimated four hours a month for the existing simulators. Tasks will include the installation of software updates and the real time resolution of problems encountered by the trainers and students. A formal logging of problems and issues will be important to maintain knowledge base. Additional time and effort will be required if more simulators are installed. Additional administration effort will be required to implement the full simulator package of student training, testing, and tracking.

## Considerations for Reaching Full Product Deployment

Future deployment within Caltrans may require installation of additional simulators and installation of simulators into trailers for transport to remote training. The following issues should be considered.

### *Equipment Issues*

The simulators occupy a large footprint and are not easily repositioned. Placement of the simulators in a space must allow for sufficient floor space behind and alongside the simulator seats to allow comfortable movement of students and trainers. Trainers should be able to look over the shoulder of the students operating the simulators. Space for stools or chairs behind the simulator seat would allow students and trainers to comfortably observe the simulator operation for an extended time.

Installation of the simulators into a trailer requires a significant design effort to optimize the utilization of limited space. The existing simulator display support structure will not support the displays during transport. The displays will have to be removed and packaged for transport, which is very time consuming. By mounting the displays directly to the trailer wall, the simulator can be shifted closer to the wall to increase floor space behind the simulator seat. A semi-permanent attachment of the displays to the wall will require vibration and shock absorbing features. Acquisition of a customized trailer with slide outs and soft suspension will provide the best options for a mobile training unit.

The simulator power consumption must be carefully considered for any installation. Electrical circuit modifications will be required in typical facilities. An uninterruptible power supply (UPS) should be used to protect the simulators.

## *Policy Issues*

A detailed plan for integration of the simulators onto the Caltrans intranet will be required. Caltrans maintains strict computer network security regulations to protect their infrastructure. The simulators must be connected to the internet to allow for remote access by the vendor to troubleshoot the system. During this evaluation, AHMCT provided technical support by using a modem to access the internet for updates and troubleshooting. Connection speeds were low and prevented successful updates in some cases. Plans for an internet connection are required.

# Chapter 7: Conclusions and Future Research

Key contributions of this research project included:

- State-of-the-art heavy equipment simulators proved to be feasible for Caltrans training use.
- Training plan templates were developed for new employee training with simulators, including a self-guided training plan. Performance of trainees on the simulators can be further assessed with built-in metrics while performing the tasks on the simulators.
- Simulator transport in an existing 48-foot trailer was evaluated, and layouts for simulator arrangement were generated. Two simulators can be comfortably mounted, and up to six simulators would fit into the existing 48 ft-trailer to move them to other districts.
- Cost-benefit analysis of simulator use versus real equipment use showed much lower ownership and operating costs for the simulators. Simulators would still theoretically be cost-effective if an additional ten hours of simulator training reduced the training needed on the real equipment from ten to seven hours.
- Cost-benefit analysis of stationary simulator use versus traveling simulator training showed that training at META with stationary simulators has the lowest cost per student if the students are local to META. If simulators are driven to a district and local students attend, the total costs and costs per student are very competitive. Flying in students to the training location increases the costs significantly so that the scenarios where local students are trained are the most cost-effective.

Deployment of the simulators for Caltrans training use will benefit from one or more dedicated support persons to perform simulator maintenance and troubleshooting. If the simulators should be transported to other districts, the purchase of a customized trailer is recommended.

Future research work includes the following:

- Advanced training plans can be developed with varying depth and training time on the simulators.
- Exploration of regular use of VR goggles.

- Quantification of simulator training benefits by comparing student groups with and without simulator exposure and their training times on real equipment.
- Generation of more training material.

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# Appendix A: Trainee Survey

**Trainee survey for BEST training (to be administered by Caltrans to trainees)**

*Please try to answer at least three questions.*
*Do not include personal identifiable information.*

1. How realistic was the simulator?

2. Was the simulator user-friendly?

3. Please comment on the Human-Machine-Interface (the controls, pedals, screen, etc.).

4. Please comment on the feedback to you as operator (vibrations, sounds, optical feedback).

5. Did your confidence to operate the real heavy equipment based on the simulated equipment rise?

6. Do you have suggestions on how to improve the use of this training equipment?

# Appendix B: Trainer Survey

**Trainer survey for BEST training (to be administered by Caltrans to trainers)**

*Please try to answer at least three questions.*
*Do not include personal identifiable information.*

1. Was the simulator effective in achieving your training goals?

2. Did you have enough time with the trainee to accomplish your training goals?

3. Did the trainee have enough time on the machine to accomplish the training goals?

4. Were the simulator software and training modules sufficient to accomplish your training goals?

5. Did you have to supplement the simulator in any way?

6. Do you have suggestions to improve future training sessions?

# Appendix C: BEST Training Simulator Integration Template

## Contents

# Objectives

- Develop a plan for integrating the Caterpillar and John Deere simulator machines into the BEST training class for new Caltrans heavy machinery operators.
- Guide instructors' exercise selections to accommodate students of different skill and experience levels.
- Allow flexibility in simulator and equipment selections.

# General Procedures

- Students should log their simulator usage on a paper form with date, names, modules, and simulators used.
- Students should receive at least 30 minutes each on a given simulator/module combination, including setup time.
  - Allow an extra 10 minutes for the first student since they will not have the benefit of seeing others use the simulator.
- Choose exercises from the list of options presented below based on student experience and desired skill focus. It is not necessary to proceed through the exercises sequentially.
  - Basic controls exercises can be skipped even for new students if the instructor is able to teach the necessary controls at the beginning of a different exercise.
- Many of the exercises are meant to be partially completed either because the exercise runs long or because certain parts of the exercise are unnecessary for a training session.
- The exercises should be restarted between students rather than students switching seats and continuing the same instance of the exercise.
  - Example: When a student finishes the first trench in "Dig Footings," they should restart the exercise so that the next student can dig the same trench rather than continuing to the next trench.
- Students should be divided into groups and assigned to a particular machine at the beginning of the training session. They should be encouraged to sit near the machine and observe other students while waiting for their turn.
- When excavator and motor grader training occur simultaneously, the Caterpillar simulator should be used for the motor grader and the John Deere should be used for the excavator.
  - The Caterpillar motor grader module seems to be more beginner friendly. Both excavator modules work well for this training.

# Excavator Training – John Deere Simulator

***TO RESTART EXERCISES:*** *Press the "RESTART" button on the touch screen.*

| Exercise | Comple-tion time | Target students | Description |
|---|---|---|---|
| "Basic Controls" | 10-20 minutes | No experience with excavators or unfamiliar with ISO/SAE controls | Students become familiar with the bucket controls by moving it to a number of designated positions. They are also introduced to skid-steer driving controls by maneuvering through an obstacle course. |
| "Truck Loading" | Restart after first truck is filled; 10-20 minutes | No experience with digging | A truck is filled with material excavated from a bench. The exercise provides good repetitive digging practice that requires less precision than trenching. |
| "Trenching" | Restart after digging the trench (before the box); 20-30 minutes | Prior experience with digging | A trench and pipe box are excavated. The instructions have proven difficult to follow and guidelines disappear partway through the exercise. |
| "Arc Swipe" | 20-30 minutes | More advanced students with previous experience with ISO/SAE controls | Bucket is maneuvered through a number of arc patterns. Requires multi-axis control of the bucket. Challenging for beginners. |

# Excavator Training – Caterpillar Simulator

***IMPORTANT:*** *These exercises are a part of the "Advanced Construction Excavator" module, not the "Medium Hydraulic Excavator" module. In this usage, "Advanced" refers to the technical capability of the software, not the difficulty of the exercises.*

***TO RESTART EXERCISES:*** *Press the ESC ("escape") key on the wireless keyboard and use the mouse to exit to the main menu.*

| **Exercise** | **Comple-tion time** | **Target students** | **Description** |
|---|---|---|---|
| "Controls Familiarization" | 10-15 minutes | No experience with excavators or ISO/SAE controls | Briefly introduces students to each physical control and its corresponding machine function. Good onscreen instructions require minimal instructor assistance or documentation reference. |
| "Bench Loading" | 10-20 minutes | No experience with digging | A truck is filled with material excavated from a bench. |
| "Dig Footings" | Restart after first trench; 15-25 minutes | Prior experience with excavators and plenty of time to complete the exercise. | A more thorough trenching exercise in which footings are excavated for an entire small building. |

# Motor Grader Training – John Deere Simulator

***TO RESTART EXERCISES:*** *Press the "RESTART" button on the touch screen.*

| **Exercise** | **Comple-tion time** | **Target students** | **Description** |
|---|---|---|---|
| "Basic Controls" | 20-30 minutes | No experience with graders or joystick grader controls | Introduces physical controls and their corresponding machine functions. Challenging for beginners without guidance. A very clear handout or instructor assistance is necessary to complete the exercise. |
| "Material Spreading" | TBD | Prior experience operating joystick-control graders (including completion of the previous set of exercises) | A row of material is graded smooth over several passes. |

# Motor Grader Training – Caterpillar Simulator

| Exercise | Comple-tion time | Target students | Description |
|---|---|---|---|
| "Controls Familiarization" | 10-20 minutes | No experience with graders or joystick grader controls | Introduces physical controls and their corresponding machine functions. More self-explanatory and forgiving than the equivalent John Deere exercise. Can benefit from use of third-person view to understand what's happening. |
| "Straight Line Operation" | <15 minutes | Beginners who have completed "Controls Familiarization" | Simple exercise for practicing driving the grader without using articulation. |
| "Articulated Turning" | <15 minutes | Beginners who have completed "Straight Frame Operation" | A simple exercise for learning to use the articulation function of the grader to maneuver through tighter areas. |
| "Rough Grading" | 10-30 minutes | Prior experience operating joystick-control graders (including completion of the previous set of exercises) | A row of material dropped by a dump truck is graded smooth over several passes. |

# Appendix D:
# Self-guided BEST training template

- Students should log their simulator usage on a paper sheet with date, names, modules and simulators used.

From "SimU Campus" Load Screen:

- Select "Demo" – do not log in.
- Under "Demo a Simulation" select "Advanced Construction Excavator."
- Under "Training Exercise" select "Dig Footings"
    - Other exercises are available if every student gets a chance to try the "Dig Footings" exercise.

Figure: Screenshot from software

# To Begin Each Exercise:

- Fasten the seatbelt before beginning the exercise.
- Honk the horn to begin the exercise. It is the lower button on the left joystick.
- If the previous user didn't reset the ignition, throttle, and hydraulic lockout, you will have to do so. Once they are in the correct "off" positions, you will turn on the ignition, turn the throttle to maximum, and disengage the hydraulic lockout.

# In the “Dig Footings” Exercise:

Dig the first trench and then restart the exercise for the next student.

- Drive over to the highlighted position at the beginning of the trench (to the left).
- Dig between the white lines and empty your dirt into the red box to the right. Halfway through the trench you will get a second red box.
- Dig deep enough to see a glowing green plane. Try to uncover the entire plane without digging deeper or wider than necessary.
- You may have to dig a little wider than the bucket width to uncover the entire plane.
- When you reach the end of the trench, if you uncovered more than 90% of the plane, it will disappear and cue you to start digging the next trench.
- After you have dug this first trench, restart the exercise for the next student so they can work from a clean start (see next page).

Figure: Screenshot from software

# To Restart or Change Exercises:

- Hit the escape ("ESC") key on the keyboard.
    - The keyboard is located on the front of the right control module.
    - The keyboard has a power switch that may have been turned off.
- Select "Exit To SimU Campus"

# Appendix E:
# Traveling Scenario Cost Calculations

| **Mileage cost components for trainers or students** | **Value** | **Unit** |
|---|---|---|
| Mileage | | mi |
| Mileage reimbursement rate | | $/mi |
| No. of trainers or students | | |
| Days repeat trips | | |
| Ground travel over 50 miles? (1 = yes, 0 = no) | | |
| *Total mileage costs (if <50 miles, not compensated)* | | $ |

| **Flight cost components for students** | **Value** | **Unit** |
|---|---|---|
| Ticket price | | $ |
| Rental Car rate | | $/d |
| Students per car | | |
| No. of students | | |
| Per diem days | | d |
| Flying? (1 = yes, 0 = no) | | |
| *Total flight costs* | | $ |

| **Per diem cost components for students** | **Value** | **Unit** |
|---|---|---|
| Per diem costs in the travel county | | $ |
| Per diem days | | d |
| No. of students | | |
| Students require per diem(1 = yes, 0 = no) | | |
| *Total per diem costs for students* | | $ |

| **Mileage cost components for trainers driving the truck** | **Value** | **Unit** |
|---|---|---|
| Mileage (single way) | | mi |
| Average speed | | mi/h |
| Truck total mileage rate | | $/h |
| Days of truck driving | | d |
| Over 50 miles? (1 = yes, 0 = no) | | |
| *Total mileage costs for trainers driving the truck* | | $ |

| Per diem cost components for trainers | Value | Unit |
|---|---|---|
| Per diem costs in the travel county | | $/d |
| Per diem days | | d |
| No. of trainers | | |
| Trainers require per diem (1 = yes, 0 = no) | | |
| *Total per diem costs for trainers* | | $ |

| Travel costs for scenario (sum of totals above) | Value | Dollar |
|---|---|---|

| Personnel cost components during training | Value | Unit |
|---|---|---|
| Hours per day | | h/d |
| Number of training days | | d |
| Rate of trainers | | $/h |
| Number of trainers | | |
| Rate of students | | $/h |
| Number of students | | |
| *Total personnel costs during training* | | $ |

| Personnel cost components during simulator setup | Value | Unit |
|---|---|---|
| Hours per day | | h/d |
| Number of setup days | | d |
| Rate of trainers | | $/h |
| Number of trainers | | |
| *Total personnel costs during simulator setup* | | $ |

| Personnel cost components during simulator transportation | Value | Unit |
|---|---|---|
| Hours driven | | h |
| Number of days driven (there and back) | | d |
| Rate of trainers | | $/h |
| Number of trainers | | |
| *Total personnel costs during simulator transportation* | | $ |

| Personnel costs for scenario (sum of totals above) | Value | Dollar |
|---|---|---|

| Total costs | Value | Unit |
|---|---|---|
| **Total travel + personnel costs** | | **$** |
| **Total travel + personnel costs per student** | | **$/student** |