Development and Verification of a Truck Driving Simulator for Driver Drowsiness Studies

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Abstract

Field operational testing for the study of driver behavior requires extensive preparation and precaution measures to limit subjects risk exposure during experiment. Moreover, inherent variability in testing conditions may introduce error in the experiment results. Alternatively, a driving simulator offers the ability to replicate driving situations in a safe and repeatable experimental environment. The control of simulation conditions in a driving simulator allows independent study of driving factors and hence more efficient analysis of specific driving issues.

In this project supported by the Federal Motor Carrier Safety Administration (FMCSA) a truck driving simulator was integrated for driver behavioral studies. A partnership was established between the Center for Intelligent Systems Research (CISR) and the Modeling, Simulation and Driving Simulators (MSIS) research unit of the French National Institute for Transport and Safety Research (INRETS). This paper presents the challenges associated with realistic replication of driving with special emphasis on truck driving simulation. The implementation and the capabilities of the new simulator and its subsystems are detailed. Equipment, instrumentation, simulation program, and interfacing elements of the simulator are presented. Developments specific to truck driving simulation and driver drowsiness analysis are reviewed. Procedures for evaluation and validation of the new simulator for drowsiness experiments are also described.

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1 Introduction

Driving simulation presents indisputable advantages over field testing for driving behavior studies. The controlled and repeatable environment of driving simulators enables researchers to isolate experimental variables from other factors that might influence driver performance, improving therefore the accuracy of the recorded measures. In addition simulators allow the study of hazardous driving situations that could not be replicated by field testing without exposing subjects to unacceptable risks.

The capabilities of driving simulators can vary greatly, ranging from desktop-mounted systems with single monitor display to multi-million dollars installations capable of replicating large amplitude driving motions and detailed virtual driving environments. Despite continuous improvement in driving simulation techniques and equipment capabilities over the years, subjects in a driving simulator still interact with a simplified environment and perceive less parameters as compared to real world driving. The design and development of a driving simulator should therefore not only be guided by the intention to create the most realistic driving environment possible but also by the necessity to replicate drivers' interaction with vehicle controls and surrounding instruments. To achieve this, emphasis should be given both to the simulator performance level and to the simulator ability to reproduce the driving task being studied.

In this project a low-cost truck driving simulator for driver drowsiness studies was set up. This text details all phases of the new simulator development, from design considerations to hardware selection, fabrication and installation, and finally validation of the new laboratory for drowsiness studies. A first section reviews the challenges associated with driving simulation. Features and capabilities of the new simulator are then reviewed and requirements specific to the simulation of Commercial Vehicle operation are presented. Validation of the simulator by experts and professional truck drivers is then detailed and recommendations for potential improvements to the simulator are determined.

2 Driving simulation challenges

Driving simulation is a complex task that requires the following four basic components [1]:

- Simulation of the physics of the vehicle and its interaction with road surface
- Simulation of the surrounding environment, including other vehicles
- Integration of informative systems and displays that enable subjects to interpret the state of the vehicle model, e.g. sound rendering, instrument panels, motion base, etc

- Integration of control devices, e.g. steering wheel, accelerator pedal, brake pedal, shift lever, clutch pedal, and other vehicle controls

In the generic layout of a driving simulator the computing unit calculates the vehicle dynamics parameters according to drivers' inputs. Results for vehicle position, speed, acceleration, heading, and traffic information are then sent to the visual display system. Commands for engine noise and subsidiary simulation sounds are sent to the sound reproduction system. Control feedback signals are sent to the steering torque controller, the pedals reverse force systems, and the cabin instrument panel displays (i.e. speedometer and tachometer).

The next sections combine results from previous research and experience gained through the development of CISR new truck driving simulator to identify factors that can affect driving in a simulated environment. The understanding of the following challenges and potential issues is fundamental for the design and implementation of a driving simulator.

Display / Visual cues

Previous research has proven the importance of image refresh rate and time delay on driver's performance in driving simulators [2], [3]. Refresh rates of 60 Hz and higher are usually considered adequate. Visual delay should be minimized as much as possible and compensation techniques can be implemented if necessary to bring the system response to driver's inputs closer to real world driving conditions. Also the presence of roadside objects has been shown to improve drivers' ability to estimate their speed and therefore to enhance their driving performance [4], [5].

Sound / Audio cues

Sound rendering plays an important role in the immersion feeling of a driving simulator subject. Wind and engine noise contribute to fatigue in drivers who have logged many hours. Sirens and horns grab their attention away from the task at hand. Traffic noise can affect a driver's state of being and decision-making. Tires squealing are indicators that the vehicle is being pushed towards its handling limits.

Spatialized sound generation replicating both vehicle and traffic sounds, and vibrations transmitted to the vehicle cabin can significantly enhance the overall realism of a driving simulator.

Attention should be paid not to provide the driver with an excessively loud driving environment. Measures of physiological stress in simulators have proven that excessive levels of vehicle inside noise can create discomfort and negative response from the drivers [6].

Vehicle motion/ vestibular cues

When handling a vehicle drivers base their decisions on visual, auditory, and inertial stimuli. In some situations linear and rotational accelerations due to vehicle motion can significantly guide the driving strategy.

Previous experiments showed that the estimation of subjective speed is under estimated when based on visual cues only, resulting in people driving faster in a fixed base driving simulator than in a moving base driving simulator [7].

The authors believe that careful analysis is necessary when integrating a moving platform in a driving simulator as potential problems may arise. Inappropriate motion rendering can degrade the driving impression and contribute to simulator sickness.

The decision to include motion generation in a driving simulator has to be based on the intended function of the new driving simulator. For example, if vehicle motion feedback is necessary for training applications, it is not essential for driver drowsiness studies involving continuous highway driving.

Driving stress

Because subjects are conscious that they can not be exposed to risk as they usually are on the real road, smaller levels of stress can be experienced in a driving simulator. This should either be taken into account when designing the testing protocol of driving simulator experiments or discussed in the experiments results. To mitigate potential effects of reduced stress on drivers' performance in a simulator countermeasures can be envisaged to increase subjects' stress levels; e.g. not telling the subjects about the task to be performed or increasing the driving task workload.

Simulator sickness

Simulator sickness induced by discrepancy or delays between visual and motion stimuli perceived by subjects is a major concern for driving simulator studies. A conflict between the displayed driving scene and the inertial accelerations sensed by the drivers can be experienced both in fixed base driving simulators and in simulators equipped with moving platforms where inappropriate motion rendering can occur.

Previous research has investigated the effect of various factors on simulator sickness. Low refresh rates of the visual display, large Field-Of-Views [8], [9], excessive vehicle velocity [10], and sharp curves in the driving scenario [11] are factors susceptible to contribute to simulator sickness. Some fixed reference in the displayed image (e.g. a fixed background scene) can reduce the motion impression and provide subjects with a sense of stability. This simple alternative can help to reduce simulator sickness.

Effects that can potentially contribute to simulator sickness have to be carefully investigated in the early stages of a driving simulator setup when designing the display system and defining the driving scenario.

Driver-vehicle performance in simulator / driving simulator validation

A driving simulator could only be a valuable research tool if it has been validated for a selected driving application. No standard method exists for validating a driving simulator.

The authors believe that thorough validation of a driving simulator should include both a static evaluation of the simulator components and a subjective assessment (e.g. questionnaires filled by professional drivers or simulation experts) of the simulator ability to accurately reproduce the task being studied. According to Radwan [12] the most prominent dependent variables used in simulator validation studies are driving speed, lateral position and steering behavior.

Steering torque feedback

In the virtual environment of a driving simulator, drivers control vehicle position via inputs in the steering wheel. The simulator's steering system should be capable of instructing the driver about the amount of steering correction to apply and of transmitting driver's steering inputs to the vehicle dynamics program during simulation. Since steering is the main control device available to the driver in a driving simulator, driver's performance during experiment greatly depends on the quality of the steering torque feedback. Previous literature has extensively reported the importance of the response of steering feedback systems on driver steering activity in driving simulators [13], [14], [15], [16], [17], [18], [19], [20].

3 Development of the simulator

A partnership was established between CISR and the Modeling, Simulation and Driving Simulators (MSIS) research unit of the French National Institute for Transport and Safety Research (INRETS). This agreement associates INRETS recognized expertise in the development of driving simulation tools with CISR experience in integrating driving simulators. In this project, INRETS provided CISR with a free access to its simulation software, while CISR was responsible for integrating the new simulator hardware.

INRETS driving simulation environment

This set of simulation tools consists of several modules organized in a common architecture: ARCHISIM.

- The ***vehicle dynamics model*** receives inputs from the simulator cabin acquisition card and computes the real-time response of the vehicle in a traffic model. The vehicle parameters of INRETS passenger car model were adjusted to simulate a realistic truck dynamic behavior. The consistency of the modified model for driver drowsiness applications was then verified by experts and professional commercial vehicle drivers as detailed later in this text.

- The ***traffic model*** of ARCHISIM is able to simulate realistic driving situations involving tens of vehicles in complex traffic environments. Unlike most existing traffic simulation tools, computation of traffic in ARCHISIM is not based on car-following algorithms but on a unique method, which evaluates the space available in front of a vehicle to determine its behavior in the simulated traffic. This approach is believed to better imitate how drivers behave in real life situations and leads to a more realistic replication of traffic.

- ARCHISIM enables users to create advanced ***driving scenarios*** including vehicles, traffic signs, roadside objects, etc. The behavior of traffic vehicles can be determined autonomously or programmed to fit every applications needs.

- INRETS haptic ***steering feedback algorithm*** is based on models used in robotic tele-operation [13]. This model considers that the torque generated on the steering shaft is equivalent to the torque generated on the wheel pivot. The induced rolling effect is also taken into account in the computation of the steering torque feedback.

- Spatialized ***sounds*** from the vehicle engine and surrounding traffic environment are reproduced. Simulated effects include engine sound during vehicle start, engine sound during vehicle ride and gears up / down shifting, sound of passing vehicles. The car sound samples provided by INRETS were modified for a more realistic truck sound environment. Their frequency was decreased, their amplitude was increased, and bass sound was added to the original signals to amplify the truck cabin trembling effect.

Specificities of a Commercial Vehicle driving simulator

Many aspects of commercial vehicle operation differ from passenger vehicle driving. Features specific to truck driving were identified and particular issues involved in the duplication of a truck environment were considered including:

- The height of the truck cabin is critical in the limited space of a laboratory since high cabin roofs can intersect projector beams. This concern should guide the selection of the cabin for the new simulator.

- A hood must be placed in front of the truck cabin to replicate the driving view of most long-nose heavy trucks commonly found on U.S. roads.

- A dominant view of the road ahead should be displayed to reproduce the high driving position of heavy trucks.

- A gear box must be integrated with both automatic driving and manual driving modes to simulate the different gear shifting modes found in U.S. trucks.

- The sound and vibrations transmitted to the vehicle cabin must reproduce the noisy and trembling environment of a real truck cabin.

- Rear view projection should be available in the simulator cabin to allow drivers to manage the behavior of their trailer as they usually do on the road.

Based on these requirements necessary equipment was designed and integrated in the new simulator as detailed in the next section.

Hardware

In a driving simulator the driver interacts with a “simplified” driving environment. Due to physical limitations of the simulator, the driver perceives few parameters during simulation as compared to real world driving. A driving simulator should aim both for replication of an embedded and realistic driving environment and for accurate imitation of the driving task under study. CISR developed its truck driving simulator for driver drowsiness studies according to the organization illustrated in Figure 1.

CISR decided not to include a motion base in its new truck simulator. If moving bases can improve the subject’s driving impression they are believed to have a limited effect in drowsiness detection experiments, where low-accelerations highway driving is mostly involved.

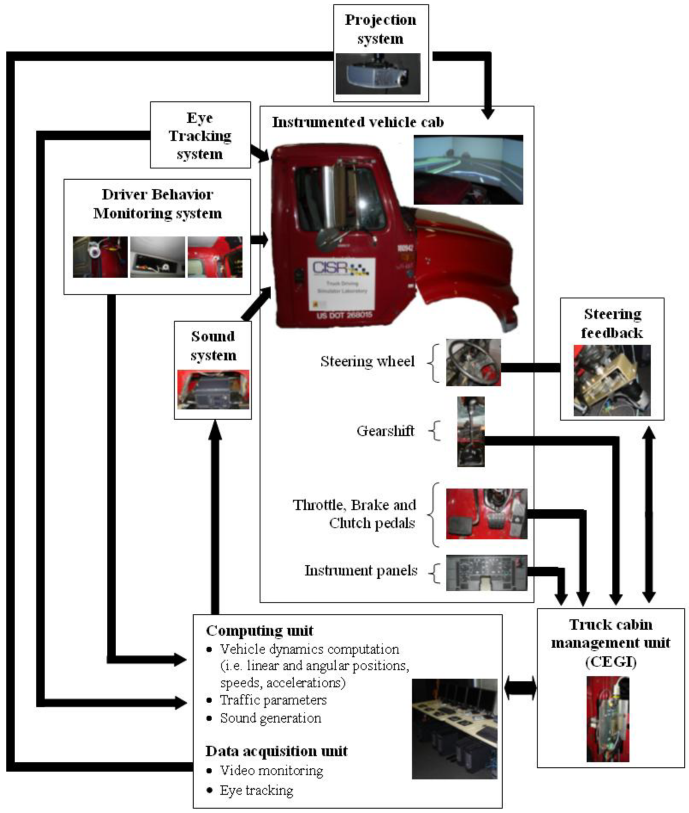


Figure 1: CISR Truck Driving Simulator

In most low-cost driving simulators, the same computer is responsible for data acquisition from the vehicle cabin, calculation of vehicle dynamics, traffic, and sound models, and generation of force feedback commands for in-vehicle controls. A key point in this simulator is the use of a dedicated micro-controller to manage vehicle cabin interfacing and steering actuator control processes. This additional interface layer (called Generic Instrumentation Electronic Card or CEGI) receives inputs from the vehicle cabin sensors, transmits all measured information to the computing unit of the vehicle dynamics model, controls in-vehicle indicators and dashboard gauges, and sends commands to the steering actuator power module. This second electronic unit then uses Pulse Width Modulation (PWM) to generate steering torque signals to be sent to a CC motor.

- **Truck cabin**

The first challenge in setting up a new driving simulator is to design the layout of the display system (i.e. projectors and screens) around the vehicle cabin in the available laboratory space, see Figure 2. The available projecting distance, the width of the displayed scene viewed by the driver, and the lab dimensions should guide the selection of vehicle cabin, projectors, and screens as interference between cabin and projected beams should be avoided. An International 8100 truck cabin was selected based on its relatively small size and weight in its class, see Figure 3.

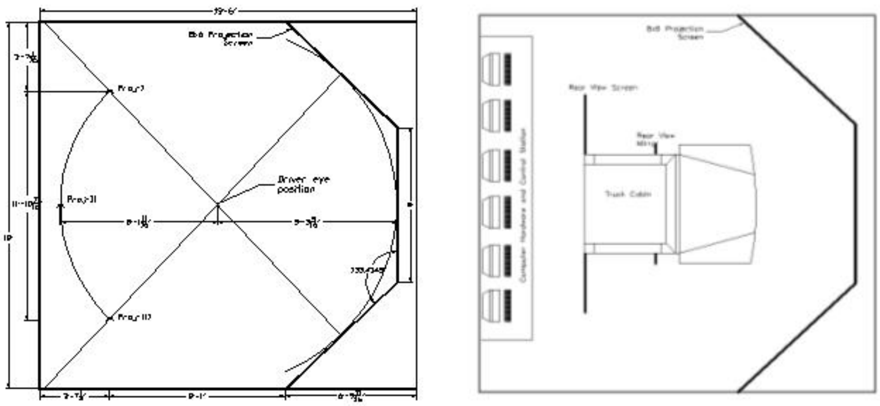


Figure 2: General layout of the driving simulator display system

Figure 3: Driving simulator truck cabin

- **Projectors**

The choice of projectors depends on the desired Field-Of-View (FOV). While larger FOV produce better immersion of the driving subjects in the virtual environment, they have also been found to contribute to simulator sickness. Compromise values for front projection FOV angles generally range between 110° and 160°.

Both front and rear projections were required for the truck driving simulator. While three projectors and screens enable a 135-degree wide front vision, the rear vision is ensured by two projectors and screens, one for each side, viewed through the truck side mirrors.

The good contrast ratios, brightness levels, and image sharpness achieved by DLP-based projectors make this technology a good and affordable choice for driving simulation applications.

- **Screens**

If curved screens theoretically produce better optic flow rendering, additional precautions are necessary to avoid image deformation and achieve correct alignments at image jointures. On the other hand borders between screens potentially visible to the drivers are inevitable when using flat screens. An alternative is to place these borders behind the vehicle cabin pillars from the driver's perspective. By not seeing the border of each screen, the driver will have the impression of a single continuous image projected in front of him. Therefore, if curved screens represent the best solution for expensive high-fidelity driving simulators, flat screens remain a good choice for low to medium fidelity simulators.

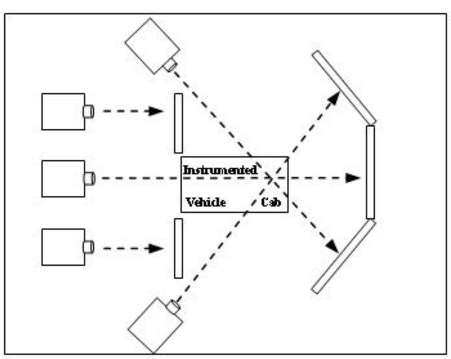
The research team believes that a simple screen design using white mat finish non-reflective display materials can achieve acceptable levels of performance.

The following basic rules must be considered to determine the screens positions, see Figure 2:

1. To avoid optical distortions, the driver should sit at equal distances from the center of each screen.

2. Distance between the screens and the driver is crucial. Placing the driver too close to the screens implies large angles between the screens and would compromise the driver's impression of seeing a single continuous image. On the other hand, placing the driver too far away from the screens would limit the width of the scene observed by the driver. Driver's positioning is commonly considered adequate, when the driver is placed 9 to 10 feet from the screens. The screens orientation angles are obtained as a consequence of this requirement, see Figure 2.

For CISR new truck simulator the research team adopted direct projection for the three front screens and back projection for the two rear screens, see Figure 4.



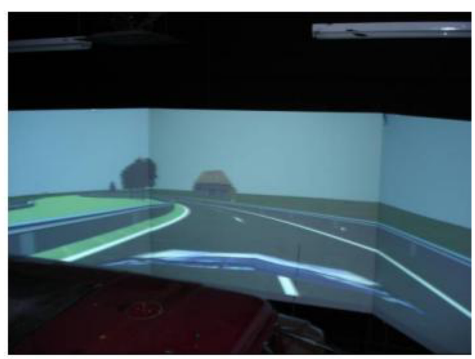


Figure 4: Front and rear projection in the truck driving simulator

- **Computer hardware**

Creating complex 3-D driving scenes involves highly demanding graphic applications that require sufficient computing power. Both processor and graphic cards performance levels are crucial for real-time generation of detailed virtual environments.

Seven networked PCs run the new truck driving simulator. Five PCs (Intel Pentium 4 processors at 3.0GHz with 1024MB SDRAM) equipped with large memory video cards (128MB ATI Radeon 9800 Pro) perform the highly demanding graphic computation of the projected 3-D driving scenes. One PC is interfaced with the truck cabin to compute vehicle dynamics, traffic and sound effects. The last computer manages and records signals from the Eye Tracker and video monitoring systems.

- **Steering feedback system**

Computer controlled DC motors provide one of the best options for steering feel system because they offer high output torques and good response time at reasonable costs. Faros Inc. of France supplied the steering system hardware. A DC motor produces the feedback torque. The controller card designed by INRETS hosting the steering feedback algorithm controls the torque motor, see Figure 5. Delocalized computing of the steering response ensures good update rates of the vehicle response during simulation.

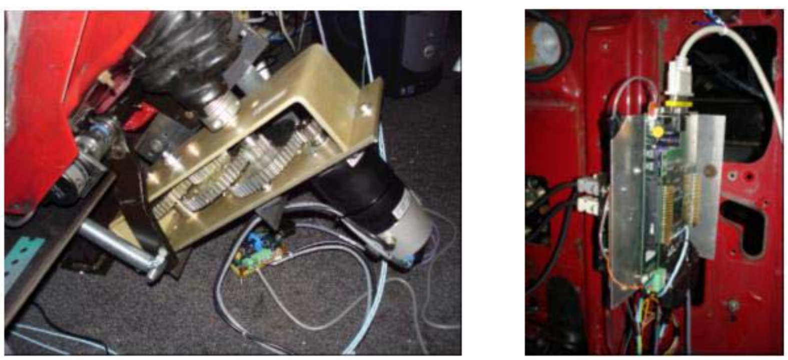


Figure 5: Faros steering feedback system and INRETS control unit

The torque actuator is connected to the steering shaft through a set of spur gears with a 7:1 gear ratio. The large gear ratio allows the amplification of torque ratio. To prevent the steering wheel from turning endlessly a mechanical stopping mechanism is provided. A steel pin mounted on a gear stops against a bolt preventing the steering wheel from turning more than 3.5 revolutions in each direction. Steering alignment errors can produce undesirable steering torque and cause premature wear-out of the steering elements. To compensate for small mounting errors a flexible coupling is used to connect the steering shaft to the DC motor shaft.

In the new truck simulator, the parameters of the steering torque response system were adjusted using subjective evaluations to achieve a realistic steering feel (see section 4).

- **Gearbox system**

The resistance of the gearbox system to driver's control inputs should be representative of a real transmission. Faros, Inc supplied the manual stick shift Gear Box system. The new system is an adaptation of the INRETS gearbox system developed for a car simulator. The system is capable of simulating a 10-speed gear ratio manual stick shift transmission. A set of levers and springs create the feeling of gear shifting. Gear position is determined by a round steel pin locking into one of the six cavities machine in a steel plate. A flip switch located in the lever hand knob determines higher gear ratios. A set of three potentiometers is used for sensing the current gear position. Two potentiometers determine the longitudinal and lateral position of the round steel pin while a third potentiometer, located in the flip switch in the lever, determines the high speed gear position. The shift lever was modified and a mounting frame was fabricated to assemble the gear box inside the vehicle cabin.

Figure 6: Faros gear box system and final assembly in simulator cabin

- **Cabin interface materials**

Vehicle cabin instruments, controls and switches all have to be integrated in the driving simulator and interfaced with the simulation software to reproduce the normal operation of a real vehicle and measure drivers' inputs during experiment.

To measure pedals motion during simulation optical encoders were mounted on the throttle, brake, and clutch pedals, see Figure 7.

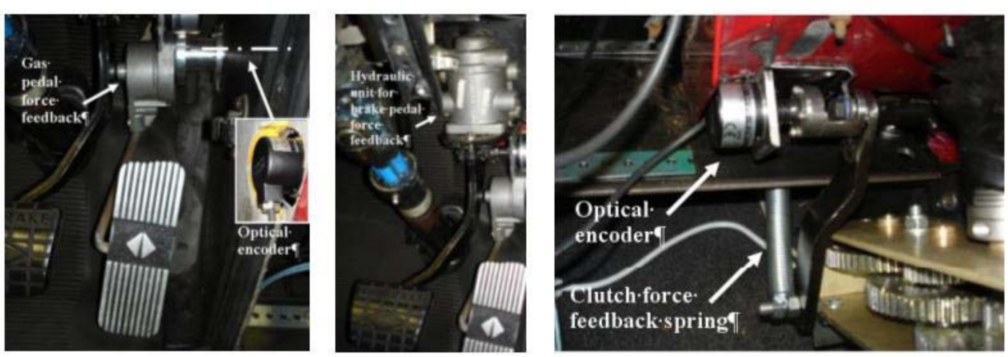


Figure 7: Optical encoders mounted on the truck cabin pedals

Incremental encoders with 500 pulses per revolution and push-pull output were selected.

New pedal mechanisms had to be designed and fabricated to reproduce pedals feel originally created by hydraulic systems. Passive spring and lever mechanisms were used to generate resistance in the pedals.

Electronic circuits and connectors were fabricated for appropriate interfacing of cabin sensors (i.e. optical encoders and potentiometers) and for operation of cabin instruments (i.e. cabin displays and dashboard gauges), see Figure 8. A special hardware was also designed to host all communication and control cards.

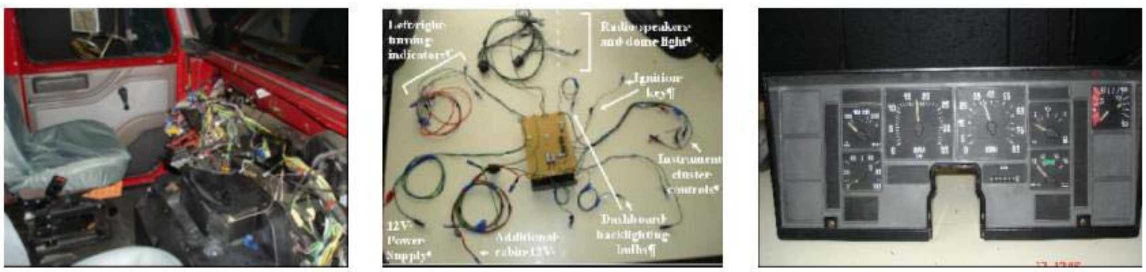


Figure 8: Cabin instruments wiring, connecting interface, and instrument panel

- **Sound system**

INRETS sound generation algorithm is capable of generating both vehicle sounds (e.g. engine sounds during vehicle start and acceleration/deceleration) and sounds from surrounding traffic. A multi-channel sound system composed of five speakers and a subwoofer was installed in the new truck simulator. Each element was strategically placed in the cabin to optimize the spatial sound rendering. The sub-woofer was attached to a steel plate, which is bolted to the truck cabin to transmit vibrations to the cabin during simulation.

Driving scenario

Developing the right type of driving environment is key to the successful simulation of any driving task. Each element of the driving scenario has to be defined by the researcher according to the experimental protocol. This include definition of the roadway, definition of the surrounding environment and other static objects, definition of other vehicular traffic, definition of all the events that will occur during the experiment, and the type of data that needs to be recorded during the experiment. Improper or poorly defined scenario will only produce incorrect and useless data.
Because driving simulation has many limitations in terms of computing and graphic requirements, driving scenarios should be defined based on the unique sequence of tasks and events required to simulate the driving situation being studied.

For studying driver drowsiness, the driving scenario should mainly consist of long and monotonous driving sections susceptible to induce driver's boredom and fatigue. Based on statistical data on the characteristics of accidents involving driver's drowsiness, the following scenario was developed for the truck simulator:

- Rural interstate highway with speed limits of 55-65 mph
- Early morning and nighttime driving
- Very little traffic and other activity in the surrounding representing a monotonous and calm atmosphere

This scenario includes realistic sound, visual effects and other pre-defined events regarding road traffic and traffic controls.

CISR decided to develop a driving scenario based on a real interstate rural highway and acquired hard copies of plans and profile drawings from Kansas Department of Transportation. These drawings cover a 52 miles section of Interstate 70 highway. Alignment, traffic, and other environmental conditions on this highway are very consistent with that required for fatigued/drowsy driving.
In collaboration with INRETS, CISR extracted geometric design information from the drawings (i.e. horizontal and vertical curvatures, cross-section data, marking information, etc) and created a 3-D roadway environment using OpenGL Performer graphics library from Silicon Graphics. Vehicles, traffic signs, roadside and background objects were then added to the model, see Figure 9. An exhaustive sequence of driving actions and traffic events was defined to complete the driving scenario.

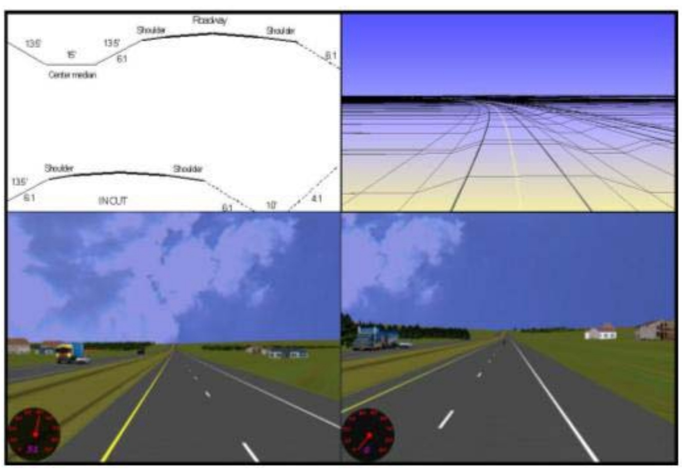


Figure 9: Alignment data, 3-D mapping, and finalized driving scene

Specific equipment/set up for drowsiness studies

Additional hardware was required in the truck driving simulator to measure and record driver's behavior and level of alertness/sleepiness during the drowsiness studies.

Video images provide valuable information for studying driver's behavior. The truck driving simulator is equipped with a digital video monitoring and recording system. Infra red cameras capture images of driver's face and body, hands, feet, and displayed driving scene as viewed from the inside the cabin, see Figure 10.

Figure 10: Infra-red images of driver's body, hands, and feet and driving scene

The simulator lab is also equipped with an eye tracking and measuring system. The system measures and records the line of gaze and the pupil diameter of the driver during experiment.

4 Tuning and validation of the truck driving simulator

The last phase of the truck driving simulator setup consisted on adjusting the system parameters to achieve realistic truck driving rendering and validating the new simulator for driver drowsiness studies based on subjective evaluations.

Adjustments to the vehicle dynamic model and simulated traffic

To get a realistic truck driving rendering in various vehicle controls - specially steering - the vehicle parameters of INRETS passenger car model had to be modified. The vehicle inertial parameters, the suspensions and tires constants, and the steering and gear-shifting characteristics of an International 8100 truck were entered in INRETS model. Because the experiments to be conducted in the simulator do not involve driving situations with severe dynamic vehicle responses, this approach, when supplemented by a rigorous verification of the resulting truck behavior, was adequate for this study.

Testing the simulator

After completing the installation of hardware and software, the simulator components had to be tested for accuracy, reliability, and authentication of data acquisition.

Simulation under fully loaded conditions were performed for prolong periods of time to test the system for reliable performance. Potential hardware weak points were identified and replaced by alternative solutions; e.g. the gear box wiring design was modified to prevent future cable breakage.

Many problems can also arise during operation of any distributed and/or networked system due to network congestion, memory usage, or other conflicts, which can cause crashing of the whole simulation. The system was tested for all these problems and modifications/reconfigurations were made for continuous system operation; e.g. anomalies in the computation of traffic vehicles interaction were corrected, and problems of computational overload due to excessive graphic demand were solved.

Subjective evaluation

Evaluation of the simulator was performed based on subjective evaluation by experienced personal. Because driving feeling differ between heavy commercial vehicles depending on their type, brand and model, size, load, etc the new simulator had to produce a driving feeling representative of an average heavy truck vehicle. CISR asked three professional truck drivers to drive the simulator, and based on their advice the following parameters were adjusted for a more universal truck driving feeling:

- Steering Ratio
- Maximum Steering Angle
- Steering Torque
- Total Vehicle Load
- Maximum Braking Torque
- Gear Ratio

CISR then asked other CMV drivers to subjectively evaluate CISR truck simulator after the above adjustments were performed. Each of the drivers completed a practice session and was asked to fill out a questionnaire regarding performance of various controls and functions of the simulator. Drivers were asked to evaluate overall realism, responsiveness, and feel of the simulator steering, gearbox, and pedals systems. Additional measures included:

- Sound Intensity
- Sound Direction
- Sound Overall Realism
- Display Graphics

- Display Size/View
- Display Overall Realism
- Instruments Overall Realism
- Scenario Vehicles
- Scenario Roadway
- Scenario Surroundings
- Scenario Traffic
- Scenario Overall Realism
- Cabin driver seat
- Cabin Overall Interior
- Cabin Overall Realism
- Side Mirrors Size
- Side Mirrors View
- Side Mirrors Overall Realism

Overall drivers' evaluation averaged 1.8 on a scale of 1 to 5 (1 being very close to real truck and 5 being very unrealistic). The overall response for the steering performance was 1.7.

The last task in the truck simulator development was the validation of the simulator for driver's drowsiness studies. CISR invited a panel of distinguished experts from the driving simulation and human factors research fields to assess the new laboratory set up for drowsiness studies. The new simulator received very positive feedback from the experts. Minor recommendations were taken into account and corresponding adjustments were implemented in the driving simulator.

5 Recommendations for potential improvements and perspectives

Based on drivers' opinions and outcomes of the drowsiness experiments conducted in the new truck driving simulator, enhancements to the current set up can be determined:

- To avoid anti-aliasing problem in the displayed images, graphic cards with higher memory could be installed. Although driver sickness has not been experienced in this simulator, the presence of anti-aliasing problems in projected images has proven to contribute to simulator sickness.

- To improve the realism of the truck cabin environment, additional hardware can be integrated to increase the level of vibration transmitted to the cabin. Options available include the installation of a vibrating seat system and vibrating actuator below the truck cabin. ARCHISIM simulation package already has the capability to interface and control a vibrating seat in the vehicle cabin of the driving simulator.

- The measuring robustness of the eye tracking system currently used in the simulator has shown limitations. Calibration of the system to each driver is also a delicate procedure. A more flexible and robust eye tracking system could improve the quality of eye measures during experiment.

This new simulator is also a great tool for a variety of driving safety related studies. Possible applications of the simulator include studying the effect of various environmental or vehicle factors on driver behavior (e.g. influence of vehicle noise/vibration, driver distraction sources), assessing specific driver-vehicle ergonomic issues, developing in-vehicle acquisition systems for driver performance recording, etc. However, appropriate validation needs to be performed to evaluate the suitability of the simulator for each of these applications.

LIST OF REFERENCES

[1] **Gruening J., Bernard J., Clover C. and Hoffmeister K.,** "Driving simulation" *SAE Special Publications*, v 1361, Feb, 1998, 980223, *Vehicle Dynamics and Simulation, 1998*, p 49-59.

[2] **Hogema J. H.,** "Compensation for delay in the visual display of a driving simulator" *Simulation*, v 69, n 1, Jul, 1997, p 27-34.

[3] **Sudarsan S. P., Cohen C. J., Du L. Q., Cobb P. N., Yager E. S. and Jacobus C. J.,** "Influence of video characteristics of simulator images on remote driving performance" *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, v 2, 1997, p 1062-1066.

[4] **Glaser R. A. and Fisher D. L.,** "Driving simulators: Are they valid test environments for ITS development?" *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting*, 1997.

[5] **Levine O. H. and Mourant R. R., "**Effect of visual display parameters on driving performance in a virtual environments driving simulator" *Proceedings of the Human Factors and Ergonomics Society*, v 2, 1996, p 1136-1140.

[6] **Kim Jung-Yong, Park Min-Yong and Park Chang-Soon,** "Psycho-physiological responses reflecting driver's emotional reaction to interior noise during simulated driving" *Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Association, 'Ergonomics for the New Millennnium'*, Jul 29-Aug 4 2000, San Diego, CA.

[7] **Reymond G., Kemeny A., Droulez J. and Berthoz A.,** "Role of lateral acceleration in curve driving: Driver model and experiments on a real vehicle and a driving simulator" *Human Factors,* v 43, n 3, 2001, p 483-495.

[8] **Lin James Jeng-Weei, Duh Henry B.L., Parker Donald E., Abi- Rached Habib and Furness Thomas A.,** "Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment" *Proceedings - Virtual Reality Annual International Symposium*, 2002, p 164-171.

[9] **Lee Gene C.H., Yoo Younghak and Jones Sherrie,** "Investigation of driving performance, vection, postural sway, and simulator sickness in a fixed-based driving simulator" *Computers & Industrial Engineering*, v 33, n 3-4, Dec, 1997, p 533-536.

[10] **Mourant R. R. and Thattacherry T. R., "**Simulator sickness in a virtual environments driving simulator" *Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Association, 'Ergonomics for the New Millennium',* Jul 29-Aug 4 2000, San Diego, CA, United States, p 534-537.

[11] **Nilsson L.,** "Behavioural research in an advanced driving simulator - experiences of the VTI system" *Proceedings of the Human Factors and Ergonomics Society*, 1993.

[12] **Radwan E., Al-Deek H., Bauer C. and Klee H.,** "Driving Simulator Technologies. - Final report, 1998" University of Central Florida, Orlando.; Florida State Dept. of Transportation, Tallahassee*, Technical report, NTIS* Order Number: PB99-119174.

[13] **Espié, S., Mohellebi, H., and Kheddar A.,** "A high performance / low-cost mini driving simulator alternative for human factor studies", *Proceedings of the 2003 DSC North America, Dearborn, Michigan, ISSN 1546-5071*.

[14] **Godthelp J.,** "Precognitive control: open and closed loop steering in a lane change manoeuvre" *Ergonomics,* Vol. 28, 1985, pp. 1419-1438.

[15] **Miyamoto Takao, Momiyama Fujio and Fujioka Takehiko,** "Steer-restoring torque controlled driving simulator for developing steering road feel" *SAE Special Publications*, n 892, Nov, 1991, *Commercial Vehicle Suspensions, Steering Systems, and Traction*, p 83-88.

[16] **Liu A. and Chang S.,** "Force feedback in a stationary driving simulator" *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, v 2, 1995, p 1711-1716.

[17] **Howe J. G., Rupp M. Y., Jang Bong-Choo, Woodburn C. M., Guenther D. A. and Heydinger G. J.,** "Improving steering feel for the national advanced driving simulator". *SAE Special Publications*, v 1228, Febr, 1997, 970567, *Research into Vehicle Dynamics and Simulation*, p 135-145.

[18] **Jang B.C.,** "A mathematical model a power steering system for implementaion in a driving simulator" *MS thesis, The Ohio state university*, 1996.

[19] **Fujioka Takehiko, Shirano Yasuyuki and Matsushita Akifumi,** "Driver's behavior under steering assist control system" *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, 1999, p 246-251.

[20] **Chen L. and Ulsoy G.,** "Experimental validation of a robust steering assist controller on a driving simulator" *Proceedings of the American Control Conference*, Anchorage, AK, May 8-10, 2002.