University Transportation Research Center - Region 2

Final Report

Truck Driver Fatigue Assessment using a Virtual Reality System

Performing Organization: Rowan University

October 2016

Sponsor:
University Transportation Research Center - Region 2

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

Research

The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

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The modern professional must combine the technical skills of engineering and planning with knowledge of economics, environmental science, management, finance, and law as well as negotiation skills, psychology and sociology. And, she/he must be computer literate, wired to the web, and knowledgeable about advances in information technology. UTRC's education and training efforts provide a multidisciplinary program of course work and experiential learning to train students and provide advanced training or retraining of practitioners to plan and manage regional transportation systems. UTRC must meet the need to educate the undergraduate and graduate student with a foundation of transportation fundamentals that allows for solving complex problems in a world much more dynamic than even a decade ago. Simultaneously, the demand for continuing education is growing – either because of professional license requirements or because the workplace demands it – and provides the opportunity to combine State of Practice education with tailored ways of delivering content.

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16. Abstract

In this study, a fully immersive Virtual Reality (VR) based driving simulator was developed to serve as a "proof-of-concept" that VR can be utilized to assess the level of fatigue (or drowsiness) truck drivers typically experience during real-life driving conditions. This study also involved examining the impact of varying driving conditions (i.e., weather conditions and driving time (day or night)) on drivers' fatigue measure. To fulfill these goals, four drivers (two fatigued and two unfatigued) were allowed into the developed VR-based driving simulator to drive a VR-based truck at varying driving conditions. These conditions included clear day time, rainy day time, clear night time, rainy night time, foggy day time, rainy foggy day time, foggy night time, and rainy foggy night time conditions. Two fatigue measures (sway ratio and reaction time) were introduced and computed (or measured) using the VR-based simulator for all drivers. The computed measures were analyzed using multi-factor statistical analysis (ANOVA) procedures. The simulations conducted and the results obtained showed that VR-based driving simulators are a viable alternative to traditional driving simulators when developing technologies that assess drivers' drowsiness (or fatigue) levels. The results also showed that sway ratio and reaction time fatigue measures were successful at characterizing the fatigue levels of drivers. This is the case because these measures were capable of clearly distinguishing between the two groups of drivers. It was also found that the sway ratio fatigue measure was influenced by weather conditions (mainly rainy conditions) employed during VR-based simulations.

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EXECUTIVE SUMMARY

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BACKGROUND

Driver fatigue is a significant contributing factor to numerous fatal traffic crashes resulting in death or injury every year. Fatigue is invisible and there is no single symptom that can be exclusively identified to assess or recognize it in advance. Fatigued or drowsy truck drivers (i.e., truckers) experience reduced ability to control vehicles, reduced natural reflexes, and reduced recognition and perception capabilities (1). For all these reasons, driver fatigue is often called the hidden killer that creates great socioeconomic concerns (e.g., risk to other motorists). Transportation experts, lawmakers and the general public have to find solutions for these concerns.

Many regulations are already in place to safeguard truckers against falling asleep while driving or losing reaction time due to lack of sleep. Driving laws are employed to control truckers and limit them from driving while fatigued. For example, the current Hour-of-Service (HOS) rules require truckers to have a minimum off-duty hours ranging between eight to ten hours. HOS rules also require truckers to drive for a maximum of ten to eleven hours before going off-duty (2). According to Dick et al. (2006) (2), these rules are well-received by truckers and trucking companies and the implementation of these rules has resulted in reducing collisions and injury rates. Despite the benefits of these set rules, technologies are still needed in order to be able to characterize drivers' fatigue and further reduce crashes and collisions in the trucking industry.

Various studies have been conducted to develop or evaluate technologies that can be used to characterize and identify fatigued truck drivers. For instance, Wang et al. (2014) (1) developed a multilevel Ordered Logit model (MOL), an Ordered Logit model (OL), and an Artificial Neural Network (ANN) model to detect truckers drowsiness. To develop these models, the researchers collected information regarding eyelid closure, pupil diameter, lane position, and angle of steering wheel using a camera placed in a motion-based driving simulator. The model parameters were measured for various truckers during an eight hours night shift in the simulator. Based on the results, the researcher reported that MOL model had the highest accurate drowsiness detection rate. The researchers also reported that considering individual differences improves the model's (i.e., MOL) ability at detecting truckers drowsiness.

Jagannath and Balasubramanian (2014) developed a methodology (3) to assess early fatigue in drivers by evaluating a set of multimodal fatigue measures. This study involved twenty male drivers who performed 60 minutes of driving in a static driving simulator. The driving simulation was carried out by evaluating surface electromyography (sEMG), electroencephalography (EEG), seat interference pressure, blood pressure, heart rate, and oxygen saturation level of the drivers. Based on the sEMG results, the researchers observed that the drivers experienced significant physical fatigue (i.e., back and shoulder muscle groups) after completion of the simulation. The results also showed, according to Jagannath and Balasubramanian (2014), significant changes in the drivers' bilateral pressure distribution in the thigh and buttocks region. All in all, the researchers concluded that implementing an approach that utilizes multimodal fatigue measures is helpful in understanding the influence of physical and mental fatigue on drivers.

Lal and Craig (2002) assessed a driver fatigue detection technique (4) that relies on electroencephalography and psychological assessment using a driving simulator. The study involved examining the psychophysiological changes in 35 randomly selected drivers (26 men and 9 women). Based on simulation results it was reported that significant electroencephalographic changes in the drivers were observed. These changes indicated that the drivers were fatigued or tired. It was also observed that delta and theta activities (i.e., frequency bands defining EEG) were higher for fatigued drivers than those for unfatigued drivers. These higher delta and theta values were associated with increased drivers' anxiety, tension-anxiety, fatigue-inertia and reduced vigor activity. The researchers also reported that drivers' heart rates were lower after the completion of the simulation and blink rates have also changed. It was concluded that these fatigue measures could potentially be utilized in developing effective fatigue countermeasure devices.

Forsman et al. (2013) developed a methodology (5) through which drowsiness can be detected when drivers are experiencing moderate levels of fatigue. A total eighty seven driver fatigue measures were evaluated in this study using a high-fidelity driving simulator. Forty one drivers were subjected to two driving conditions (i.e., 29 subjected to night-time driving conditions resulting in moderate fatigue levels and 12 subjected to day-time driving conditions resulting in control fatigue levels). From among the eighty seven fatigue measure evaluated, the researchers reported that variability in steering wheel and measures of lateral lane position variability were the most dominant; correlating well with other independent measures of fatigue (such as psychomotor vigilance test results). The researchers also reported that these two fatigue measures can be utilized to develop a cost-effective and easy-to-install alternative technologies for in-vehicle detection of drivers' drowsiness.

Hallvig et al. (2013) compared fatigue measures obtained (6) from actual real-life driving conditions and those obtained from driving simulators. The goal of this comparison was to determine the extent for which driving simulators can be utilized to simulate real-life driving conditions and characterize drivers' fatigue. This study involved collecting fatigue measures (i.e., driving performance, sleep-related physiology, and instinctive sleepiness) from ten drivers. Those measures were first collected for drivers under real-life truck driving conditions. The measures were also collected for the same truckers driving in a high fidelity simulator. Through comparing the collected results the researchers reported that simulators are more subjective and induce more physiological sleepiness when compared to real driving. In driving simulators, the researchers observed that drivers tend to move laterally (i.e., left and right from centreline of lane) while in real-life driving they tend to actually move to the left of the centreline as well as reducing speeds when they are sleepy. Ultimately the researchers concluded that the use of simulators is a viable option to conduct driver fatigue studies noting that simulators induce higher sleepiness levels on drivers than what they actually experience in real-life driving.

In summary, researchers (1, 2, 3, 4, 5, and 6) have utilized various measures to characterize fatigue and drowsiness in truck drivers. For the majority of studies presented above (as well as other studies 7, 8, 9, 10, 11, 12, 13, 14, and 15), a driving simulator was utilized to evaluate the ability of these measures at characterizing drivers' fatigue. This indicates that driving simulators provide a viable option for evaluating driving induced fatigue/drowsiness. All the available driving simulators; however, do not provide an immersive environment in which drivers may experience actual driving conditions. While they may be deemed as an acceptable option for characterizing drivers' fatigue (6), a more realistic fully-immersive truck driving simulation may provide better assessment of drivers' fatigue measures. In addition, available driving simulators do not have the capability of simulating varying traffic conditions (heavy, medium or low traffic), weather and environmental conditions (rain, fog, clear), and other roadways construction related conditions (lane-closures and sudden traffic stops). Therefore, to address these limitations there is a need to develop driving simulators that take advantage of Virtual Reality capabilities as a potential advancement in truck driving simulation. Advancements in Virtual Reality technology offer the opportunity to develop such fully-immersive simulations while at the same time allow for evaluating the effects of various conditions on drivers' fatigue measures. Reduction in Virtual Reality installation costs over the last few years make such simulations a viable option.

OBJECTIVES

The overall goal for this study is to develop a fully-immersive truck driving simulator using Virtual Reality. This simulator will serve as a "proof-of-concept" that Virtual Reality can be utilized to assess the level of fatigue truck drivers typically experience during real-life driving conditions. The ability of the developed simulator to characterize fatigue measures will also be evaluated. In addition, the impact of varying driving conditions (i.e., weather conditions and driving time (day or night)) on drivers' fatigue measure will be quantified.

VIRTUAL REALITY (VR) BASED DRIVING SIMULATOR

Virtual Reality (VR) can be defined as a system for developing and replicating real-life (or imaginary) environments using the-state-of-the-art computer graphics (i.e., three-dimensional, 3D) and input/output devices. Users can be immersed in these environments and have the ability to interact and complete tasks. Available hardware and software technologies are typically used to create successful VR applications for different engineering disciplines. Initial engineering applications of VR concentrated on providing methods for three-dimensional input and stereoscopic viewing. Over the past five years, several advanced VR applications (e.g., storm water and flood pattern simulations) have assisted researchers and officials in making complex decisions (i.e., which areas to evaluate). The following subsections provide a description of the hardware devices and computer programs (software tools) used in developing a VR-based driving simulator.

Hardware Devices

The hardware devices that were needed to develop a VR-based driving simulator consisted of one gaming seat and one gaming steering (or racing) wheel (Figure 1).The seat was modified to represent seats typically found in trucks. Specifically, the original gaming seat allows drivers to lean back more than typical truck seats. As a result, the gaming seat was modified by attaching a wooden base to it. The steering wheel was then mounted on the modified gaming seat to simulate steering wheels in trucks. The modified seat had a gas pedal, a brake pedal, and a clutch pedal while the steering wheel had buttons that can be used to simulate signal blinkers, engine retarders, and spike or trailer breaks. It is important to note that other more advanced seats and control devices are available; however, due to budget constraints this configuration was selected.

Figure 1: Modified Gaming Seat and Gaming Steering Wheel Utilized to Develop VR-Based Driving Simulator.

Software Development

The computer programs (software) of the developed VR-based driving simulator included two main components. These components are environment generation to simulate real-life roadways weather conditions, and other traffic conditions. The software component of the VR-based driving simulator also included the programming necessary to accurate simulate real-life trucks. In addition, the computer programs included a data collection component. The following subsections provide a description of these components.

Environment Generation

In order to simulate real-life driving conditions and develop a successful VR driving simulator, it was necessary to include various components such as roadways, traffic, and weather conditions as the environment in which driving will occur. To develop the environment, Unity VR package was utilized. In this package, real-world roadways were simulated by first collecting Global Positioning System (GPS) data form Google Maps. This data contained latitude, longitude, and elevation information of actual roadways. This information was collected for a route connecting Washington, D.C. to New York City passing through the New Jersey Turnpike (I-95). The collected GPS data was processed to compute relative distances between the different locations on the roadway. A Haversine Formula (16) was utilized to compute these distances and estimate coordinate points (Cartesian x, y, and z) for the selected roadway route. To draw smooth roadways, the estimated coordinate points were utilized to fit the Catmull-Rom spline formula (17).

This information was incorporated into Unity to generate graphics. Other roadway features available in Unity, such as lane markings, guidance signs, cautionary signs, trees, clouds, etc., were also included to generate a realistic environment (Figure 2). In addition, Unity prepackaged weather conditions (i.e., clear sky, partly cloudy sky, cloudy rainy sky, dawn and dusk, fog and glare, day and night driving etc.) were also utilized to make the VR-based driving simulator realistic.

Simulated Truck

Unity was also utilized to simulate a truck consisting of a tractor and a trailer (representing a semitrailer truck). The tractor had a width of 8 ft. (2.3 m) and a length of 18 ft. (5.51 m). The trailer had a width of 8 ft. (2.3 m) and a length of 28.5 ft. (8.7 m). UnityCar package was utilized to simulate the truck. This package include fully modeled cars and trucks, scripted physics and controls. UnityCar code was modified to realistically simulate the experience of driving a semitrailer truck. For instance, the UnityCar code was modified to allow for attaching the trailer to the tractor using a hinge joint. This facilitates realistic truck turns when a driving simulation is ongoing. The code was also modified to allow for addition of loads to the trailer for simulating loading and unloading truck. Signal blinkers, head and back lights, as well as twelve gears were also defined into the simulated truck.

Data Collection

The software component of the VR-based driving simulator also included a data collection code that allows for continuously recording information about the simulation. This data included the position of the driver within at the roadway, number of lane crossing with/without using signals, the lane in which the truck is located, and simulation environmental conditions. Drivers' reaction time to press a button in response to a simulated change in environment (i.e., appearance of a random red dot on the screen) was also recorded during the simulations.

Figure 2: Virtual Reality (VR) Based Truck Driving Simulator.

PLAN FOR EVALUATING DRIVERS' FATIGUE

A testing plan was prepared to evaluate the potential for using the developed VR-based driving simulator in assessing truck drivers' fatigue levels. This testing plan involved four drivers run in the VR-based driving simulator at varying driving conditions. These conditions, as shown in Table 1, included: (1) clear day time, (2) rainy day time, (3) clear night time, (4) rainy night time, (5) foggy day time, (6) rainy foggy day time, (7) foggy night time, and (8) rainy foggy night time conditions. The four drivers were classified into two groups: fatigued drivers and unfatigued drivers. The fatigued drivers group included two drivers who ran the driving simulation after completing eight hours of regular work. The unfatigued drivers were tested in the morning when they were still fresh. Comparison of the data collected from both groups was utilized to determine the ability of the VR-based driving simulator and the collected fatigue measures to distinguish between the two groups.

Before completion of the actual driving simulations (i.e., simulations used to collect data), the drivers were advised to obtain eight hours of sleep in the night prior to the planned simulation run. Once the drivers acknowledged that they had enough sleep they were allowed to the VR-based driving simulator. These simulations were for only 30 minutes to offer the drivers the chance to gain experience on driving the truck in the VR-based simulator. The drivers were then asked to leave and come back the next day to run additional simulations. Each driver was then allowed to drive the VR-based truck for two hours with the weather conditions varying (Table 1) every 15 minutes. The collected data was analyzed according to the procedure discussed in the following section to determine the difference in fatigue levels between the drivers.

Table 1: Testing Plan to Evaluate the Developed VR-Based Driving Simulator

Driving Condition	Simulation Duration (min)	Fatigued Drivers (1 & 2)	Unfatigued Drivers (3 & 4)
Clear Day Time	15	✓	✓
Rainy Day Time	15	✓	✓
Clear Night Time	15	✓	✓
Rainy Night Time	15	✓	✓
Foggy Day Time	15	✓	✓
Rainy Foggy Day Time	15	✓	✓
Foggy Night Time	15	✓	✓
Rainy Foggy Night Time	15	✓	✓

DATA ANALYSIS PROCEDURE

The data analysis approach employed in this study involved analyzing truck position data collected using the VR-based driving simulator. This data was utilized to compute a fatigue measure referred to herein as sway ratio. Figure 3 presents an example truck position within the VR simulation world. As can be seen from this figure, a global coordinate system was established to define the position of the truck at every instance during a simulation run. The coordinates of the truck (i.e., X_o, Y_o, and Z_o) define the position of the truck in reference to the established global coordinate systems (X, Y, and Z) at Point O.

Figure 1 also shows the definition of the non-sway and sway zones utilized to establish the sway ratio fatigue measure. The width of the non-sway zone (shaded area in Figure 1) was defined, in the transverse Z-direction, as the summation of the truck's width (7.55 ft. (or 2.3 m)) and 1.65 ft. (0.5 m) clearance distance from both sides of a lane's center line (dashed line in Figure 1). As a result, the total width of the non-sway zone is approximately 10.83 ft. (3.3 m) as shown in Figure 3. It is noted that the clearance distance (total 3.28 ft. (1 m)) was selected to account for typical truck lateral wandering patterns. The region outside the non-sway zone was defined as the sway zone.
Utilizing these definitions, truck position data was analyzed to determine whether drivers were within the non-sway zone or the sway zone. Table 1 below presents a sample of truck position data collected using the VR-based simulator. This data was collected at a rate of one data point (or location) every approximately 0.5 seconds. A computer program was developed to analyze this data and determine the number of times a driver was within the sway zone and the number of times the same driver was within the non-sway zone. It is important note that this computer program was developed to account for instances where drivers were changing lanes throughout the simulation. If a driver was changing lanes, position data were considered to be in the non-sway zone. Based on this analysis, the sway ratio was defined as the number of occurrences a driver was within the sway zone (when not changing lanes) divided by the number of occurrences a driver was within the non-sway zone. The higher is the sway ratio the more drowsy or fatigued is the driver.

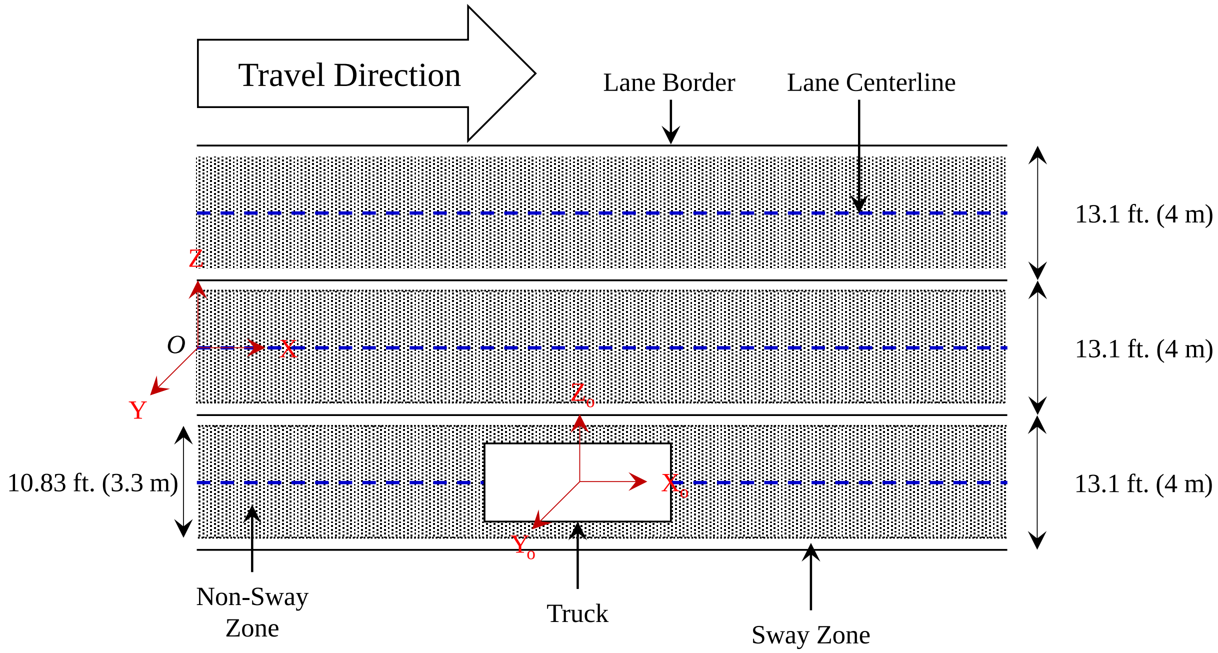


Figure 3: Example Truck Position and Definition of Sway Zone.

In addition to the sway ratio, the concept of reaction time was also utilized to assess drivers' fatigue levels. As mentioned previously, during a simulation drivers were asked to click a button when a randomly position circular red dot shows up on the simulation screens. The time required for a driver to react and accomplish this activity was recorded at various times throughout the simulation. The higher is the reaction time the drowsier or more fatigued is the driver. A discussion of the sway ratio and reaction time results obtained from analyzing VR-based driving simulations is presented in the following section.

Table 2: Example Truck Position Data Collected Using VR-Based Simulator

Time Stamp (H: M: S: mS)	Position Coordinate X_o, ft. (m)	Position Coordinate Y_o, ft. (m)	Position Coordinate Z_o, ft. (m)
11:56:51:716	47061.71 (14344.41)	0.82 (0.25)	24473.75 (7459.60)
11:56:52:235	47078.51 (14349.53)	1.77 (0.54)	24504.00 (7468.82)
11:56:52:715	47094.52 (14354.41)	2.66 (0.81)	24533.04 (7477.67)
11:56:53:222	47110.79 (14359.37)	3.44 (1.05)	24562.83 (7486.75)
…	…	…	…

DISCUSSION OF RESULTS

Sway ratios and reaction times for fatigued and unfatigued drivers were computed and are presented in Figures 4 and 5 below. Driver position data was collected for each of the four drivers and was analyzed using a MATLAB script according to the data analysis procedure discussed above. The following subsections provide a discussion of these results to determine whether the suggested data analysis procedure, and ultimately the VR-based simulator, is capable of distinguishing between the two groups of drivers tested. The following subsections also provide a discussion of the impact of weather conditions on drivers' fatigue levels along with the Analysis of Variance (ANOVA) statistical analysis conducted on the collected data.

Sway Ratio and Reaction Time

Figure 4 presents the sway ratios computed for both unfatigued and fatigued drivers allowed into the VR-based driving simulator. As can be seen from this figure, the sway ratios for fatigued drivers were higher than those obtained for unfatigued drivers. This was the case for all weather conditions considered. These observations suggest that fatigued drivers were swaying more than unfatigued drivers when conducting the VR-based simulation. Such observations were expected because unfatigued drivers were "fresh" (i.e., relatively not as tired) when compared to fatigued drivers. Based on these observations, one; therefore, may argue that the sway ratio is a measure that is capable of distinguishing between the fatigue levels of drivers. These observations may also suggest that the VR-based simulator was successfully developed and used in characterizing the drivers' fatigue and drowsiness levels.

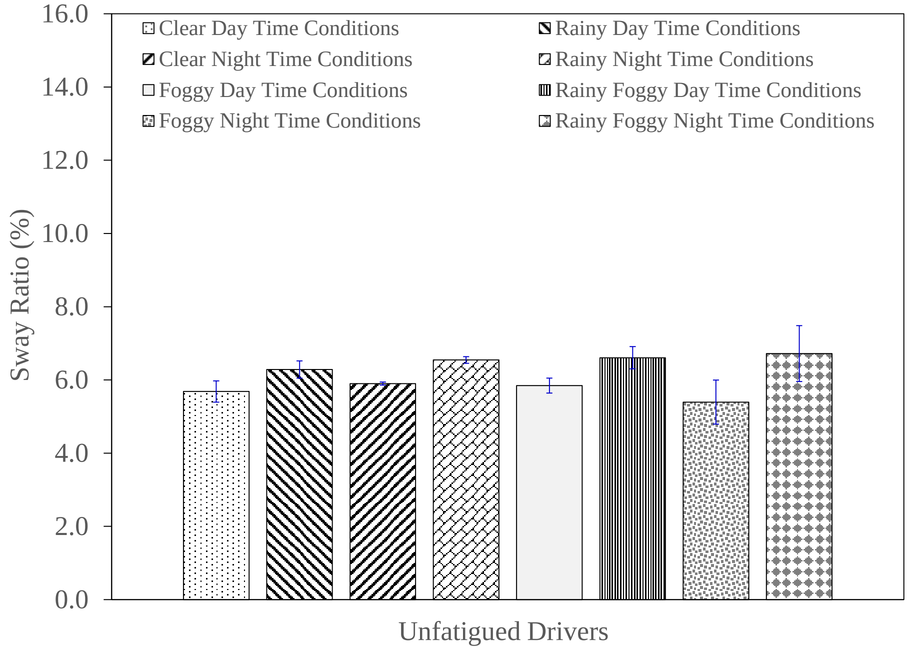
Figure 5 illustrates the reaction times for both unfatigued and fatigued drivers. Similar to the sway ratio results (Figure 4), the reaction times shown in Figure 5a and 5b for unfatigued drivers were lower than those for fatigued drivers at all weather conditions considered. These results are mainly attributed to lower alertness levels and higher drowsiness levels in fatigued drivers. Similar to the sway ratio results (Figure 4), these results were also expected because fatigued drivers usually are drowsier and less alert than unfatigued drivers. Therefore, it can be concluded that the reaction time may also be a viable measure for characterizing drivers' fatigue levels and that the VR-based driving simulator was successful.

Impact of Driving Conditions on Drivers' Fatigue Levels

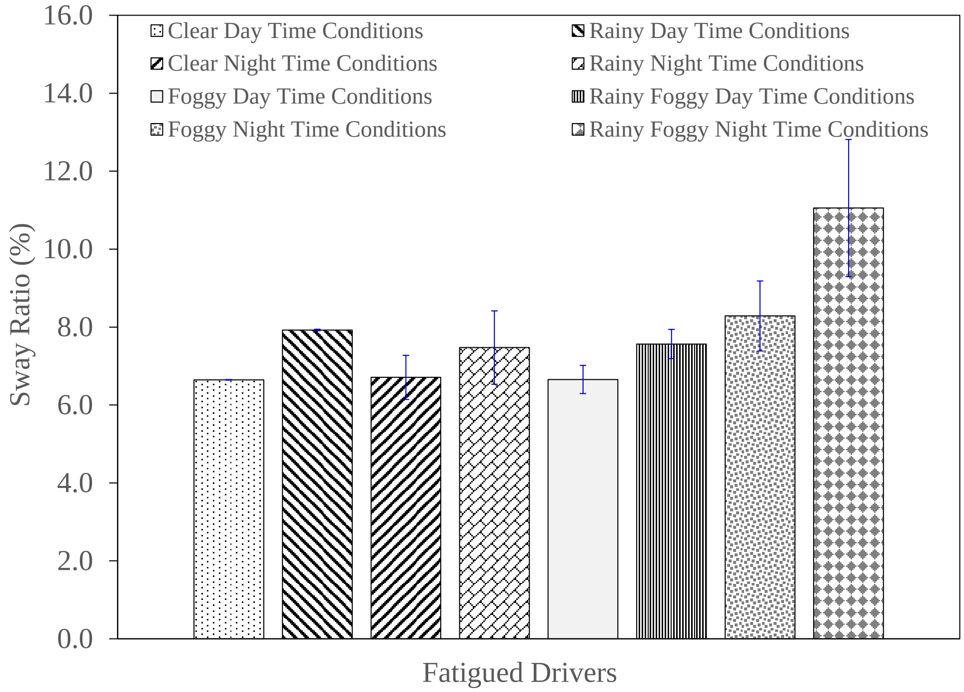
The results presented in Figures 4 and 5 below can also be utilized to evaluate the impact of weather and driving time conditions on drivers' fatigue and drowsiness levels. By comparing the sway ratio results (Figure 4) for all drivers conducting the simulation during clear day time conditions and those obtained for all drivers conducting the simulation during clear night time conditions, it can be seen that for both of these driving conditions the sway ratios were relatively similar. This suggests that driving time when running the simulation did not have an impact on the sway ratio results. It is noted; however, that all drivers conducted these (day and night) simulations during regular work hours (i.e., 8 AM to 5 PM); thus, explaining why the sway ratio for both conditions was similar. Having the drivers' conduct the simulation during regular work hours was employed because the simulator was developed as a "proof-of-concept" and future studies using the simulator will involve more accurate simulations.

Similarly, the sway ratio results (Figure 4) for fatigued and unfatigued drivers conducting the simulation during rainy day time conditions were higher than those for the same drivers conducting the simulation during clear day time conditions with the impact of rainy conditions being more pronounced on fatigued drivers. This observation indicates that driving under rainy conditions may influence drivers' ability to control the VR-based truck (i.e., swaying more). As a results, this observation may suggest that the existing rainy conditions utilized in the VR-based simulator are sufficient to evaluate the impact of rain on drivers' fatigue. Similar observations can be made by comparing clear night time conditions and rainy night time conditions (Figure 4).

In addition, the results in Figure 4 show that the sway ratios for fatigued and unfatigued drivers conducting the simulation under foggy day time conditions were relatively similar to those obtained for drivers conducting the simulation under clear day time conditions. This observation indicates that applying a foggy condition did not have an impact on the sway ratio results for both fatigued and unfatigued. When comparing the same foggy and clear results but for night time conditions, the sway ratios for both conditions in unfatigued drivers were similar while in fatigued drivers the sway ratio under foggy night time conditions were higher than clear night time conditions. These observations generally indicate the foggy conditions did not have an impact on the sway ratio results; suggesting that additional improvements may be needed to the VR-based simulator or better fatigue measures to characterize the impact of this condition on drivers' fatigue.



(a)



(b)

Figure 4: VR-Based Sway Ratios Obtained for: (a) Unfatigued Drivers and (b) Fatigued Drivers.

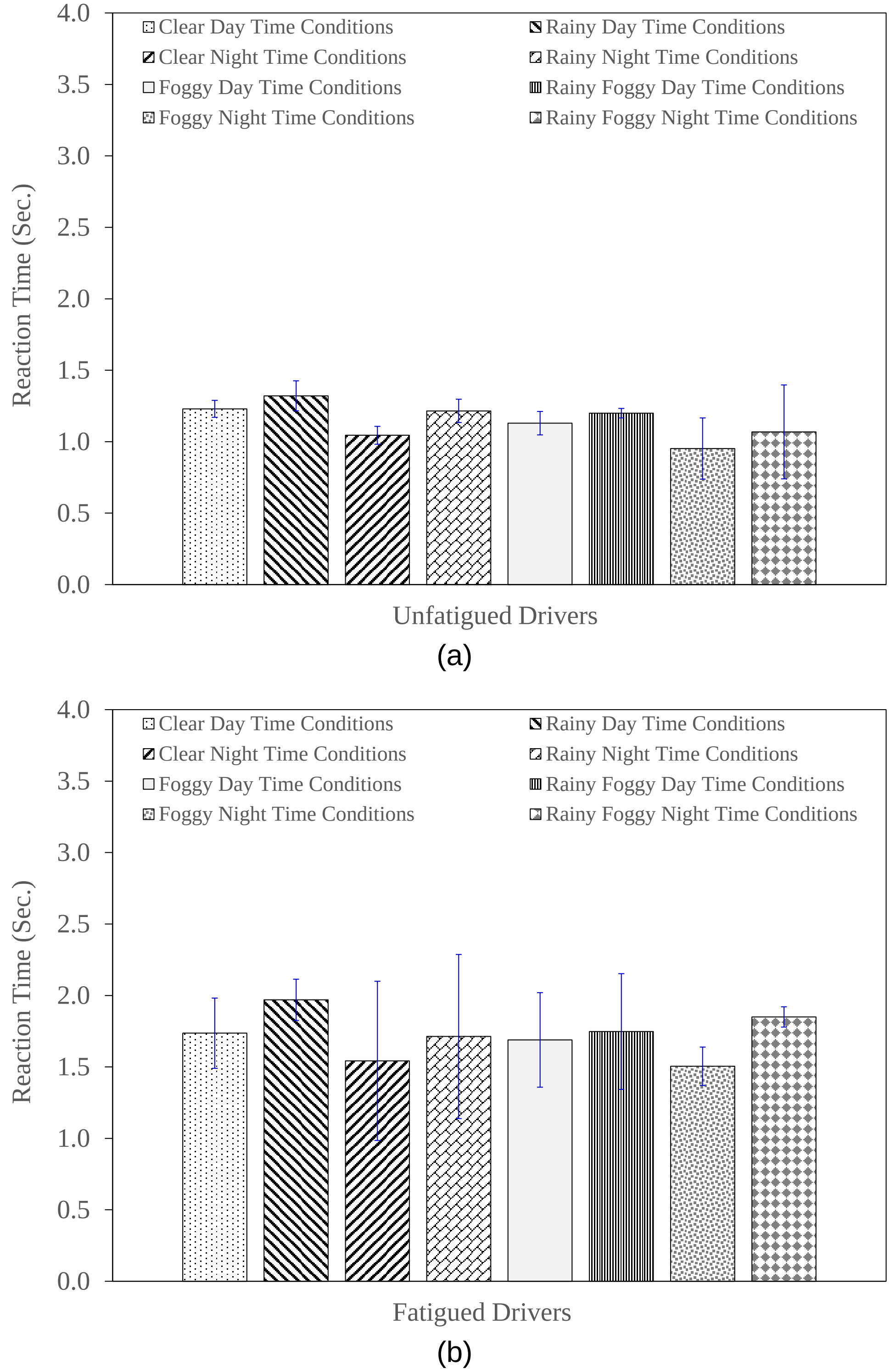


Figure 5: VR-Based Reaction Times Obtained for: (a) Unfatigued Drivers and (b) Fatigued Drivers.

Furthermore, by comparing the sway ratio results (Figure 4) for fatigued and unfatigued drivers conducting the simulation under rainy foggy conditions (i.e., either day or night) to those obtained for simulations conducted under clear condition, it can be seen that sway ratio values for foggy rainy conditions are higher than those for clear conditions. This indicates that when both conditions are applied to the simulation the drivers were swaying more than when these conditions were not applied.

In a similar fashion the results in Figure 5 can also be utilized to compare the impact of simulation weather and driving time conditions on drivers' reaction times. For instance, the reaction times for unfatigued drivers (Figure 5a) are relatively similar for all driving conditions (around 1.12 seconds). Similarly, reaction times for fatigued drivers (Figure 5b) were similar (around 1.72 seconds) for all driving conditions considered. These observations indicate that drivers' reaction times were not impacted the weather and driving time conditions. This was expected because reaction times were measured as the time needed to press a button when a circular red dot shows in front of the driver. Based on this definition, clicking a button will not be influenced by which driving condition applied in the simulation but rather it is directly influenced by the drivers' fatigue level.

STATISTICAL ANALYSIS

A multi-factor Analysis of Variance (ANOVA) was conducted to evaluate the statistical significance of the differences observed in obtained sway ratios for fatigued and unfatigued drivers. In addition, the ANOVA analysis was conducted to evaluate the significance of the impact of weather and driving conditions on sway ratios for both groups of drivers. Tables 3 presents the ANOVA results for VR-based computed sway ratios. As can be seen from Table 3, the difference between sway ratios obtained for fatigued drivers and those obtained for unfatigued drivers is significant (i.e., F-value = 16.825 and α-value = 0.009 < 0.05) at 95% confidence level. The results in Table 3 also show that the impact of rainy weather conditions was the only factor influencing the sway ratio results. All other factors (i.e., driving time, foggy weather conditions, and all two-way interactions) were found to have an insignificant impact on VR-based sway ratios.

Table 3: Statistical Analysis Results (ANOVA) for Computed Sway Ratios

Statistical Factor	F-Value	α-value
Fatigue Level (Fatigued or Unfatigued)	16.825	**0.009**
Driving Time (Day or Night)	2.233	0.195
Rainy Conditions	7.761	**0.039**
Foggy Conditions	2.326	0.188
Fatigue Lev. * Driving Time	2.001	0.216
Fatigue Lev. * Rainy Conditions	0.545	0.494
Fatigue Lev. * Foggy Conditions	2.053	0.211
Driving Time * Rainy Conditions	0.363	0.573
Driving Time * Foggy Conditions	2.089	0.208
Rainy Conditions * Foggy Conditions	0.572	0.483

Tables 4 presents the ANOVA results for VR-based reaction times measured for both fatigued and unfatigued drivers. ANOVA results presented in Table 4 show that the difference between reaction times for fatigued drivers are significantly different (i.e., F-Value = 254.384 and a-value = 0.000 < 0.05), with 95% confidence, than those obtained for unfatigued drivers. This confirms the observations made previously that measuring drivers' reaction times is a measure that capable of differentiating between fatigued and unfatigued drivers. The ANOVA results (Table 4) also show that driving under rainy conditions had a significant impact on drivers' reaction times. All other factors (i.e., main factors and two-way interactions) were found to insignificantly influence reaction times. It is noted that although the ANOVA results show that reaction times may have been significantly influenced by rainy conditions, it is still believed that weather conditions did not have an influence on reaction times due to the concept used for collecting this data.

SUMMARY AND CONCLUSIONS

In this study, a fully immersive Virtual Reality (VR) based driving simulator was developed to serve as a "proof-of-concept" that VR can be utilized to assess the level of fatigue (or drowsiness) truck drivers typically experience during real-life driving conditions. This study also involved examining the impact of varying driving conditions (i.e., weather conditions and driving time (day or night)) on drivers' fatigue measure. To fulfill these goals, four drivers (two fatigued and two unfatigued) were allowed into the VR-based driving simulator at varying driving conditions including: clear day time, rainy day time, clear night time, rainy night time, foggy day time, rainy foggy day time, foggy night time, and rainy foggy night time conditions. The four drivers were classified into two groups: fatigued drivers and unfatigued drivers. Two fatigue measures (sway ratio and reaction time) were computed (or measured) using the VR-based simulator for all drivers. The collected measures were analyzed using multi-factor statistical analysis (ANOVA) procedures.

Based on the results of the conducted simulations and the subsequent statistical analyses results, the following conclusions were drawn:

- The developed VR-based driving simulator along with the introduced drivers' fatigue measures (i.e., sway ratio and reaction time) were found to be successful at distinguishing between the two groups of drivers (i.e., fatigued and unfatigued). As a result, it can be concluded that VR-based driving simulators provide a viable alternative to traditional driving simulators when developing technologies that assess drivers' drowsiness (or fatigue) levels.
- The sway ratios obtained for drivers conducting the VR-based simulations under clear day time conditions were similar to those obtained from simulations conducted under clear night time conditions. This suggests that the sway ratio was not able to distinguish between the two conditions. It is noted; however, that all drivers conducted these day and "night" simulations during regular work hours (i.e., 8 AM to 5 PM); thus, explaining why the sway ratio for both conditions was similar. Therefore, additional simulations are needed to fully ascertain these observations.

- The sway ratio fatigue measure was influenced by weather conditions (mainly rainy conditions) employed during VR-based simulations. This is the case because the sway ratios obtained for drivers (fatigued and unfatigued) driving under rainy conditions were higher than those obtained for drivers driving under clear conditions.
- Reaction times collected for the various drivers were not significantly influenced by weather conditions employed during the simulation. This is mainly attributed to the nature of how these reaction times were collected (i.e., press a button when a random circular red dot is shown on the screen).

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