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Transportation Research Procedia 71 (2023) 156–163

Transportation Research Procedia

www.elsevier.com/locate/procedia

XV Conference on Transport Engineering, CIT2023

Validation of a Driving Simulator for Speed Research on Two-lane Rural Roads

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Abstract

The number of driver behaviour studies based on driving simulators has grown in recent years. However, driving simulators must be validated to ensure that they are helpful for experiments and that collected data help understand driver behaviour in actual conditions. This research study aims to validate the driving simulator of the Road Laboratory of the ETSI Caminos, Canales y Puertos at the Universidad Politécnica de Madrid (Spain). The study used a two-lane rural road with a length of 13 km. Speeds were measured on the road, and its 3D model was made and adapted to the driving simulator. Thirty-four volunteers drove on the simulator. A statistical study was made between the speeds in the field and the simulator at six curves with different radii. Another statistical study was done with the calculated 15th, 50th and 85th percentiles of speed data measured. The 85th percentiles of simulator speeds were slightly higher than actual driving ones. The 50th percentiles were very close. The 15th percentiles of simulator speeds were slightly lower than actual driving ones. In addition, simulator drivers accomplished a questionnaire after driving. Most of them assessed the quality and similarity of the virtual environment compared with the actual world as medium or high. They also assessed the similarity between the simulator's driving task and the actual road as medium or high. The results of these comparative speed studies and driver surveys support the relative validation of this simulator.

Keywords: Driving simulator; Validation; Highway; Rural Road;

1. Introduction

Numerous studies have shown that simulators can be an effective tool for researching about the speed of drivers on a highway (Bella, 2008; Bella et al., 2014), the lateral position of the vehicle within the lane (Bella, 2005b; Van Der Horst & De Ridder, 2007), the visual demand to which drivers are subjected (Easa & He, 2006), the sight distance (Lioi et al., 2022), the headway choice (Risto & Martens, 2014), the handling of devices while driving (Reed & Green, 1999) and other aspects related to driver behaviour (Bassani et al., 2018, 2019).

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2352-1465
10.1016/j.trpro.2023.11.070

Some advantages of using driving simulators in research are that they allow doing tests in a safe environment that can be configured easily and cheaply, experiments can be controlled and repeated under identical conditions (Blana, 1996; Janson Olstam et al., 2008), and it is easy collecting data during trials, that were difficult to collect in actual driving (Bham et al., 2014; De Winter et al., 2012).

To use a simulator for research, it must be validated properly. The first studies on simulators spoke about fidelity, not validation. Some authors claim that it is essential that the operation of the vehicle, the visual representation and the behaviour of the objects in the environment are as realistic as possible (Allen et al., 2010; Janson Olstam et al., 2008). Other authors think that greater fidelity does not always positively affect the result. It depends on the objectives the simulation wants to achieve (De Winter et al., 2009; Tichon & Wallis, 2010; Blana, 1996). It is not easy to measure the fidelity of a simulator, although there are some attempts to do so (Kaptein et al., 1996; Roza, 2005). In any case, the fidelity of reproduction is one of the aspects that most affect the economic cost and the consumption of resources of the simulator (Tiu et al., 2020).

Research methods have limitations, and it is helpful to understand the scope of these limitations in simulators (Bittner et al., 2002). To use a simulator in research, it is necessary that the drivers' behaviour in the simulator can be extrapolated to what they would have in the same conditions during actual driving. Therefore, the simulator and the virtual scenario in which the simulation runs must model the aspects of reality necessary for the test results to be sufficiently valid (Blaauw, 1982; Blana, 1996; Helman & Reed, 2015).

Validation of simulators frequently compares magnitudes measured during actual driving (e.g. speed, position within the lane) with those measured while driving in the simulated environment. The literature speaks of two types of validation: absolute and relative validation (Blaauw, 1982; Blana, 1996; Godley et al., 2002). Absolute validation occurs when the magnitudes measured in the simulator are the same as those measured while driving a real car. Relative validation refers to the fact that, without being the same, the order of magnitude and direction of the variations observed in the measurements carried out in the simulator coincide with those of the measurements taken during actual driving. Some authors have pointed out that to use the results obtained in research, there must be a relative validation of the simulator, but absolute validity is not essential (Bella, 2008; Törnros, 1998).

Törnros et al. (2018) compared drivers' speeds when going through a tunnel in the actual and simulated sections. Using an analysis of variance, they studied the effects of certain factors on speed and lane position. They found that drivers drove faster in the simulator than in reality, but the speed level was comparable in both situations (Törnros, 1998).

Bella conducted several studies to calibrate and validate the European Interuniversity Research Center for Road Safety's driving simulator under different driving conditions (Bella, 2005a, 2005b, 2008, 2013; Bella et al., 2014). In the study carried out in 2008, he compared the speeds measured on a real road with those of its equivalent in the simulator. He measured the speeds of the vehicles at 11 points on the actual road and the speeds of 40 drivers at the same points on the simulated road. He checked the normality of the actual and simulated samples and compared the mean speeds at the checkpoints, noting higher values for the speeds in the simulator. The difference between the speed in the simulator and the speed in the field ranged from 1.06 km/h to 11.95 km/h. He concludes that "the simulator induces similar responses from the drivers to those they would perform on the real road". He considers that these results provide a relative validation of the simulator that makes it helpful in studying drivers' behaviour relative to speed on conventional roads (Bella, 2008).

Bassani et al. (2018) conducted a similar experiment to validate the fixed-base driving simulator at the Politecnico di Torino (Italy). They used thirty-three drivers in actual and simulated driving. Instead of using spot speeds at several points, they compared speeds' percentiles. To check the fidelity of the virtual scenario, participants completed several questionnaires. After a statistical analysis of the results, they concluded that the relative validation of the simulator to predict speeds on two-lane rural roads was obtained. They stated that the speed differential between actual and simulated contexts increases as the speed increases. The authors attributed this difference in speed behaviour to a difference in the risk perception between the two contexts (Bassani et al., 2018).

Llopis et al. (2016) also compared the real and simulated speeds. Results showed that, for speeds below 90 km/h, the average speed was very similar in the field and simulator. For higher simulated speeds, the average speed in the real environment was lower than the simulated one. They also asked participants to complete a questionnaire to assess the similarity between the virtual and real environments. They considered that objective and subjective validation was obtained (Llopis et al., 2016).

2. Materials and Methods

This research study aimed to validate the driving simulator of the Road Laboratory of the ETSI Caminos, Canales y Puertos at the Universidad Politécnica de Madrid (Spain). The section of the road chosen for the experiment was the route between the towns of Carabaña and Estremera in the Southeast of the Region of Madrid, with an approximate length of 13 km and composed of two sections:

- M-221 highway from kilometre 18, at the Carabaña exit, to kilometre 26, where the M-221 highway intersects with the M-222. This section's Average Annual Daily Traffic (AADT) was 1810 veh/day, with 10.88% heavy vehicles. Terrain rolling.
- M-222 highway from kilometre 14, the intersection between M-221 and M-222, to kilometre 19, at the entrance to the town of Estremera. This section's AADT was 1047 veh/day, with 14.71% heavy vehicles. Terrain level.

Table 1 shows the main characteristics of the six curves under study. Radii were between 150 and 1535 m.

Table 1 - Description of the curves studied.

Curve	Radius (m)	Terrain
C1	150	Rolling
C2	500	Rolling
C3	750	Rolling
C4	450	Level
C5	800	Level
C6	1535	Level

Speeds on the actual road were measured using a Laser speed meter. No passenger cars and vehicles not travelling in free-flow were discarded. The final result comprised 939 speed measures, more than 150 on each of the six curves.

To model the road in 3D, data from the geometry of the layout, digital elevation models and video recordings of the route were used. The software was Autodesk Infraworks for the road layout, and 3DS Max, also from Autodesk, for 3D modelling.

The simulator of the Road Laboratory of the *Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos (Universidad Politécnica de Madrid)* was used for the tests. Their main characteristics were:

- CPU Intel Core i9 - 10900 2.80 GHz - RAM 16 Gb - OS Windows 10 Pro
- Graphic card NVIDIA GeForce GT 1660
- Computer screens: 3 x 27'' - resolution 1920x1080 pixels - frame rate 60 Hz
- Steering wheel, pedals and gear lever: Thrustmaster
- Simulation software: Assetto Corsa
- Telemetry software: Motec

A total of 34 volunteers performed the driving tests in the simulator. Table 2 summarizes the distribution of the sample by age and gender. The average age was 36.6 years old. Table 3 shows data about the driving experience. Most drivers had more than ten years of driving license, and only two had less than two years of experience.

Table 2 - Characteristics of the drivers' sample.

Age				**Gender**	
21-34	**35-48**	**49-62**	**63-77**	**Male**	**Female**
58.82 %	20.59 %	17.65 %	2.94 %	66.00 %	34.00 %

Table 3 - Driving experience. Left: years of license. Right: kilometres/year.

Driving license years				km/year		
<2	2- 5	5 – 10	>10	<10000	10-20000	>20000
5.88 %	11.76 %	26.47 %	55.88 %	20.59 %	38.24 %	41.18 %

Each participant faced the 48-min experimental protocol. The protocol included: (i) Pre-drive: introduction and explanations (participants were asked to drive as they do in actual driving); (ii) driving on a training circuit to enable drivers to become familiar with the simulator; (iii) 3 minutes rest period; (iv) experimental driving on section 1; (v) 3 minutes rest period; (vi) experimental driving on section 2; (vii) Post-drive questionnaire to gather information on the experience of participants in the simulation. The data of distances travelled and instantaneous speeds were recorded with a frequency of 1 Hz for each trial.

3. Results and Discussion

3.1. Participants' Fidelity Perception

After the driving simulator test, all the participants had to answer a questionnaire about the fidelity of the simulation. Their responses served to do an initial fidelity validation of the simulator. Regarding the answers to some questions about the realism of the simulation and the similarity of the driving tasks in the simulator with those of reality, a vast majority of drivers rate the level of realism as medium or high. Regarding the answers about the participant's driving speed perception, very few drivers thought they went slower in the simulator than in reality. Table 4 summarizes the answers to some questions about the participant's perception of the level of realism.

Participants' perception of the simulator scenario fidelity shows that most qualify it as medium-quality. These are not bad results, but surely the scenario needs to be improved in future works.

Table 4 - Answers to questions about the level of realism of the simulation.

	Low	Medium	High
Level of realism of the road model and its surroundings	14.7 %	44.1 %	41.2 %
Level of realism of the road model	8.8 %	47.1 %	44.1 %
Level of realism of the surroundings of the road	3.3 %	33.3 %	36.4 %
Similarity between the driving tasks simulator/reality	14.7 %	50.0 %	35.3 %
Naturalness of driving in the simulator	20.6 %	52.9 %	26.5 %

3.2. Speed' samples statistical analysis

The description of the actual road's speed samples and the simulator's speed samples for the six curves are shown in Table 5. The speed results of two participants were discarded given that they were outliers. The Kolmogorov-Smirnov normality test was performed on these 12 samples. Since the smallest P-value among the tests performed is greater than 0.05, the idea that all samples come from a normal distribution could not be rejected, with 95% confidence level.

Table 5 - Simulator and actual road speed samples: N (number of measures), Mean, Standard Deviation, Kolmogorov-Smirnov normality test p-value.

	Simulation Speed (km/h)				Actual Road Speed (km/h)			
Curve	**N**	**Mean**	**Std. Dev.**	**KS p-val**	**N**	**Mean**	**Std. Dev.**	**KS p-val**
1	32	77.72	19.56	0.88	154	74.71	8.49	0.06
2	32	90.88	20.68	0.75	153	89.34	12.65	0.19
3	32	87.10	18.38	0.82	154	90.99	14.01	0.24
4	32	92.99	17.89	0.72	156	96.04	12.60	0.12
5	32	100.30	23.43	0.75	155	98.28	13.90	0.27
6	32	100.65	18.83	0.55	167	97.11	16.25	0.29

On each curve, the sample of the speed on the simulator was compared with the speed measured on the actual road. W-test was carried out to compare the medians of the two samples. The null hypothesis was "*median1 equal median2*"; the alternative hypothesis was "*median1 not equal to median2*". In all the comparisons, the P-value is greater than 0.05; therefore, there is no statistically significant difference between the medians at the 95% confidence level.

F-test was done to compare the Standard Deviations of the samples on each curve: *sigma1* and *sigma2*. The null hypothesis was: "*sigma1 equal sigma2*"; the alternative hypothesis was: "*sigma1 not equal to sigma2*". There is a statistically significant difference between the Standard Deviations of the samples at the 95% confidence level on curves C1 to C5. However, on curve C6, the P-value is greater than 0.05, and there is no statistically significant difference between the Standard Deviation of the two samples in that curve. These results prove that the variability of the speeds in the simulator is more significant than on the actual road, even though the sample of speeds in the simulator is smaller.

The Kolmogorov-Smirnov Test was run to compare the distributions on each curve of the two samples. In this case, on curve C1 the P-value is less than 0.05; there was a statistically significant difference between the two distributions at the 95% confidence level. However, on curves C2 to C6, the P-value is greater than 0.05, and there is no statistically significant difference between the two distributions at the 95% confidence level. Curve 1 is the one with the smallest radius. Other researchers indicated that speeds in small radius curves are usually lower in the simulator than in reality (Bassani et al., 2018; Bittner et al., 2002). This is also the case in this research, as had been seen in the median value.

3.3. Speed percentiles' samples statistical analysis

A new set of samples was generated, corresponding to 85%, 50% and 15% percentiles of the speeds on each curve. The denomination for those speeds was V85, V50 and V15. In addition, the Kolmogorov-Smirnov normality test was performed on each of these samples. The description of the samples is in Tables 6 and 7.

Figure 1 compares the percentiles of the speeds on the road and the simulator, depending on the radius of the curves. It shows that field and lab results of the V50 speed percentile were very similar. The maximum value of the difference was 3.3 km/h (3.7%), with an average of 0.8 km/h (<1%) and a standard deviation of 2.5 km/h (2.8%). V15 speeds in the simulator were lower than speeds on the road, with a maximum difference of 9.1 km/h (11.7%) and an average of 4.9 km/h (6.2%). Differences grow as the curve radius decreases. The profiles of the V85 speed show that speeds in the simulator were generally larger than speeds on the road and had a more significant dispersion; these results agree with other authors (Bassani et al., 2018; Wynne et al., 2019). Here, the maximum difference was 14.8 km/h (14.1%), with an average of 8.0 km/h (7.6%).

Comparisons were made between the means, medians and standard deviations of these samples taken two by two: *V85real* vs *V85simulator*, *V50real* vs *V50simulator*, and *V15real* vs *V15simulator*. In addition, the distributions were compared using the Kolmogorov-Smirnov test. An F-test was done to compare standard deviations, a t-test to compare the sample's means, and a Mann-Whitney W-test to compare medians. Results indicate that there was not a statistically significant difference between the two samples at the 95% confidence level. Results from the Kolmogorov-Smirnov test to compare distributions indicate that there is not a statistically significant difference between the two distributions at the 95% confidence level. The comparison between speed percentiles on the actual road and the simulator indicates no statistically significant difference. Therefore, they could be considered members of the same population.

Table 6 - Speeds V85, V50 and V15, in Km/h.

	V85		V50		V15	
Curve	**Actual Road**	**Simulator**	**Actual Road**	**Simulator**	**Actual Road**	**Simulator**
C1	84.05	98.88	74.00	76.75	65.00	59.76
C2	104.00	114.32	88.00	86.50	77.60	73.64
C3	106.05	104.10	89.00	86.50	76.00	71.04
C4	109.00	110.91	93.50	96.10	84.00	74.86
C5	114.90	126.79	97.00	97.10	83.10	77.39
C6	114.00	125.06	97.00	100.30	81.00	80.87

Table 7 – Description of percentile samples V85, V50 and V15.

	V85 Real	V85 Simulator	V50 Real	V50 Simulator	V15 Real	V15 Simulator
Count	6	6	6	6	6	6
Average	105.33	113.34	89.75	90.54	77.78	72.93
Std. Dev.	11.27	11.13	8.61	8.85	6.98	7.27
Median	107.53	112.62	91.25	91.30	79.30	74.25

4. Conclusions

Results from the experiment indicate that a relative validation of the simulator is obtained for the speed behaviour in rural roads similar to that used in this research because the comparison between the speed profiles obtained from the data recorded in the measurement sites shows a good correspondence of driver behaviour on the actual road with that in the simulator. Consequently, it can be asserted that the driving simulator of the Road Laboratory of the ETSI Caminos, Canales y Puertos at the Universidad Politécnica de Madrid (Spain) is a helpful research tool for driving speed behaviour on rural roads. The following future lines of research can be indicated:

- Continue performing simulator validation procedures under different driving circumstances than those described here.
- Improve the fidelity of the scenarios used for the simulation.

5. Acknowledgments

Grant PID2021-122471OB-I00 funded by MCIN/AEI/ 10.13039/501100011033 and by ERDF A way of making Europe.

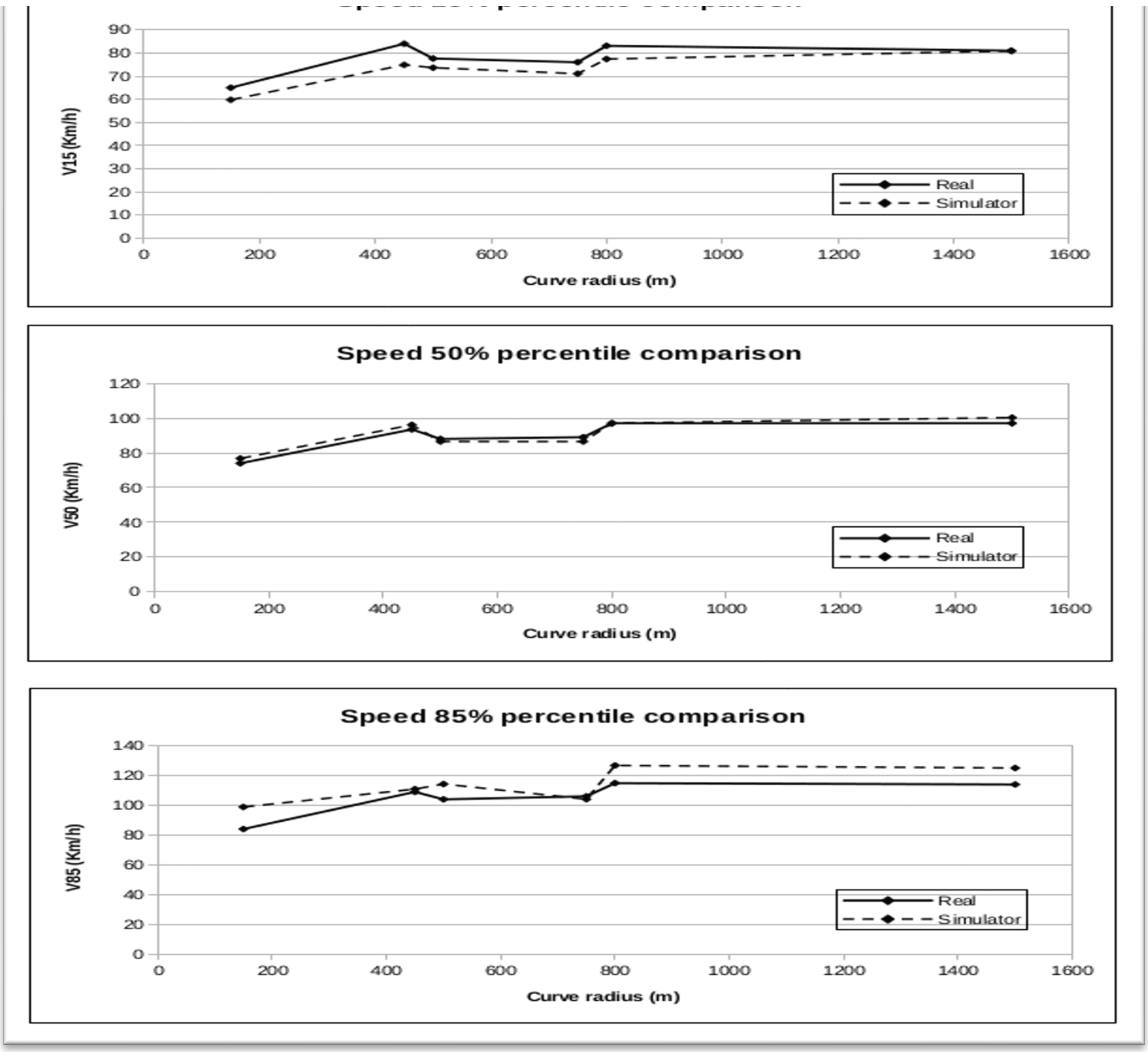

Figure 1 – Comparison of profiles of speed' percentiles V85, V50, and V15

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