ANALYSIS OF DRIVER BEHAVIOR FOR MOBILE WORK ZONES USING A DRIVING SIMULATOR

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ABSTRACT

This study is aimed at validating a driving simulator for study of driver behavior in work zones. Previous studies had indicated the lack of safe vantage points at critical locations as a challenge in validation of driving simulators. For comprehensive validation of the driving simulator, a framework is proposed which is demonstrated using a fixed-base driving simulator. Objective and subjective evaluations were conducted, and validation of the driving simulator was performed at specific locations and along the highway. Field data were collected for a partial lane closure using a global positioning system (GPS) along the work zone and supplemented with video recordings of traffic data at specific locations in the work zone. The work zone scenario was reconstructed in a driving simulator and analyzed with 46 participants. The results from the simulator were compared to the field data. Qualitative and quantitative validations were performed to evaluate the validity of the driving simulator. The qualitative evaluation results indicated that the mean speeds from the driving simulator data showed good agreement with the field video data. The quantitative evaluation established the absolute and relative validity of the driving simulator. The results of subjective evaluation of the simulator indicated realistic experience by the participants. This study has validated the driving simulator in both absolute and relative terms. This paper has described validation framework, the application of which was demonstrated by validation of a driving simulator.

1. INTRODUCTION

Work zone safety is a high priority for transportation agencies and the highway construction industry because of the growing number of work zone fatalities. Field data collection is complex and at times hazardous because it involves taking measurements under uncontrolled environmental, weather and traffic conditions. A driving simulator provides an innovative and safe way to conduct work zone studies. To demonstrate the use of driving simulators as an effective tool for research on driver behavior, a large amount of research has been carried out, including the effect of traffic-control devices (TCDs), the influence of drugs, alcohol, hypo-vigilance, and fatigue on driving performance, driver distraction, etc. (1, 2, 3, 4, 5) has been studied.

Driving simulator studies have advantages over field testing as they allow the study of driving situations that may not be replicable in field tests for a wide range of scenarios. Driving simulator studies also permit the collection of various types of data. Additionally, subjects can be tested in a laboratory under safe conditions and their reactions can be observed using multiple TCDs without exposing the researchers to unsafe road conditions.

A driving simulator, however, must be validated before it can be used as a research tool. Driving simulators can be validated at the absolute and relative behavioral levels (6). Behavioral validation can be performed by comparison of performance indices from a driving simulator experiment with indices from the real environment. The present study discusses both absolute and relative behavioral validity of a driving simulator.

A driving simulator is absolutely valid if the difference between the magnitudes of critical driver performance variables such as speed, acceleration etc., observed in the driving simulator and those in the real world is statistically insignificant. A driving simulator is relatively valid if the differences with experimental conditions are in the same direction, and have a similar magnitude (7).

Among the many studies on the behavioral validity of driving simulators, none has used field measurement devices over the driving length of the study. Most studies have focused on validity at specific locations of the highway.

The present paper describes a framework that can be used for systematic validation of driving a simulator, including the use of a global positioning system (GPS) for validation of a driving simulator to overcome the issue of availability of safe vantage points. The application of the proposed framework is demonstrated by examining a fixed-base driving simulator for a work zone study.

2. VALIDATION FRAMEWORK

The proposed driving simulator validation framework categorizes the validation process into objective and subjective evaluations. The objective evaluation is divided into qualitative and quantitative validations. It further distinguishes the
process into validation at specific locations and along the highway. Behavioral validation, including both relative and absolute validations, can be performed at the specific locations and along the highway. Subjective evaluation is performed by surveying participants to rate the simulator components and the simulated scenario.

The validity of the driving simulator in the Advanced Simulation and Virtual Reality Laboratory at the Missouri University of Science and Technology was performed qualitatively and quantitatively for a work zone based on comparison with field data. The field data were collected using a GPS at sub-second time intervals along the highway and by video cameras at specific locations. First, the qualitative validation is proposed for comparison of driver behavior in the driving simulator with driver behavior in the real world. This validation was carried out to determine if the results should be further validated quantitatively or any improvements should be made to the simulator. The quantitative validation was performed by statistically comparing the driving simulator data with the data collected at specific locations along the highway and along the highway. Data at specific locations can be collected using fixed video cameras for traffic flow characteristics such as traffic volume, headways, vehicle speeds, etc. Data along the highway can be collected using GPS or aerial photography such as with a helicopter, a balloon or a tall building. Various examples of data collection using these techniques can be found in the literature (8). In the quantitative validation, both absolute and relative validations can be performed. Subjectively evaluation can also be performed to capture participants’ experience in the driving simulator. The subjective validation can provide a basis to determine if the simulator components and the driving experience through the scenario were realistic.

The use of GPS as described in this study to evaluate the validity of the simulator along the highway serves two purposes. First, it can be used to collect data at locations where continuous data cannot be collected using other devices. Second, it can be used to collect detailed data along the highway at short time intervals. A GPS is capable of collecting accurate data such as location (latitude, longitude, and elevation), speed, and distance traveled for driver behavior related studies.

3. METHODOLOGY

This section describes the field data collection process, details of the driving simulator study, and discusses analysis of the data to validate the driving simulator.

3.1. Field Data Collection

Work zone data were collected on I-44 West Bound near Doolittle, Missouri, between Exits 184 and 179. The mile markers indicated the highway location, which decreased towards Exit 179. I-44 near Doolittle is a rural four-lane divided highway with a wide median. The work zone was about 2 miles long, from mile marker 181.6 (start of temporary signs) to 179.4 (end of work area). The left lane was closed and the lane closure was one-mile long with tubular markers on the lane marking. The advance warning area was 1.2 miles, and signs were placed on both sides of the highway. The work zone speed limit was 60 mph, 10 mph below the normal posted speed limit. The horizontal alignment was mostly on a tangent along the advance warning area and the work area. However, upstream of the advance warning area had two horizontal curve on an uphill with a climbing lane.

Placement of work zone traffic signs and the data collection points in the work zone are shown in Table 1, and Figure 1 presents the locations and work zone configuration. Video data were recorded using high definition (HD) video cameras from an outer road between 12 and 3 PM in the advance warning area, from the overpass in the work area, and work zone termination area. The traffic conditions varied from congested queued to free flow conditions during the three hours.

Vehicle speeds were obtained using vehicle recognition software from the recorded videos. The software was calibrated for each site before the data were extracted. To validate the data extraction, laser speed guns were used at each site, and the vehicle speeds were compared with the speeds obtained from the software. Laser speed guns have an estimated accuracy of ±1 mph (9). The video data was then processed to extract the speed of free flowing passenger cars. Vehicles were assumed to be free flowing when their time headway was more than 5 seconds (10).

The GPS data were collected autonomously at 10 Hertz using Omnistar HP service for accuracy, as the GPS equipped vehicle traveled repeatedly on I-44 WB. The accuracy of the data using the HP service is estimated to be 0.33 feet horizontal and 0.5 feet vertical (11). The GPS collected data at locations where the video data could not be collected (e.g., at the ‘Road Work Ahead’ sign) as it was not accessible from the outer road.

3.2. Driving Simulator Study

Missouri S&T Driving Simulator

The driving simulator is a fixed-base Ford Ranger pick-up truck equipped with different sensors to measure steering operation, speed, acceleration/deceleration, braking, etc. It is connected to three LCD projectors, and three networked computers with Ethernet connections. The computer that processes the motion of the vehicle was defined as the master and two other computers as the slaves. The projection screen has an arc angle of 54.6°, an arc width of 25 feet, and a height of 6.6 feet. The field of view is around 120°.

The resolution of the visual scene generated by the master is $1024 \times 768$ pixels, the slaves are $800 \times 1200$ pixels, and the refresh rate is 30 to 60 Hertz depending on the scene complexity. The driving simulator is also equipped with a system that replicates the sound of an engine. A more detailed description of the system structure, projection system, and the data acquisition process can be found in Wang et al. (12).

Scenario Construction

The GPS data collected were used to construct the work zone scenario, including work zone setup, placement of signs, the road geometry including the horizontal alignment, the vertical profile, the roadside elements of the work zone activity area and the advance warning section. The upstream section of the work zone consisted of a tangent to allow the drivers to reach the freeway speed and then a section of 0.4 miles reproducing the road geometry at location FW.
Table 1. Data Collection Locations using GPS, Video Camera and Driving Simulator

<table>
<thead>
<tr>
<th>Locations</th>
<th>Description</th>
<th>Mile Marker</th>
<th>GPS</th>
<th>Video</th>
<th>Driving Simulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>FW</td>
<td>upstream of work zone</td>
<td>183.4</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>RWA</td>
<td>‘Road Work Ahead’ sign</td>
<td>181.6</td>
<td>Y</td>
<td>-</td>
<td>Y</td>
</tr>
<tr>
<td>WZF</td>
<td>‘$1000 Fine’ sign</td>
<td>181.4</td>
<td>Y</td>
<td>-</td>
<td>Y</td>
</tr>
<tr>
<td>DNP</td>
<td>‘Do Not Pass’ sign</td>
<td>181.2</td>
<td>Y</td>
<td>-</td>
<td>Y</td>
</tr>
<tr>
<td>LLC1</td>
<td>‘Left Lane Closed’ sign</td>
<td>181.0</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>SL</td>
<td>work zone speed limit sign</td>
<td>180.8</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>LLC2</td>
<td>‘Left Lane Closed’ sign</td>
<td>180.6</td>
<td>Y</td>
<td>-</td>
<td>Y</td>
</tr>
<tr>
<td>TA</td>
<td>start of taper area</td>
<td>180.4</td>
<td>Y</td>
<td>-</td>
<td>Y</td>
</tr>
<tr>
<td>CA</td>
<td>construction activity area</td>
<td>180.0</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>EW</td>
<td>end of lane closure</td>
<td>179.4</td>
<td>-</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

‘Y’ indicates data collected at that location
‘-’ indicates data not collected at that location.

The section between FW and RWA in the real world was not simulated because of the sharp horizontal curves and the uphill grade as they cannot be realistically simulated with a fixed-base driving simulator. This highway section also has a climbing lane (not simulated) between MM 182.4 and 182.0 for heavy vehicles. The advance warning signs were placed at exact locations corresponding to the actual locations, photographed using a digital single-lens reflex 12 megapixels camera.

Participants

Potential participants were screened with the use of a questionnaire and were selected only if they met the following requirements: in possession of a valid US driver license, no health problems that would affect their driving, did not suffer from motion sickness, no prior experience of driving in a simulator, and no prior knowledge of the research project. The selected participants had normal or corrected-to-normal vision and did not report any form of color deficiency.

Forty-six participants, mostly Missouri S&T students and staff ranging in ages from 19 to 53 years, took part in the experiment. The mean age was 25.3 years and the standard deviation was 7.9 years. Out of the 46 participants, sixteen (35%) were females, five had been driving for more than 15 years, 23 had been driving between 5 and 15 years, and 18 had been driving between 1 and 5 years.

Experiment

All participants completed a survey before and after the driving simulator experiment. The pre-experiment questionnaire evaluated the participants on alertness and eligibility by inquiring about alcohol and drug use during the last 24 hours. Participants were first given a brief introduction to the driving simulator experiment and advised to adhere to traffic laws as they would in real work zone traffic conditions. The participants were also told that they could quit the experiment at any time in case of any discomfort. To familiarize them with the simulator, the environment, and the instructions, participants were instructed to drive through a trial environment. Each participant drove through the constructed work zone scenario after the trial run.

Post-Experiment Questionnaire

Each participant completed a post-experiment questionnaire, which evaluated the driving simulator based on the participants’ experience. The participants rated the simulator components compared to their real-world experience on a scale of 1 to 7 (13), with 1 indicating unrealistic and 7 indicating very realistic conditions. The participants were asked to rate the driving simulator’s components and the driving simulator’s environment.

3.3. Data Analysis

The qualitative and the quantitative validations, as mentioned earlier, were performed at specific locations and along the highway. The qualitative and quantitative validations were performed with the data collected using the video cameras and the GPS, and compared with data from the driving simulator. The qualitative validation was performed by graphical comparisons of the real world data with the driving simulator data, whereas the quantitative validation was performed by conducting statistical and error tests. The statistical tests also evaluated the absolute validity of the driving simulator. This
sub-section describes the statistical and the error tests carried out.

**Validation at Specific Locations**

Parametric tests such as the t-test assume that the data are normally distributed. A test of normality was, therefore, conducted to ensure the data were normally distributed. For absolute validity, the mean speeds from the driving simulator and the video data were compared using the t-test, which at each location was dependent on the equality of variance. The equality of variance was verified to ensure that the appropriate statistical test was carried out.

A normality test, which is the Shapiro-Wilk test (14), was conducted at each location in the driving simulator and in the field study to test the hypothesis that the data were normally distributed. The test was conducted at 0.05 level of significance. The test compared the sample distribution of the speeds obtained in the simulator with the video data against the normal distribution and a p-value was obtained. If the p-value for each location was less than or equal to 0.05, the hypothesis would be rejected.

The mean speeds from the video data collected at specific locations were compared using the t-test with the mean speeds of the participants in the driving simulator at the same locations. The null hypothesis (H0) was MSs - MS = 0, and the alternative hypothesis (H1) was MSs - MS ≠ 0, where MSs equals the mean speed of vehicles at a location in video recording, MS equals the mean speed of participants at a location from the driving simulator data.

The t-test assumes equal variance for the two samples compared. To validate this assumption an F-test was conducted at each location. The F-ratio is the ratio of the two variances of the participants in the driving simulator at the same locations. The critical values of F-ratios were obtained from the F-distribution with degrees of freedom (DF) defined later in this section. For a location, the null hypothesis (H0) and alternative hypothesis (H1) were:

- H0: s2 = s2, reject H0 when F-ratio > F-valuecritical (1)
- H1: s2 ≠ s2, accept H1 when F-ratio > F-valuecritical (2)

where:

- s2 = variance of sample speeds from video data at a location, and
- s2 = variance of sample speeds from the driving simulator at a location.

The confidence interval (CI) of the difference of the means was computed to determine the upper and lower limits of the difference. For the null hypothesis to be accepted, the difference of the means should fall inside the confidence interval.

Further, the percentage deviation, D, between the mean speeds from the simulator and that from the video data was calculated as:

\[ D = (MS_s - MS) / MS_s * 100 \] (3)

**Validation along the Roadway**

To compare the speed profiles from the driving simulator with those of the GPS, error tests were conducted. These tests were conducted as they do not impose any restriction or require assumptions about the data set. Most statistical tests require assumptions of normality and the data to be mutually independent. The normality test cannot be performed accurately for a small sample size as was the case with the GPS data. Hence, error tests were found to be appropriate for comparison of driving simulator data and the GPS data. The error tests were used to quantitatively measure the closeness of results from the simulator compared to the field data. One such error test is the Theil’s inequality coefficient (U) and its components which divide the errors into clearly understandable differences between the simulation results and the field data. These errors tests have been commonly used in validation of microscopic traffic simulation models, e.g. (15) and financial econometrics, e.g. (16).

The statistic called Theil’s inequality coefficient is defined as (15):

\[ U = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^{N} (MS_s - MS_v)^2}}{\sqrt{\frac{1}{N} \sum_{i=1}^{N} (MS_s)^2 + \frac{1}{N} \sum_{i=1}^{N} (MS_v)^2}} \] (4)

where MSs = mean speed for each location, and

\[ D = (MS_s - MS_v) / MS_s * 100 \] (3)

In the above equation, the simulation model is a perfect fit when U equals zero, i.e., MSs = MSv for all ‘i’. If U = 1, then the simulation model is completely different from the real system. Theil’s inequality coefficient can be decomposed into smaller errors, which provides a useful means of breaking up the total error. These smaller errors represent specific type of errors in the model. The errors were evaluated based on the following proportions (15):

- \[ U_M = \frac{(\mu_s - \mu_v)^2}{\sqrt{\frac{1}{N} \sum_{i=1}^{N} (MS_s - MS_v)^2}} \] (5)
- \[ U_S = \frac{(S_s - S_v)^2}{\sqrt{\frac{1}{N} \sum_{i=1}^{N} (MS_s - MS_v)^2}} \] (6)
- \[ U_C = \frac{2(1 - \rho)S_s S_v}{\sqrt{\frac{1}{N} \sum_{i=1}^{N} (MS_s - MS_v)^2}} \] (7)

where:

- \( \mu_s \) = average of the mean speeds at all locations from driving simulator
- \( \mu_v \) = average of the mean speeds at all locations from GPS data
- \( S_s \) = standard deviation of the mean speeds in simulator
- \( S_v \) = standard deviation of the mean speeds from GPS data
- \( \rho \) = correlation coefficient

\( \rho \) can be calculated as:

\[ \rho = \frac{1}{N} \sum_{i=1}^{N} (MS_s - \mu_s) (MS_v - \mu_v) \] (8)

The proportions \( U_M \), \( U_S \), and \( U_C \) are called the bias, the variance and the covariance proportions of \( U \), respectively. They are useful as a means of breaking down the differences in the mean speeds from the simulator and the GPS into its
characteristic sources. $U_M$ is an indication of systematic error, since it measures the extent to which the mean values of the simulated and GPS data deviate from each other. A large value of $U_M$ would mean that a systematic bias was present and the mean speeds were different from the driving simulator and the GPS. A high value of $U_S$ would mean that the GPS data varied considerably while the simulator data showed little variation, or vice versa. $U_C$ measures nonsystematic errors, i.e., it represents the remaining errors after deviations from mean speeds have been accounted. For any value of $U > 0$, the ideal profiles of speeds from the driving simulator and the GPS over the three sources of errors are $U_M = 0$, $U_S = 0$, and $U_C = 1$ (16).

For use in the error tests, the speeds observed using the GPS over the roadway from MM 181.6 to MM 180.0 were compared with those observed from the driving simulator. This comparison was carried out by calculating the mean speeds for every 500 feet for every run. The driving simulator and the GPS data consisted of speeds captured at every 0.1 seconds.

4. OBJECTIVE EVALUATION

The objective evaluation of the driving simulator was performed in terms of both qualitative and quantitative validations. The qualitative validation compared the driver behaviors from the driving simulator with those obtained from the field study. The quantitative validation involved the absolute and the relative validations by statistical comparison of the mean speeds obtained from the driving simulator with those from the video data at specific locations along the roadway.

4.1. Qualitative Validation

As quantitative validation is detailed and time consuming, this study introduces qualitative validation as a first step before more detailed testing is carried out. The qualitative validation evaluates if the quantitative validation should be carried out or improvements in the driving simulator are required. Qualitative validation requires graphical comparison of results from the results of the driving simulator and the real world. It is, therefore, proposed that GPS data be collected in the real world for comparison with the driving simulator data. GPS data also provides the capability to validate along the highway rather than mainly at specific locations. Data collected at specific locations can supplement the GPS data collected for more detailed validation.

Qualitative validation was carried out to test if the driver behavior in the simulator was similar to the real world. Figure 2 shows the comparison of speeds obtained from the video data, the GPS data and the driving simulator. It was observed that the speeds of the drivers did not depend on the elevation of the section but was influenced by the advance warning signs, the taper area and the construction area of the work zone.

It was found that the driver behavior was similar at specific locations along the roadway in the real world captured by the video recording and in the driving simulator. In both cases, the speeds of the drivers decreased from the location at the left lane closed sign (LLC1) to the location at the end of the work zone (GW). Thus, further evaluation was carried out to validate the driving simulator quantitatively with the video data.

Additionally, the driver behavior was qualitatively validated along the entire roadway in the simulator and in the real world by comparing the simulator data and the GPS data. The comparison of the speed profiles from the GPS study and the driving simulator study seems to point to the reliability in the results from the simulator. Out of the 18 sections along the roadway shown in Figure 2, the driver behavior in the simulator and that from the GPS seems to be similar at 17 sections. The speeds of the drivers decreased from the RWA to the DNP in both the GPS and the driving simulator data. In both cases, the mean speeds of the drivers increased from the DNP to the LLC1. As the drivers approached the LLC2, the mean speed measured by the GPS and driving simulator decreased. Five hundred feet after the speed limit sign (SL) the driver behavior in the simulator was different from that in the real world because there was significant speed reduction in the driving simulator. This reduction in speed can be attributed to the slowing down of drivers to reduce their speed after noticing the reduced speed limit sign. Additionally, the lack of motion base in driving simulator lowers the perception of the speed to which the drivers were trying to reduce.

The drivers increased their speed from LLC2 till they noticed the construction zone (1000 feet before the CA) and then decreased as they approached the CA. Thus, good correspondence was noted between the driver behavior in the simulator data and the field data (GPS) which indicated the relative validity of the driving simulator. Thus, further evaluation was carried out to statistically test the absolute and relative validities of the driving simulator.

4.1. Quantitative Validation

The qualitative validation indicated a good correspondence in the driver behavior in the real world and in the driving simulator at specific locations and also along the entire roadway. Thus, quantitative validation was carried out to evaluate the absolute and relative validities of the driving simulator.

At Specific Locations

The mean speeds from the video recording were compared with those from the driving simulator at the following locations: i) upstream of the work zone (FW), ii) left lane closed sign (LLC1), iii) ‘60 mph’ speed limit sign (SL), iv) inside the construction zone (CA), and the end of the work zone (EW). Table 2 shows the means and the standard deviations of speeds from the video data (MS) and those from
the simulator (MS<sub>S</sub>) at the five locations. The comparison of the mean speeds from the field data with those from the simulator demonstrates the relative validity of the simulation. The difference between the mean speeds (MS<sub>S</sub> – MS<sub>R</sub>) ranged from -1.5 mph (at the speed limit sign SL) to 1.8 mph (at the freeway location FW). For the locations SL and the CA, the mean speeds were 1.5 mph and 0.9 mph lower for the simulator compared to the field study.

On the freeway upstream of the work zone (FW), the percentage deviation equalled 2.6% which indicated that the drivers drove at higher speeds in the simulator. This value shows that the speeds recorded in the simulator were higher for the less demanding location, perhaps due to lower risk of crashes in the simulator than in the real world. This finding was consistent with those of the study conducted to validate the use of a driving simulator for a two-lane rural road (17). At the location of the speed limit sign, the deviation was -2.4%, indicating that the speeds recorded in the simulator were lower for the locations where the drivers had to make relatively complex maneuvers. This finding was consistent with the validation of a driving simulator for a crossover work zone (10). Bella also found that the speeds were lower in the simulator than in the real world at the speed limit sign in the advance warning area. Thus, the speeds were higher in the simulator when the drivers accelerate on the freeway whereas they were lower when the drivers decelerate in the work zone.

From Table 2, the standard deviation was found to be higher in the real world than in the driving simulator at FW, EW, and the LLC1 locations. This indicated larger variations in the speeds of drivers in the real world compared to the driving simulator when they were not reducing their speeds. It must be kept in mind that driving in the simulator is not affected by other vehicles. The standard deviation at the location CA was higher in the driving simulator compared to the real world. This indicated lowest variation in speeds from the field data as very limited data were available from this location because of congested traffic flow, i.e. most vehicles were not free flowing.

A Shapiro-Wilk test was carried out on the video data and the driving simulator data collected at five locations and the results are presented in Table 2. The test revealed that the data were approximately normally distributed, i.e., the p-values were greater than 0.05 and it fitted a Gaussian distribution at the five locations in the field and also in the driving simulator.

Table 3 shows the results of F-test, t-test and power analysis for each location. The results of F-test indicate that the null hypothesis was accepted, that is, the variance of the speeds in the driving simulator and in the field was equal at the SL location. Since the variance was unequal at four locations as evidenced from Table 3, the field observations and the simulator results were compared at each location using tests that does not assume equality of variance.

The t-test indicated that the difference in the mean speeds lies within the confidence interval. Thus, the null hypothesis was accepted at a 5% level of significance at the five locations, and there was no significant difference between the mean speeds in the driving simulator and those in the real world. Therefore, the absolute validity of the driving simulator was obtained. Also, the relative validity of the driving simulator was obtained since the speeds were not statistically different and varied in the same direction in the video data and in the driving simulator data.

Thus, the results of the statistical analysis indicate that the driving simulator experiments were valid, both relatively and absolutely, at all the locations and confirm that the driving simulator yields speeds similar to those observed in the real world and the differences in the mean speeds were insignificant. The lower speeds in the simulator at the location of a complex maneuver may reflect the lack of motion cues that influence driver behavior in the real world.

**Along the Roadway**

Since qualitative validation indicated similar driver behavior in both the driving simulator and the field captured by the GPS, the quantitative validation was carried out using error tests to evaluate the absolute and relative validity of the driving simulator along the simulated roadway. The error tests were conducted for the mean speeds calculated at every 500 feet from the driving simulator and the GPS. The Theil inequality coefficient (U = 0.022) indicated that the driving simulator was perfect in predicting the driver behavior in real world.

As described previously, the Theil inequality coefficient was further decomposed into three proportions: bias, variance, and covariance. The bias proportion (U<sub>B</sub> = 0) indicated that the mean speed from the simulator was the same as the real world i.e., there was no systematic errors. This indicated the absolute validity of the simulator along the entire roadway. This was also indicated by the t-tests conducted at specific locations. The variance proportion (U<sub>S</sub> = 0.13) was not significant or troubling but the dispersion in the speeds were experienced in the real world and in the driving simulator. The small sample of the GPS data might be one of the reasons for the small difference in the degree of variability. The covariance proportion (U<sub>C</sub> = 0.87) was high, demonstrating that the speeds in the driving simulator significantly co-varied with the real world. Thus, the relative validity of the driving simulator was obtained along the roadway. The small nonsystematic error indicated by the covariance proportion is less worrisome and can be reduced by decreasing the variance proportion.

Thus from the error tests, the absolute and relative validity of the driving simulator was also obtained by comparing the speeds from the driving simulator along the entire roadway with those obtained by the GPS from the real world. With the larger sample size from the GPS and improvements to the driving simulator, the variance proportion and covariance proportions are expected to approach 0 and 1, respectively.
The results show that the participants were comfortable with the driving simulator as they rated the various components and characteristics to be realistic. All of the values were much higher than the neutral value of 4. The steering wheel was rated highest among the driving simulator components. Among the various aspects of the driving scenario, road geometry was rated highest indicating that the use of GPS to construct the road scenario effectively replicates the real world.

6. CONCLUSIONS AND RECOMMENDATIONS

This paper presents the framework for objective and subjective evaluations of a driving simulator. Validation was divided into quantitative and qualitative validations, which were performed along the roadway and at specific locations where additional data were collected. The validation of the driving simulator was performed by comparing the vehicle speeds from a real work zone with those from the simulator.

The qualitative comparison indicated that the driver behavior was similar in the driving simulator and in the real world at specific locations and also along the entire roadway. Since the qualitative validation indicated good correspondence in the driver behavior, the quantitative validation was performed. The quantitative validation was carried out using statistical tests to evaluate absolute and relative validity at specific locations. For the quantitative validation at specific locations, the absolute and relative validity of the driving simulator were analyzed at five locations and t-tests were conducted. From these tests it was concluded that the field speeds and the driving simulator speeds were essentially the same. Therefore, the driving simulator was validated absolutely and relatively at these locations.

From the error tests, the bias proportion showed that the mean speed of the GPS data and that of the simulator data were the same. This indicated the absolute validity of the driving simulator along the entire roadway. The high value of covariance proportion also demonstrated the relative validity of the driving simulator. The subjective evaluation of the driving simulator showed that the participants rated the driving simulator realistic in both the simulator components (for braking, acceleration, and steering) and the driving scenarios (surrounding terrain, road geometry, and feel of driving). Road geometry was rated most realistic, indicating that the use of GPS to reconstruct the road in a simulator was effective and provided realistic experience.
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8. REFERENCES