DRIVING SIMULATOR FOR ROAD SAFETY DESIGN: A COMPARISON BETWEEN VIRTUAL REALITY TESTS AND IN-FIELD TESTS

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ABSTRACT: V*irtual reality simulations conducted by driving simulators represent a methodology to assess both the quality of road design and road safety in a safe, controlled, and replicable environment.*

Nowadays, there are numerous studies that use driving simulators to analyze the driver's response when specific road safety treatments are planned before these are implemented. This approach allows the road designer/scientist to estimate the potential safety effectiveness of the countermeasure/design configuration considered.

However, although virtual reality simulations are potentially extremely useful in the evaluation of road configuration design and treatments effectiveness, they also have cons. The two most important are the limitations in the reproducibility of the realworld environment and the difference in drivers' behavior due to the awareness that they are conducting a test.

In this context, our research compared the data collected during virtual reality experiments with those collected in the field with an instrumented vehicle, after a few years from the implementation of the specific safety measure on a real road. Statistical analyses were conducted to compare the results of the two experiments to demonstrate the reliability of the virtual simulations and to identify the limitations.

KEYWORDS: *driving simulator, road safety, virtual reality, road safety treatments, road safety measures effectiveness, in-field test*

1. INTRODUCTION

Making safe roads and decreasing the number of accidents, deaths and injuries on the roads is one of the greatest challenges of this century.

Nowadays technology allows scientists, engineers, and technicians to approach road safety including also human behavior. Virtual reality represents one of the instruments that allow road engineers to understand and evaluate in a safe and controlled environment how both road configuration and other contingent factors, affect human behavior.

When an unsafe road section is identified as a "black spot", e.g., through an analytical accident analysis, the Road Administration (RA) works "to change" the road configuration, improving aspects related to road traffic safety. The solution selected is then implemented on the road and only a few years after the intervention, it can be observed whether the proposed countermeasure has been effective (or not). This type of reactive approach requires investing high budgets to correct the road deficiencies and waiting years to see if the solution proposed was useful in the accident mitigation phenomenon (not always proving its effectiveness).

The use of virtual reality approach, instead, allows to investigate the described phenomenon in a proactive manner (before the accident occurrence), using a controlled, safe and ethical test environment (Calhoun and Pearlson, 2012). Virtual reality also allows to perform a safe, controlled, reproduceable and standardized experiment (de Winter et al, 2012). In fact, the researchers define the "road environment" within a scenario able to describe the main phenomena to be studied, for example, different road geometry (Bassani et al., 2019b; Bobermin at al., 2021; Montella et al., 2018), different intersection layout (Danaf et al., 2018; Kekez et al., 2022) or different cross section organization (Bella, 2013; Ben-Bassat and Shinar, 2011; Mecheri et al., 2017; Domenichini et al., 2018); or introducing events describing specific road users' interactions or limited sight distance (e.g., driver-pedestrian with occlusion, etc.) (Bassani et al., 2019a; Domenichini et al., 2018)

Unfortunately, the use of driving simulators also has cons to be considered. Limited physical, perceptual, and behavioral fidelity of the instrument (driver simulator) affect both the experimentation reliability and the driver's interest in the test, especially if the vehicle cannot reproduce the vehicle performances in an accurate way (de Winter et al, 2012; Boda et al., 2018; Pawar et al, 2022). The possibility to transfer the study results to "an actual road safety countermeasure construction" needs the results to be evaluated in terms both of fidelity and validity. The first validation processes were defined since the last century (Blaauw, 1982; Klee et al., 1999). The term

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"fidelity" has been used to describe the ability of the driving simulator to reproduce the sensory stimuli present in a real driving environment. This ability was strongly dependent on the quality of the equipment (e.g., motion system, projector, screen and display, simulacrum and sound) (Kaptein et al., 1996). Wynne et al. (2019) conducted an extensive literature review concerning driver simulator validation studies. According to the definition given in Blaauw, the word "validity" describes the ability of the study to accurately represent the drivers' behavior in a real world. The study considered two types of validity: absolute validity and relative validity (Blaauw, 1982).

The most used parameter to check the quality of the driving simulator results was drivers' speed (Cao et al., 2015; Bella 2008; Bham et al., 2014; Yan et al., 2008; Branzi et al., 2017). Often the speed was coupled with other parameters describing the drivers' performance such as acceleration/deceleration or lateral position (Blana and Golias, 2002; Chen et al., 2021; Kazemzadehazad et al., 2021) and drivers' reaction time (McGehee et al., 2000; Engen, 2008).

The literature shows that in the analysis of road safety the use of the driving simulator represents a great opportunity for road engineers and scientists to assess preliminary the impact of a specific engineering treatment. The virtual reality evaluation allows also to define the best safety solution with reference to the specific road safety objective and without any implementation cost. The objective of this research is to complete the research conducted in 2017 (Branzi et al., 2017) also investigating the ability of the LaSIS driving simulator to reproduce the drivers' behavior when different safety countermeasures were present along the road. This validation study compared the speed profiles of the driving simulations and the real world drivers, evaluating where the results are similar and which effects could instead cause differences in drivers' behavior and in virtual reality results exploitation.

2. METHODOLOGY

2.1 Research history and overview

Via Pistoiese was studied by our research group in recent years, especially concerning pedestrian safety. Statistics on accidents in Florence always placed this street in the first places in terms of danger, especially for vulnerable road users (VRUs) (Domenichini et al., 2014).

The safety problems of the street were different, and they included the high speed, the high level of interaction between traffic and VRUs due to the strong traffic demand, the geometrical configuration (a long straight about 4 km), and the high presence of commercial activities, residential areas, and parking stalls along the road.

To improve the road safety of the area, part of the street was interested by a reconfiguration project, where numerous traffic calming measures were defined and implemented with the aim of limiting the speeding phenomena, including:

- introduction of both raised pedestrian crossings and/or raised intersections to control the speed along the section;
- installation of a raised median curb to avoid overtaking maneuvers, but which can be performed only by the emergency vehicles;
- reduction of the lane width to the standard value for this type of street;
- introduction of high perception elements to improve the driver perception of the context.

A few years before the road modification, the entire reconfiguration project was studied in virtual reality. In Domenichini et al. (2018) and in Branzi et al., (2018) the good results obtained from the experimentation were extensively described.

In 2018 the safety solutions evaluated in virtual reality were implemented along via Pistoiese and nowadays are part of the road environment. In this context a new experimentation was conducted by the authors to monitor the effectiveness of the engineering treatments over time, and to understand if the results obtained by the LaSIS driving simulator are reliable.

This latter experiment was conducted in-field with a specific device named V-BOX HD2, which is similar to a black box capable of recording the kinematic parameters of the moving vehicle. The experiment can be considered as a validation experiment for the result obtained in the virtual reality evaluation comparing speed and acceleration/deceleration behavior. Figure 1 represents the research approach and the connection between the two different tests conducted, in virtual reality and in-field.

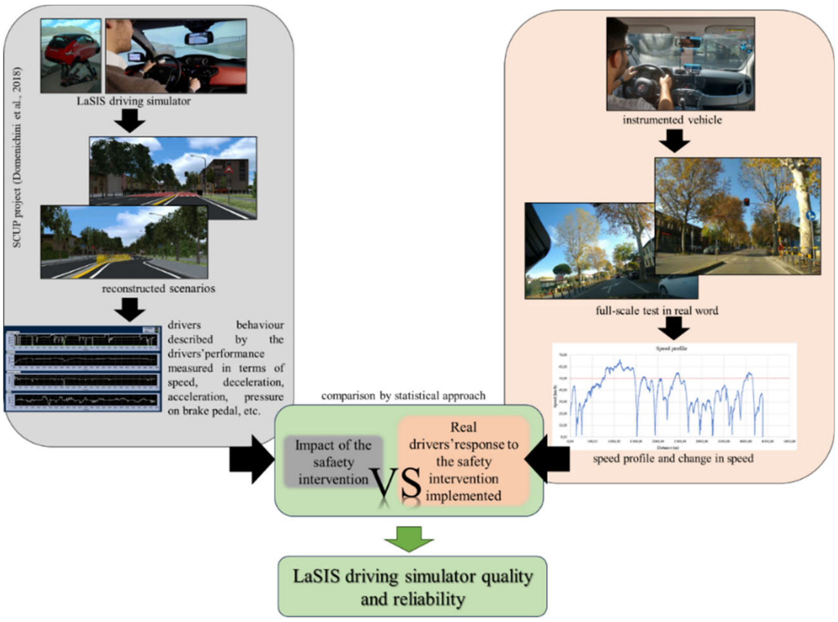

Fig. 1: Overview of the research

2.2 Detailed description of the road context

Via Pistoiese is a street located in the suburban area of Firenze, classified as an urban collector road (it serves penetration movements but also VRUs movements for commercial and residential activities). The road geometry is simple, and it is composed by one curve (R=250 m) that connects two straights which are connected to the road network with roundabout intersections. The road segment is about 4.5 km long (Figure 2).

Fig. 2: via Pistoiese (Firenze)

The cross section is about 18 m wide. On the roadside, a 2.00 m wide parking area and two sidewalks are present (1.50 m wide) on both sides. A wide cross section is dedicated for motorized traffic, and it is organized in different configurations along via Pistoiese as described below:

- different number of lanes (segments with one lane per direction and segments with one lane in one direction and two lanes in the other one);
- presence/absence of a median curb that does not allow left turn maneuvers;
- numerous and different traffic calming interventions (such as raised pedestrian crossing, raised platform in the intersection, chicanes, etc.).

In this paper, the analysis was conducted with reference to the road segment interested by the traffic calming treatments (in orange in Figure 2). In Figure 3 and in Figure 4 some comparisons between the actual street and the virtual scenario are shown.

Fig. 3: via Pistoiese: real world VS virtual reality (1/2)

Fig. 4: via Pistoiese: real world VS virtual reality (2/2)

2.3 Apparatus

Two different apparatus are used in this research, the LaSIS Driving Simulator and the V-BOX HD2.

The LaSIS Driving Simulator is a motion-based simulator, equipped with a full-scale Lancia Y simulacrum fixed on a 6 degree of freedom Stewart's platform. The platform allows roll, yaw and pitch movement of the vehicle. The vehicle interior includes all commands normally available within a car, with a steering wheel with force feedback. The three rear-view mirrors, the central one and the side mirrors, are equipped with displays that project the scenario just traveled and complete the vehicle interior. The cabin is surrounded by a cylindrical screen about 200° wide where 4 projectors reproduce the driving environment. The sounds in the environment and in the participant's car are generated by a multichannel audio system. The data acquisition frequency of the apparatus is 20 Hz. According to the classification proposed by the literature in term of the ability of the device to emulate driving in real world (i.e., vehicle controls, field of view and kinesthetic), the LaSIS driving simulator can be classified as a high-fidelity driving simulator (Goode at al., 2013; Wynne et al., 2019)..

The VBOX HD2 system used for the on-field test consists of a mobile device, like an advanced black box, able to record dynamic information concerning the vehicle movement (such as speed, GPS position, acceleration, deceleration, position in the lane, etc.). The instrument needs to be fixed inside each passenger car used in the on-field experiment. The acquisition frequency is different for GPS and video information and respectively equal to 10 Hz and 60 Hz. The VBOX application allows to read the measurements synchronized and check in a remote analysis the information related to the recorded data (e.g., available satellites, traffic conditions, etc.).

2.4 Participants and procedure

Participants were recruited on a voluntary basis among students, staff, expert drivers and common people.

In both tests, drivers had to meet the following requirements:

- possession of an Italian valid driver's license;
- normal or corrected-to-normal vision.

Two samples were recruited composed of 48 users and 36 users respectively for virtual reality and on-site test. Samples do not contain people who drove in both tests due to the different time frame in which they were conducted (2015-2016 and 2021-2022), but mostly because the selection of the same participants can affect the drivers' behavior in the second experiment due to the previous experience in virtual reality. Table 1 summarizes the participants' characteristics.

Table 1: Participant characteristics

	Virtual reality experimentation		**In-field experimentation**	
	M	F	M	F
Gender	36	12	28	8
Age	42.2 (S.D. 12.7)		40.6 (S.D. 17.12)	

NOTE: S.D. standard deviation

Their driving experience (years of driving license possession) ranged between 3 years and 46 years. Except for 5 participants, all of them declared that they travelled at least 5,000 km in a year.

Each participant was tested individually, according to the two different procedures adopted respectively for virtual and full-scale tests (Domenichini et al, 2018; Meocci et al., 2023). Table 2 summarizes the main steps of the two-procedures adopted for the experimentations.

Table 2: Procedures summary

Virtual reality test	In-field test
No payment for the involvements	
Participants were not informed about the research objective	
Test duration about 35-40 min in safe and controlled environment (LaSIS laboratory)	Test duration about 35-40 min in real-word but in a defined path. No restriction of the traffic conditions was defined during the test.
The drivers' performances were recorded by the LaSIS driving simulator	The drivers' performances were recorded by the V-BOX HD2 fixed each time inside the drivers' own car

2.5 Data collection and analysis

To test the validity of the results obtained by the LaSIS driving simulator the comparison was made analysing the speed profiles obtained in virtual reality experimentation and in full-scale test.

A preliminary comparative analysis of the entire average speed profile was conducted to analyze if the simulator results showed the same patterns (and macroscopic effects) as those measured in the real world (relative validity). The comparison was made only with reference to the profile sections where there were no conditions that influenced the drivers' speed (i.e., pedestrians who cross the street in the simulation or traffic congestion in the in-field experimentation). A qualitative comparison was also carried out with reference to the V85 speed.

The absolute validity of the simulation results was evaluated by means of a statistical test. The two datasets consist of the speed measurement along via Pistoiese in virtual reality and in-field. The two datasets were preliminary verified by the Shapiro-Wilk and Levene's tests respectively for normality and homoscedasticity assumptions. In the former test H_0 states that the variable is normally distributed, in the latter H_0 states that the variables we compared had equal variance. Both the tests were conducted with a significant level of 5%.

Subsequently two tests to compare the averages of two groups and determine if the differences between them are more likely to arise from random chance were conducted, the t-Student's test for independent sample when the sample was normally distributed and the U Mann-Whitney's test, a non-parametric test, for the other samples. Both tests were conducted with reference to the null hypothesis H0: the difference in mean is equal to 0. In all cases where the null hypothesis was rejected, also the effect size was determined by the d-Cohen metric. This allows to define the strength of the relationship between two variables compared.

Finally, according to Losa et al., (2013) a regression analysis was conducted to investigate how the driving simulator experimentation reproduces the real-world performances, considering each road segment.

3. RESULTS AND DISCUSSION

3.1 Relative validity: average speed profile comparison

Figure 5 shows the result of the preliminary comparison between the two speed profiles. Specifically, in the chart were depicted the speed profile recorded in virtual reality (in red), the average speed profile recorded the in-field test (in green), the absolute difference between the two speed profiles (in light blue), and the number of lanes in the considered direction (in black). Furthermore, the red dashed line indicates the position of the pedestrian crossing axes where an event was reproduced in the virtual reality simulation (pedestrian who is crossing the street). Finally, green dashed lines indicate the position of the stop lines within the intersection and green dotted lines indicate the position of the pedestrian crossing axes.

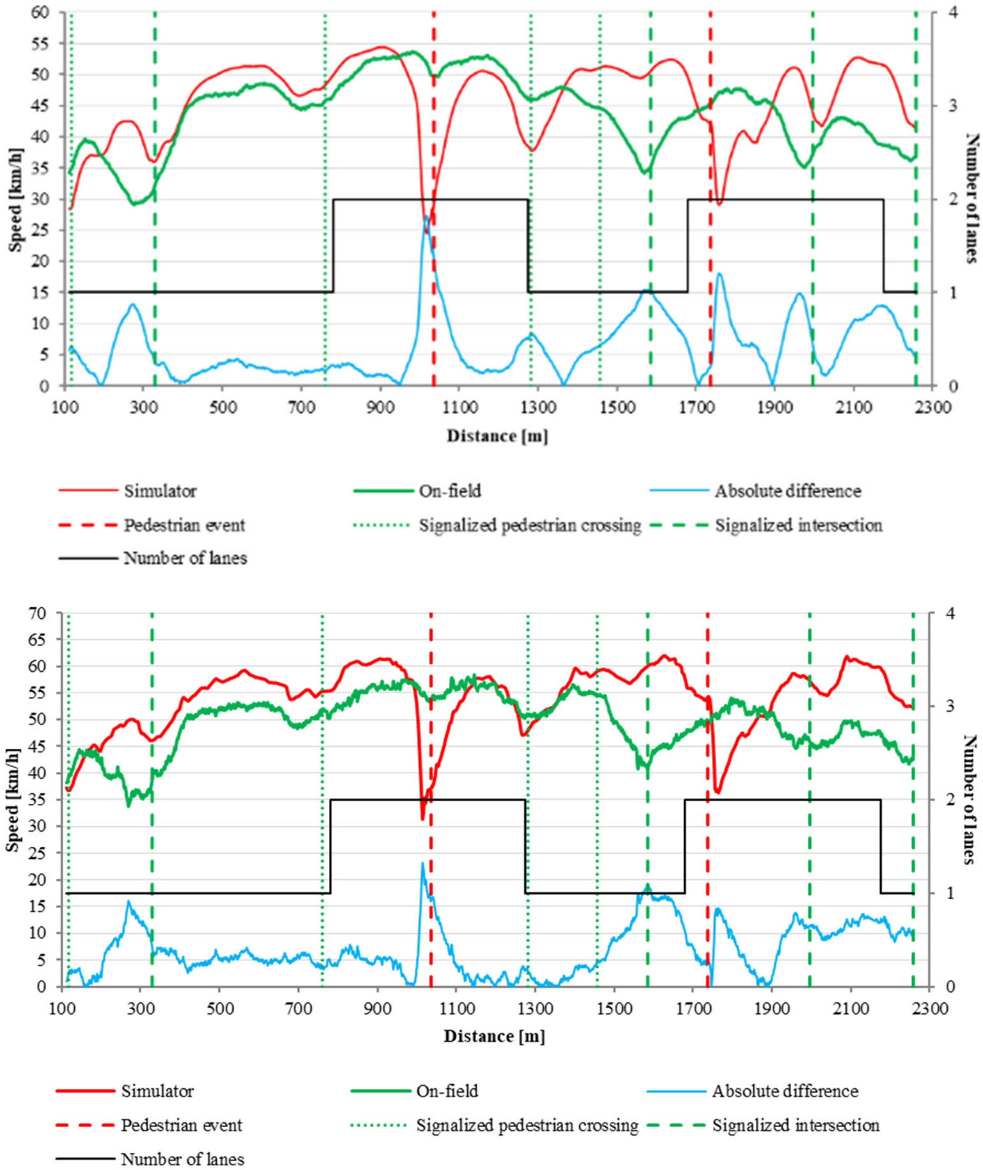

Fig. 5: speed profile comparison (above: average, below: V85)

The trend of the two profiles is similar. However, there are some areas where differences between the two profiles are noticeable. Regarding the simulator tests, the pedestrian who is crossing the street should be mentioned. This event obviously affected drivers' speed and caused significant deceleration, thus influencing the results obtained in virtual reality experimentation. This explains the negative peaks of the average profile in virtual reality (dashed red lines). On the other hand, as far as the field tests are concerned, it must be remembered that the traffic conditions were not restricted or imposed such as in virtual reality where all traffic lights were green. Therefore, drivers' speeds were sometimes reduced due to stationary traffic or otherwise significantly delayed by red lights. In this sense, the indication of the position of both the intersections and the pedestrian crossings are needed to better explain where this type of event could potentially occur. At the same time, information on the number of lanes can help to understand where traffic queues are most likely to occur. Figure 6 shows that in the areas where there were high levels of traffic or traffic queues a negative peak in the green curves was present. To overcome these issues, it seems more appropriate to compare the mean speed profiles only in similar traffic conditions (i.e., where the contingent conditions are the same for virtual reality and in-field tests), excluding therefore all the road segments where speed profiles are strongly affected by external conditions (i.e., pedestrian crossing the street in virtual reality tests (in red) and delays due to high traffic level in real world (in yellow)). Therefore, as shown in Figure 6, eleven (11) different segments were identified.

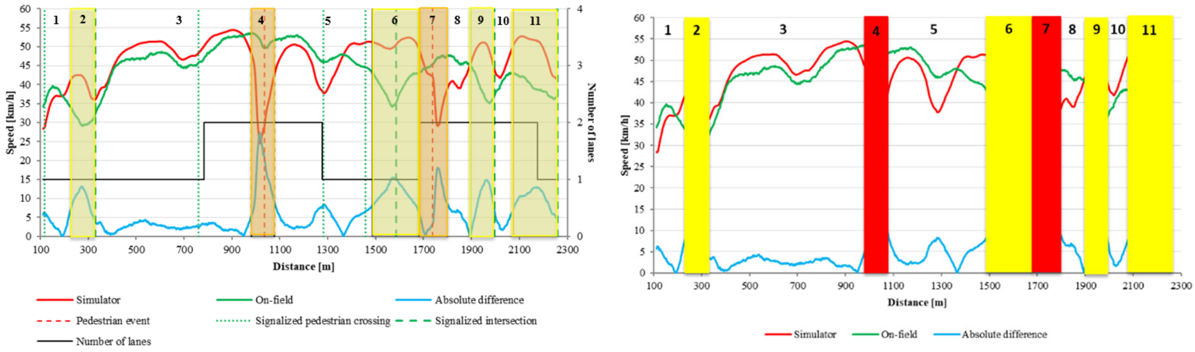

Fig. 6: identification of street segment subjected to different condition between virtual reality and real world

The 1st, 3rd, 5th, 8th, and 10th segments represent the road sections where the "contingent conditions" were the same for virtual reality and in-field tests. Thus, statistical checks of absolute validity were carried out only in these sections. The 2nd, 6th, 9th, and 11th segments represent instead the road sections where the mean speed profile for the in-field test is strongly affected by traffic conditions. These areas were highlighted in yellow. Finally, the 4th, and 7th zones describe the road sections where the mean speed profile obtained in virtual reality is strongly affected by the event where a pedestrian was crossing the street. As indicated in Domenichini et. al., (2018), the pedestrian starts crossing when the vehicle was at a stopping distance from the pedestrian crossing axes (equal about 55 meters). Therefore, the influence of the event begins 55 meters before the event takes place. The end of the influenced area was assumed equal to the one assumed in the previously mentioned study, e.g., in the point at which drivers, after braking because of the pedestrian crossing, recognize that they have regained an adequate driving speed by significantly easing the pressure on the accelerator pedal to a minimum and constant value. These areas are highlighted with a red box.

The preliminary analysis shows a relative validity of the virtual reality analysis, but obviously only where the conditions in virtual reality and in real world were the same (e.g., not strongly affected by the traffic or other events).

3.2 Absolute validity

The absolute validity was evaluated only in the road segments where the same conditions were present (1, 3, 5, 8 and 10). Therefore, segments highlighted in yellow and in red were not considered in the statistical analysis (see Figure 6). Statistical analyses were carried out considering the speed values recorded in the virtual reality and on-fields tests for a given point in the travelled path. The analysis was repeated in 50 points equally spaced out (approximately every 30 m). In Table 3 the results obtained are summarized.

Table 3: statistical test results

Distance (m)	Shapiro-Wilk's test		Levene's test	t-value	t-Student p-value	d-Cohen	U Mann Whithney p-value	Results
	Virtual reality	On-field						
112.0	**0.84**	**0.836**	<0.001	-3.941	<0.001	0.751	-	H0 rejected
141.5	0.019	**0.946**	**0.191**	-3.115	0.001	0.751	<0.001	H0 rejected
170.5	0.03	**0.635**	**0.072**	-1.47	**0.146**	-	**0.079**	H0 accepted
200.0	0.019	**0.738**	**0.112**	0.591	**0.556**	-	**0.813**	H0 accepted
229.0	0.01	**0.815**	**0.886**	4.957	<0.001	1.195	<0.001	H0 rejected
329.0	0.049	**0.303**	0.003	2.076	0.041	0.431	**0.178**	H0 accepted

358.5	**0.126**	0.006	0.004	2.032	0.046	0.398	**0.185**	H0 accepted
388.5	**0.523**	**0.101**	0.003	0.589	**0.558**	-	-	H0 accepted
418.0	0.043	**0.148**	**0.123**	0.887	**0.378**	-	**0.546**	H0 accepted
447.5	**0.130**	**0.138**	**0.211**	1.624	**0.109**	-	-	H0 accepted
477.0	**0.305**	**0.481**	**0.098**	1.981	**0.051**	-	-	H0 accepted
507.0	0.014	**0.859**	0.025	2.78	0.007	0.579	0.024	H0 rejected
536.5	0.006	**0.198**	0.042	3.154	0.002	0.656	0.01	H0 rejected
566.0	0.021	**0.158**	0.014	2.435	0.017	0.494	**0.095**	H0 accepted
596.0	0.005	**0.446**	0.007	2.237	0.028	0.439	**0.178**	H0 accepted
625.5	0.015	**0.081**	0.004	2.018	0.047	0.394	**0.224**	H0 accepted
655.0	0.008	**0.234**	0.006	1.743	**0.085**	-	**0.327**	H0 accepted
684.5	**0.331**	**0.586**	0.008	1.462	**0.148**	-	-	H0 accepted
714.5	**0.102**	**0.716**	0.044	1.638	**0.106**	-	-	H0 accepted
744.0	0.027	**0.402**	0.214	1.494	**0.139**	-	**0.301**	H0 accepted
773.5	0.003	**0.244**	0.175	1.943	**0.056**	-	**0.140**	H0 accepted
803.0	<0.001	**0.578**	0.048	2.433	0.017	0.500	**0.064**	H0 accepted
833.0	0.008	0.015	0.006	2.339	0.022	0.456	0.049	H0 rejected
862.5	**0.109**	**0.245**	0.002	1.438	0.155	-	-	H0 accepted
892.0	**0.053**	**0.434**	0.005	1.400	0.166	-	-	H0 accepted
921.5	**0.064**	**0.273**	0.006	1.109	0.271	-	-	H0 accepted
951.5	**0.073**	**0.780**	<0.001	-0.419	0.676	-	-	H0 accepted
981.0	**0.716**	**0.771**	<0.001	-3.833	<0.001	0.73	-	H0 rejected

1077.0	**0.631**	0.037	**0.06**	-8.423	<0.001	2.005	<0.001	H0 rejected
1108.5	**0.216**	0.02	**0.163**	-3.442	<0.001	0.819	0.039	H0 rejected
1140.0	**0.168**	0.004	0.048	-2.075	0.041	0.433	0.029	H0 rejected
1171.0	**0.393**	0.011	0.009	-2.075	0.041	0.422	0.042	H0 rejected
1202.5	**0.111**	**0.258**	0.015	-1.702	**0.093**	-	-	H0 accepted
1234.0	**0.805**	**0.969**	0.011	-2.563	0.012	0.519	-	H0 rejected
1265.5	**0.488**	**0.299**	<0.001	-4.871	<0.001	0.970	-	H0 rejected
1297.0	0.021	**0.878**	0.001	-4.966	<0.001	1.017	<0.001	H0 rejected
1328.5	0.0364	**0.133**	0.031	-2.99	0.004	0.619	0.007	H0 rejected
1359.5	**0.551**	**0.132**	**0.12**	-0.528	**0.599**		-	H0 accepted
1391.0	**0.363**	0.005	**0.433**	1.925	**0.058**		**0.084**	H0 accepted
1422.5	**0.722**	**0.054**	**0.371**	2.87	0.005	0.683	-	H0 rejected
1454.0	**0.299**	<0.001	**0.444**	3.369	0.001	0.802	<0.001	H0 rejected
1485.5	**0.534**	0.027	**0.280**	4.250	<0.001	1.011	<0.001	H0 rejected
1799.0	**0.058**	0.007	**0.741**	-6.624	<0.001	1.577	<0.001	H0 rejected
1831.5	**0.181**	0.007	0.004	-4.413	<0.001	0.860	<0.001	H0 rejected
1863.5	**0.232**	0.029	<0.001	-3.064	0.003	0.607	0.012	H0 rejected
1896.0	**0.118**	**0.865**	**0.319**	0.319	**0.751**	-	-	H0 accepted
1996.0	**0.060**	0.031	**0.207**	2.785	0.007	0.663	0.021	H0 rejected
2022.5	0.004	**0.244**	<0.001	1.022	**0.310**	-	**0.948**	H0 accepted
2048.5	0.021	0.004	<0.001	2.058	0.043	0.401	**0.140**	H0 accepted
2075.0	0.036	**0.410**	0.043	4.538	<0.001	0.944	<0.001	H0 rejected

Note: boldface indicates statistically significant values with 5% level of significance.

The results in terms of p-value were also depicted in Figure 7. The check describes the result each 0.5 m (for the considered road segment). In blue the segments where the H0 was accepted, that indicate the absolute validity. In grey the opposite result. Where the curve trends were similar, a relative validity can be found, but the absolute validity sometimes is not obtained. However, only the segments close to those strongly affected by traffic (in real world) or events where the pedestrian crosses the street (in virtual reality) present different curve trends and therefore, different drivers' behavior (H0 rejected).

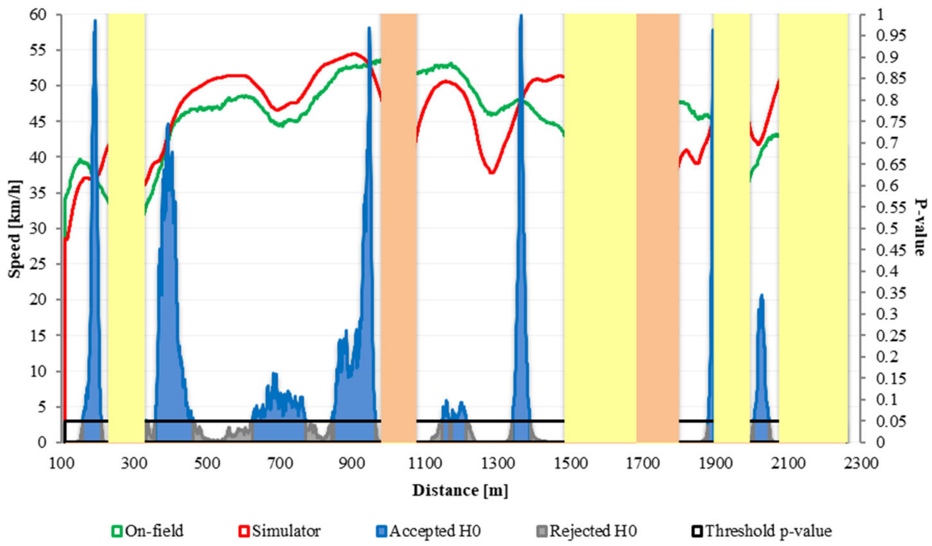

Fig. 7: results of the statistical analysis (p-value estimated each 0.5 m)

Absolute validity was also found in the road segment where a traffic calming measure is present, e.g., around a distance equal to 350 m, 700 m and 900 m where raised intersection, chicane and lane narrowing and raised pedestrian crossing are respectively present. Therefore, the virtual reality study allows to obtain a good description of the drivers' behavior, also in presence of safety countermeasures, partially confirming the finding described by Branzi et al., 2017 with reference to the street before the reconfiguration intervention (i.e., without traffic calming measures). The absolute validity was demonstrated in more than 50% of the entire road segment analyzed.

3.3 Regression analysis for validity

Finally, the regression analysis has been carried out. Figure 11 shows the regression result of the overall street. Table 4 shows instead the R^2 values obtained analyzing segment by segment, as in the previous paragraph. A good correlation among the speed values recorded during the two experimentations was highlighted in segment n.3. Lower R^2 values were instead determined in the other areas.

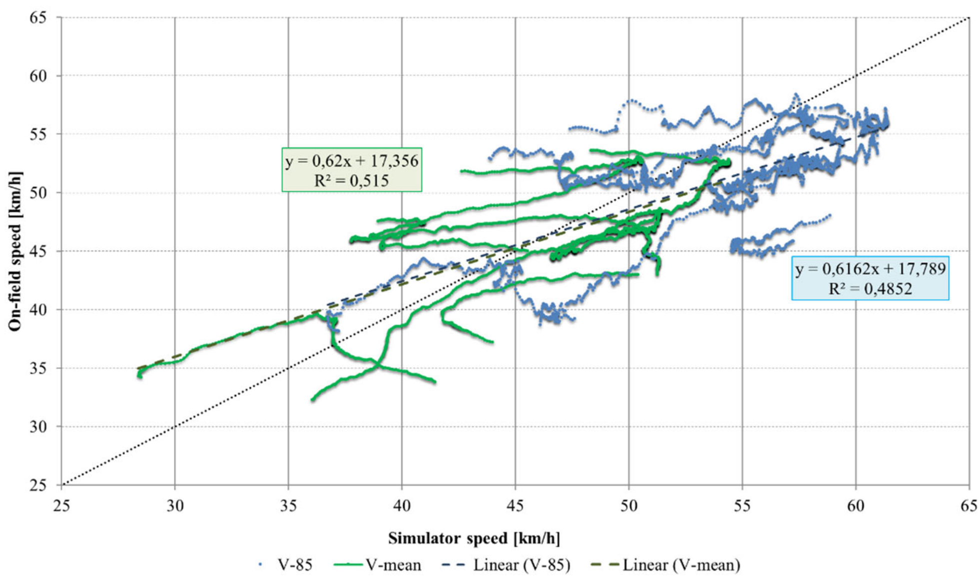

Fig. 11: regression analysis for validity (average speed and V85 speed) – overall path

Table 4: R^2 results – regression procedure for validity

Segment ID	R^2	
	Average speed	V85
1	0.0004	0.0080
3	0.8881	0.9124
5	0.0306	0.3976
8	0.1358	0.5034
10	0.6451	0.3616

The regression analysis showed very good correlation in the segments n. 3. Low values of R^2 were instead found in the other segments. The overall result showed R^2 close to 0.5 both for the average and V85 speed. The result obtained confirmed those obtained in the statistical analysis. It demonstrates also that close to the road segments interested by different "contingent conditions" the validity of the simulation can be only relative or null.

4. CONCLUSION

The analysis conducted allows to observe that drivers' behavior in virtual reality generally differs from the driver behavior in real world due, firstly, to traffic conditions and, secondly, to the different "stimuli's' perception" due to the fidelity of the driving simulator environment. The research conducted has demonstrated that events such as pedestrian crossing the street in driving simulator experimentation or real traffic conditions strongly affected the drivers' behavior. Therefore, to compare virtual reality and on-site experimentation, the same "events" and "traffic conditions" are needed.

The analysis conducted in virtual reality was evaluated both in terms of relative and absolute validity through a statistical test conducted on the entire road stretch observed and interested by different traffic calming measures. In the end also a regression analysis was made to confirm the result obtained. The two average speed profiles (obtained by virtual reality and on-field tests) presented a similar trend, maximum and minimum speed were reached in the same section if the "contingent conditions" of the experimentation were the same. In this sense, the qualitative analysis of the speed profile allows to define the relative validity of the simulation. Moreover, absolute validity was demonstrated in more than 50% of the road section analyzed. Therefore, the analysis conducted allows to demonstrate that the driving simulator study can be relevant to analyze the effectiveness of safety treatments before their implementation on real road. Moreover, this type of analysis allows the road engineering and Road Authorities to select the best engineering treatment as a function of the objective of the intervention.

It can be concluded that the LaSIS driving simulator can be considered as a valid research tool for studying the factors affecting the drivers' behavior and the effectiveness of the different traffic calming measures, confirming also the results obtained in previous research, when the same street was analyzed before the implementation of the safety intervention. The research highlights also the need to check in the "conditions evaluated" that can be quite different in virtual reality and on-field and affect the real drivers' behavior.

REFERENCES

Bassani, M., Catani, L., Salussolia, A. and Yang, C.Y.D. (2019a). A driving simulation study to examine the impact of available sight distance on driver behaviour along rural highways. Accident Analysis and Prevention, 131, 200-212. DOI: 10.1016/j.aap.2019.07.003.

Bassani, M., Hazoor, A., Catani, L. (2019b). What's around the curve? A driving simulation experiment on compensatory strategies for safe driving along horizontal curves with sight limitation. Transportation Research Part F Traffic Psychology Behavior, 6, 273-291. DOI: 10.1016/j.trf.2019.09.011.

Bella, F. (2008). Driving simulator for speed research on two-lane rural roads. Accident Analysis and Perception, 40(3), 1078-1087. DOI: 10.1016/j.aap.2007.10.015.

Bella, F. (2013). Driver Perception of roadside configurations on two-lane rural road: effects on speed and lateral placement. Accident Analysis and prevention, 50, 251-262. DOI: 10.1016/j.aap.2012.04.015.

Ben-Bassat, T. and Shinar, D. (2011). Effect of shoulder width, guardrail and roadway geometry on driver perception and behavior. Accident Analysis and Perception, 43(6), 2142-2152. DOI:10.1016/j.aap.2011.06.004.

Bham, G.H., Leu, M.C., Vallati, M. and Mathur, D.R. (2014). Driving simulator validation of driver behavior with limited safe vantage points for data collection in work zones. Transportation Research Record, 1803, 38-44. DOI: 10.1016/j.jsr.2014.02.012.

Blaauw, G.J. (1982) Driving experience and tasking demands in simulator and instrumented car: a validation study. Human Factor, 24(4), 437-486. DOI:10.1177/001872088202400408.

Blana, E. and Golias, J. (2002). Differences between vehicle lateral displacement on the road and ina fixed-based simulator. Human factors: the Journal of Human Factors and Ergonomics Society, 44(2), 303-313. DOI: 10.1518/00187200244978.

Bobermin, M.P., Silva, M.M. and Ferreira S. (2021). Driving simulators to evaluate road geometric design effects on driver behaviour: A systrematic review. Accident Analysis and Prevention, 150, 105923. DOI: 10.1016/j.aap.2020.105923.

Boda, C.N., Dozza, M., Bohman, K., Thalya, P., Larsson, A. & Lubbe, N. (2018) Modelling how drivers respond to a bicyclist crossing their path at an intersection: How do test track and driving simulator compare? Accident Analysis & Prevention, 111, 238-250. DOI: 10.1016/j.aap.2017.11.032.

Branzi, V., Domenichini, L. and Ka Torre, F. (2017). Drivers' speed behavior in real and simulated urban roads – a validation study. Transportation Research Part F Traffic Psychology, 49, 1-17. DOI: 10.1016/j.trf.2017.06.001.

Branzi, V., Meocci, M., Domenichini, L., La Torre, F. (2018). Drivers' performance in response to engineering treatments at pedestrian crossings, Advances in Transportation Studies, 2018, 1(Special Issue), pp. 55–70. DOI: 10.4399/97888255168836.

Calhoun, V.D. & Pearlson, G.D. (2012). A selective review of simulated driving studies: combining naturalistic and hybrid paradigms, analysis approaches, and future directions. NeuroImage, 59(1), 25–35. DOI: 10.1016/j.neuroimage.2011.06.037.

Changbin, C., Junhua, W. and Yangming, L. (2015). Driving simulator validation for research on driving behavior at entrance of urban underground road. In Proceedings of the 3rd international conference on transportation information and safety, Wuhan, China. 147-150. DOI: 10.1109/ICTIS.2015.7232083.

Chen, L., Xie, L., Wu, S., Guo, F., Chen, Z. and Tan, W. (2021). Validation of Vehicle Driving simulator from perspective of velocity and trajectory-based driving behavior under curve conditions. Energies, 14, 8429. DOI: 10.3390/en14248429.

Danaf, M., Hamdar, S.H., Abou-Zeid, M. and Kaysi, I. (2018). Comparative assessment of driving behavior at signalized intersections using driving simulators. Journal of Transportation Safety & Security, 10(12), 124-158. DOI: 10.1080/19439962.2016.1162892.

De Winter, J.C.F., val Leeuwen, P.M. & Happee, R. (2012). Advantages and Disadvantages of Driving Simulators: A DiscussionIn Proceedings of Measuring Behavior, Utrecht, The Netherlands, August 28-31, 2012.

Domenichini, L., La Torre, F., Tartaglia, V., Branzi, V. & Fanfani, F. (2014). Safety improvements in Urban Areas based on Human Factors principles. A case study: Via Pistoiese. In BASt - Ageing and Safe Mobility Conference 27–28 November 2014, Bergisch - Gladbach, Germany.

Engen T. (2008). Use and Validation of driving simulators. Doctoral Theses at NTNU, 2008:200.

Goode, N., Salmon, P. M., and Lenné, M.G. (2013). Simulation-based driver and vehicle crew training: Applications, efficacy and future directions, Applied Ergonomics, 44(3), 435-444. DOI: 10.1016/j.apergo.2012.10.007.

Kaptein, N.A., Theeuwes, J. and Van Der Horst, R. (1996). Driving simulator validity: some considerations.

Transportation Research Record, 1550, 30-36. DOI: 10.1177/0361198196155000.

Kazemzadehazad, S., Monajjem, S., Larue, G., and King, M.J. (2021). Driving simulator validation for speed research on curves of two-lane rural roads. In Proceedings of the Institution of Civil Engineers - Transport 2021 174:4, 248-253. DOI:10.1680/jtran.18.00033.

Kekez, D., Walton-Blane, A., Picen, T., Vinci, B., Bonner, A., Albrecht, M.A. and Black M.H. (2022). Simulator assessment of innovative designs on driver speed and trajectories. Accident Analysis and Prevention, 176, 106798. DOI: 10.1016/j.aap.2022.106798.

Klee, H., Bauer, C., Radwan, E. and AlDeek, H. (1999). Preliminary validation of driving simulation based on forward speed. Transportation Research Record, 1698, 33-39. DOI: 10.3141/1689-05.

Losa, M., Frendo, F., Cofrancesco, A., & Bartolozzi, R. (2013). A procedure for validating fixed-base driving simulators. Transport, 28(2), 420–430. DOI: 10.3846/16484142.2013.867281.

McGehee, D.V., Mazzae, E.N. and Baldwin, G.H.S. (2000). Driver reaction time in crash avoidance research: validation of a driving simulator study on a test track. In Proceedings of the Human Factor and Ergonomics Society Annual Meeting, 44(20), 3-320-3-323. DOI: 10.1177/154193120004402026.

Mecheri, S., Rosey, F. and Lobjois, R. (2017). The effects of lane width, shoulder width and road cross-sectional reallocation on drivers behavioral adaptation. Accident analysis and Prevention, 104, 65-73. DOI: 10.1016/j.aap.2017.04.019.

Meocci, M., Terrosi, A., Paliotto, A., Arrighi, R. and Petrizzo, I. (2023) Analysis of drivers' performances approaching pedestrian crossing: an in-field study for pedestrian safety improvement using real-world data and eye-tracking technology. Submitted to Accident Analysis and Prevention.

Montella, A., Galante, F., Mauriello, F. and Pernetti, M. (2018). An exploratory analysis of curve trajectories on two-lane rural highways. Transportation Research Board, Washighton D.C., 18-06797. DOI: 10.3390/su10114248.

Pawar, N.M., Velaga, N.R. & Sharmila, R.B. (2022) Exploring behavioral validity of driving simulator under time pressure driving conditions of professional drivers, Transportation Research Part F: Traffic Psychology and Behaviour, 89, 29-52. DOI: 10.1016/j.trf.2022.06.004.

Wynne, R.A., Beanland, V. & Salmon, P.M. (2019) Systematic review of driving simulator validation studies, Safety Science, 117, 138-151. DOI: 10.1016/j.ssci.2019.04.004.

Yan, X., Abdel-Aty, M., Radwan, E., Wang, X., and Chilakapati, P. (2008). Validating a driving simulator using surrogate safety measures. Accident analysis and Prevention, 40(1), 274-288. DOI: 10.1016/j.aap.2007.06.007.