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

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SUMMARY: *Virtual 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 real world environment and the difference in drivers' behavior due to the awareness that they are conducting a test. In this context, our research aims to overcome these limitations through a robust validation procedure designed to demonstrate that the results obtained in virtual reality are reliable and can be exploited to design safer roads. According to the state of the art, the statistical procedure adopted allows the comparison between data collected during virtual reality experiments with those collected in on-field experiment using an instrumented vehicle. The on-field test was conducted a few years after the implementation of the safety measures evaluated by means of a driving simulator experiment. Statistical analyses were conducted to compare the results of the two experiments to determine if the differences between them are more likely to arise from random chance or not, to demonstrate the reliability of the virtual simulations and to identify the main limitations in exploiting the results. The procedure was repeated on the road section affected by the reconfiguration intervention analyzed in virtual reality, using the same validation procedure usually adopted to validate a driving simulator before the implementation of a safety measure. The procedure demonstrates the relative validity of the virtual reality experiment and, in some road segments, also the absolute validity of the results obtained. It confirms the ability of the driving simulator to be used in the preliminary assessment of the effectiveness of the designed safety solutions.*

KEYWORDS: *Driving simulator, road safety, virtual reality, road safety treatments, road safety measures effectiveness, on-field test.*

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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. Babic et al., conducted an extensive literature review to evaluate how the road marking impacts the drivers' behavior. The research highlighted the presence of about 52 studies conducted in the past, 22 of which were conducted in virtual reality (Babic et al., 2020). Other research indicated the virtual reality as the type of experiment with the huge degree of control over the variables that (may) influence driving behavior (Farook et al, 2020). This also accounting for the economical aspects.

For example, 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). In the latter case making the expense incurred worthless and waiting for a new accident occurrence before to conduct a cost/benefit balance. This influences both interventions that little modify the road, such as the change in speed limits, and interventions that heavily change the road, such as changing the radius of a curve or the configuration of an intersection.

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).

Therefore, the virtual reality allows the researcher to evaluate one specific road-related variable per time, defining its specific effect on driver behavior and road safety especially if the single variable is considered as risky and if the on-field analysis can results in an accident (Campos et al., 2017; Farook et al., 2020). Such approach can be used not only to investigate the possible outcomes end effects of an intervention on an existing road, but can be used also to forecast possible risk in the design phase.

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.

Literature study defined the most significant current gaps of the virtual reality as an instrument to investigate driver behavior in the need to more firmly establishing criterion validity, ecological validity, and absolute validity across different configurations, applications and populations (Campos et al., 2017). Hooft van Huysduynen investigated the agreement between drivers'behaviour (actual behavior in driver simulator) and self-reported driving behaviour by questionnaire. The research investigated speeding, braking, steering, lateral positioning and maintaining distance to a preceding vehicle. Similar to other studies the correlation between the two analysed drivers'behaviour ranging near to the 50% (Hooft van Huysduynen et al., 2018). Therefore, the described research showed the importance of "transfer" the result obtained in virtual reality to the real world.

In the described context, the first validation processes were defined since the last century (Blaauw, 1982; Klee et al., 1999). Already in this research, the validation of the results was analyzed both in terms of the device ability to reproduce the sensory stimuli of the real world (e.g., engine noise, car movements etc.) and the ability of the research findings to describe the real world events. The term "fidelity" has therefore 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 world "validity" has been used to describe the ability of the study to accurately represent the drivers' behavior in the real world. The study considered two types of validity: absolute validity and relative validity (Blaauw, 1982). Validation studies are crucial in the development of each type of simulations and on the reliability of such results as also highlighted in the specific Horizon project »V4SAFETY« whose main objective is to provide a comprehensive procedure for conducting computer simulations to determine the long-term performance and impact of road safety solutions. One example is the work from Bärgman et al. (2023).

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; Hussain et al., 2019; Higueira de Frutos et al., 2023). 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; Lioi et. Al., 2023) and drivers' reaction time (McGehee et al., 2000; Engen, 2008). The listed parameters have been used for both relative and absolute validity analysis. Some research shows accordance in the results obtained by each parameter but also difference in demonstrating the absolute and relative validity and the accordance between the different parameters (Lioi et. Al., 2023). Moreover, the research conducted highlighted that the simulated speed was generally higher than the one measured on-site. Nevertheless, the same tendency of the speed profile was obtained confirming the relative validity (Goodley et al., 202; Llopis-Castelló et al., 2016). The procedures used in for validation were similar in many studies. Often, a statistical analysis was performed to demonstrate the significative (or not significative) differences between simulated and real parameters as a function of the variables considered in the validation process (e.g., t-student, ANOVA, etc.) (Bella et al., 2008; Branzi et al., 2017; Goodley et al., 2002; Higueira de Frutos et al., 2023).

The literature findings highlighted the need for the use of the driving simulator in road safety research. Virtual reality represents a great opportunity for road engineers and scientists to assess preliminary the impact of a specific engineering treatment. For example, many studies recently have been carried out on driving simulators to assess the impact of automated and connected vehicles on road safety. In fact, the potential of the tool allows us to analyze and evaluate scenarios that have not yet materialized, determining their main characteristics in advance (Ali et al., 2020; Kwon et al., 2022; Tran et al., 2021) and addressing the main issues and challenges (Deb et al., 2020; Scorpio et al., 2020; Torbaghan et al., 2022).

In road safety design 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. In simulations, the effects of different countermeasures can be compared without implementing them in the real world. The objective of this research is to complete the research conducted in 2017 (Branzi et al., 2017) investigating the ability of the LaSIS driving simulator to reproduce the drivers' behavior by comparing the results from the simulations obtained by Branzi et al., to the real-world behaviour investigated within this research. 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. While the comparison between the existing road configuration and the same road reproduced in virtual reality is essential both to validate the driving simulator and to exploit the experiments' results, few studies perform a new validation procedure of the device after the implementation of the safety countermeasures in the real world. This challenge was addressed by the research group to analyze whether the different countermeasures implemented demonstrated the effectiveness shown in virtual reality in terms of speed control. This evaluation, in this specific case, is very sensitive both to the environmental conditions and countermeasures management and maintenance, due to the perceptual nature of the safety solution implemented.The validity and the limitations of the research are discussed and the possible factors influencing the similarities and diffrences of simulated and rel behaviour are invesitgated.

2. METHODOLOGY

2.1 Reserach 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.

The countermeasures adopted are specifically evaluated to be consistent both with the drivers needs for mobility, and the VRUs needs for safety. Such cauntermeasures are specific for the urban environment (more specifically for urban collector roads). In Figure 1 the entire street was represented. In green the area interested by the reconfiguration project, in yellow the area which preserves the original configuration of the road. The numbers from 1 to 11 indicate the position of the countermeasures realized which are summarized in Table 1.

Figure 1: Street overview.

Table 1: List of the adopted countermeasures.

Number	Countermeasures description
1	Vertical deflection: sinusoidal raised and coloured pedestrian crossing
2	Horizontal deflection: chicane and narrowing
3	Vertical deflection: raised and coloured intersection
4	Horizontal deflection: chicane and narrowing
5	Vertical deflection: sinusoidal raised and coloured pedestrian crossing
6	Vertical deflection: raised and coloured intersection
7	Vertical deflection: raised and coloured intersection
8	Vertical deflection: sinusoidal raised and coloured pedestrian crossing
9	Vertical deflection: sinusoidal raised and coloured pedestrian crossing
10	Horizontal deflection: chicane and narrowing
11	Vertical deflection: raised and coloured intersection

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. Figure 2 shows some examples of the built interventions.

Figure 2: Examples of safety countermeasures.

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 described in a reliable way the real behavior.

This latter experiment was conducted on-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 3 represents the research approach and the connection between the two different tests conducted, in virtual reality and on-field.

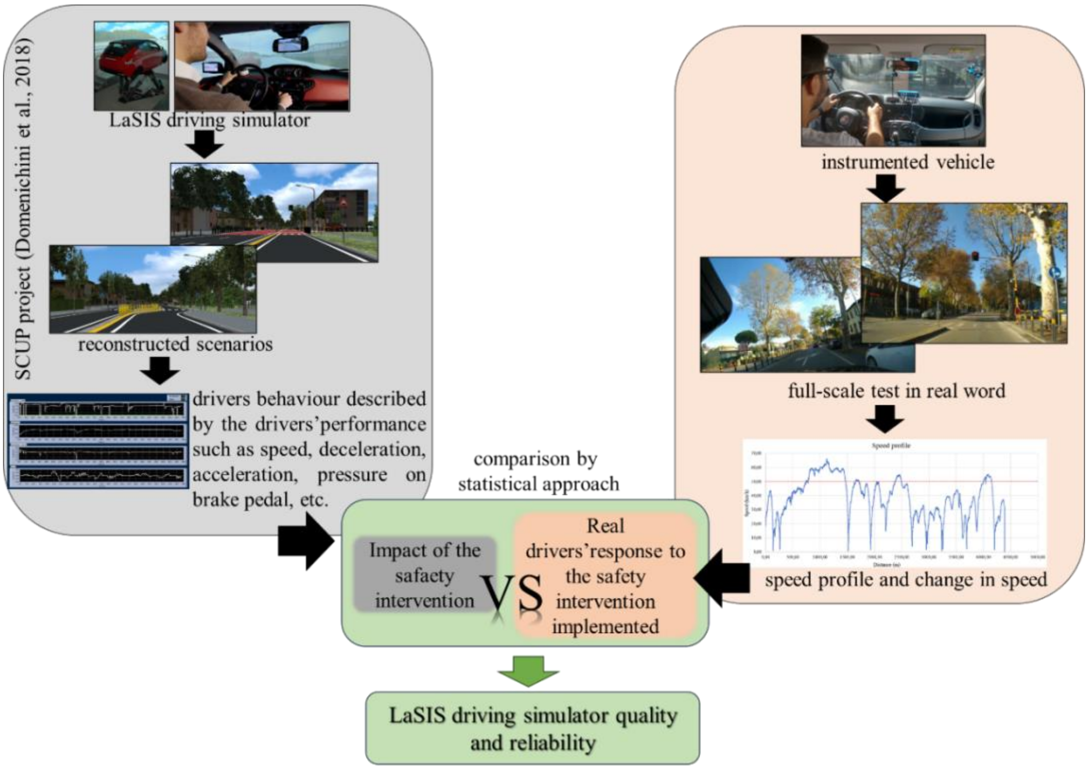

Figure 3: Overview of the research.

When the on-site experiment was conducted the reconfigured road was about 4 years old and some countermeasure appeared to be a little damaged and degraded, especially regarding the red color of the road pavement.

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 1).

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 green in Figure 1). In Figure 4, in Figure 5 and in Figure 6 some comparisons between the actual street and the virtual scenario are shown.

Figure 4: Via Pistoiese: real world VS virtual reality (1/3).

Figure 5: Via Pistoiese: real world VS virtual reality (2/3).

Figure 6: Via Pistoiese: real world VS virtual reality (3/3).

The three images show some comparisons between the road condition in the on-site experimentation and the same point in the scenario modeled for the virtual reality analysis. They allow us to observe that in the speed humps the red color of the pavement is oxidized, while for the chicane the impact of the measurement is perfectly similar in virtual reality and on-site.

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 2 summarizes the main participants' characteristics.

Table 2: Participant characteristics.

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

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 3 summarizes the main steps of the two-procedures adopted for the experimentations.

Table 3: Procedures summary.

Virtual reality test	On-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-world 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

The literature review conducted hihlighted that the average speed profile and speed variation can be considered as the most reliable parameters in driving simulator validation to describe the drivers' behaviour (Wynne et al., 2019).

To test the validity of the results obtained by the LaSIS driving simulator the comparison was made analyzing 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 on-field experimentation). A qualitative comparison was also carried out with reference to the V85 speed (the 85th percentile speed) defined as the speed that 85% of drivers do not exceed.

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 on-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 us to define the strength of the relationship between two variables compared.

A detailed analysis was repeated following the same procedure described considering three safety interventions implemented in the real world. The three locations considered were investigated considering a distance before the safety intervention ranged from 25 m and 150 m. Different analysis was referred to different effects of the traffic in the area considered. Moreover, the different distances selected to analyze the result were also referred to the entity of the intervention. The three interventions selected are located both in an area without strong traffic effect and vice-versa.The three considered countermeasures are: speed humps, lane narrowing and both.

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. According to the analysis conducted by means of the statistical tests the procedure was repeated with reference to the single intervention.

3. RESULTS AND DISCUSSION

3.1 Relative validity: average speed profile comparison

Figure 7 shows the result of the preliminary comparison between the two speed profiles. Specifically, in the chart were depicted the average speed profile recorded in virtual reality (in red), the average speed profile recorded the on-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.

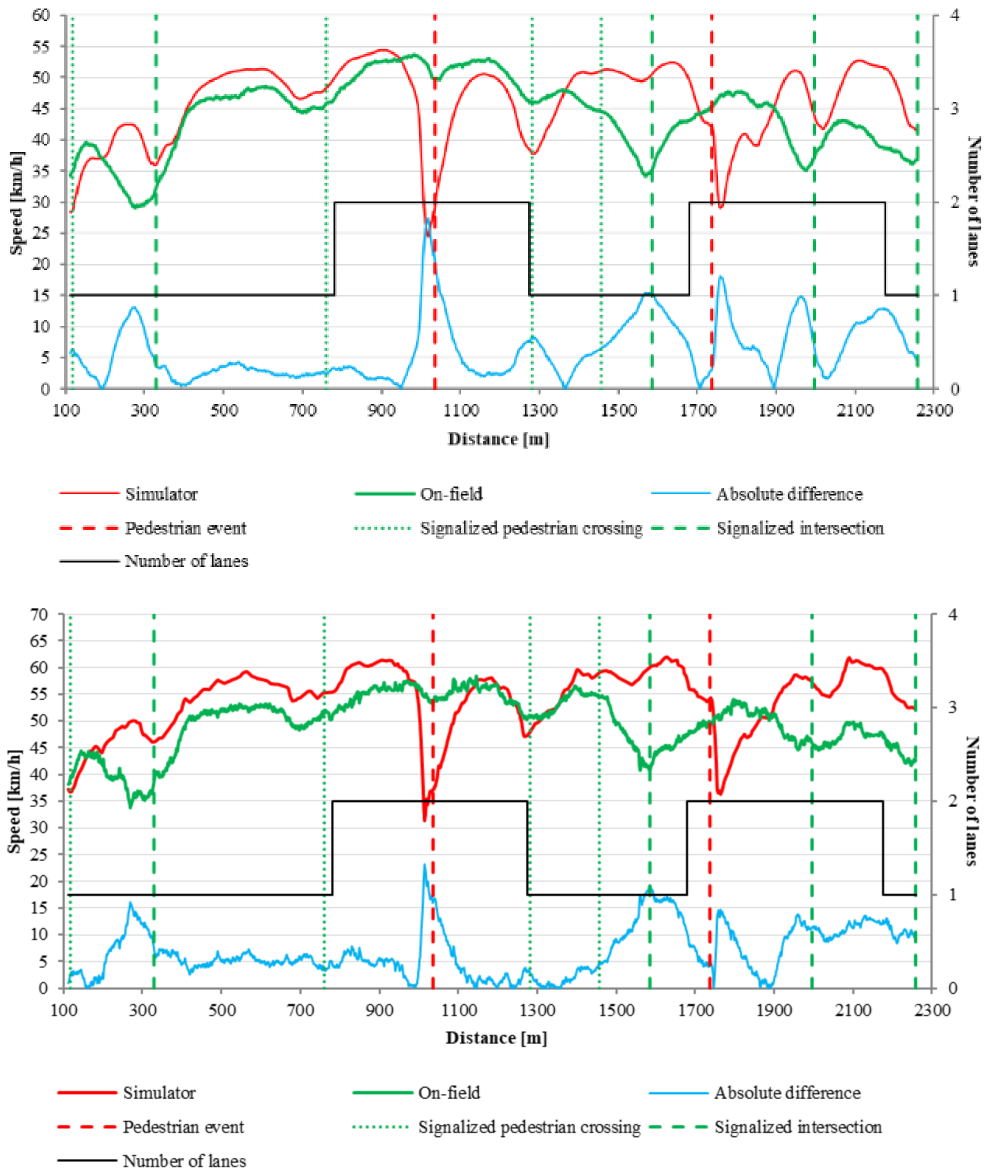

Figure 7: Speed profile comparison (above: average, below: V85).

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 on-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 8, eleven (11) different segments were identified.

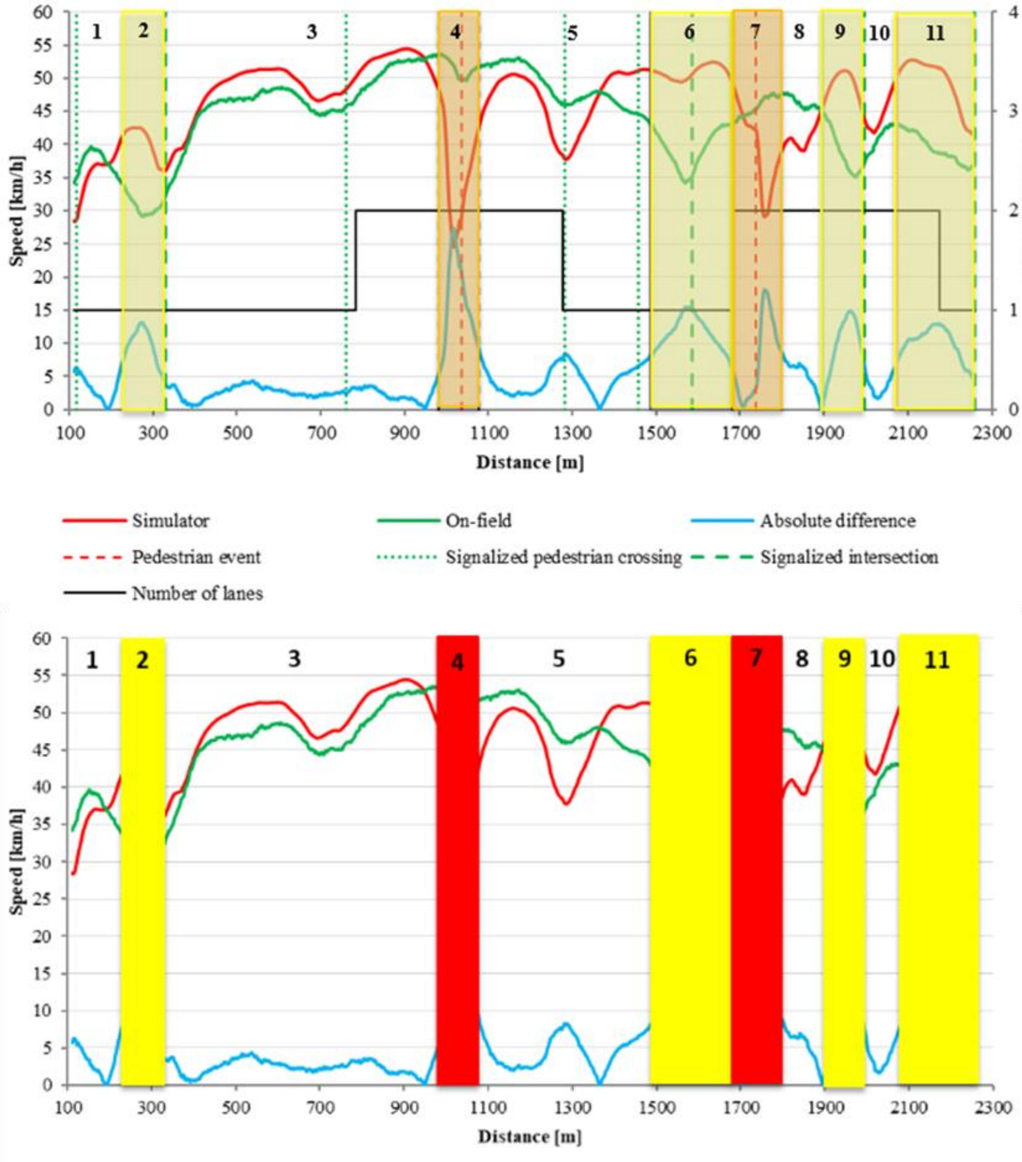

Figure 8: Identification of street segment subjected to different condition between virtual reality and real world.

The 1st, 3rd, 5th, 8th, and 10th segments represent the road sections where the "contingent conditions" were the same for virtual reality and on-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 on-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 4 the results obtained are summarized.

Table 4: Statistical test results. Part one.

Distance (m)	Shapiro-Wilk'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

The results in terms of p-value were also depicted in Figure 9. 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).

Table 4: Statistical test results. Part two.

Distance (m)	Shapiro-Wilk'test		Levene's test	t-value	t-Student p-value	d-Cohen	U-Mann Whithney p-value	Results
	Virtual reality	Virtual reality						
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.

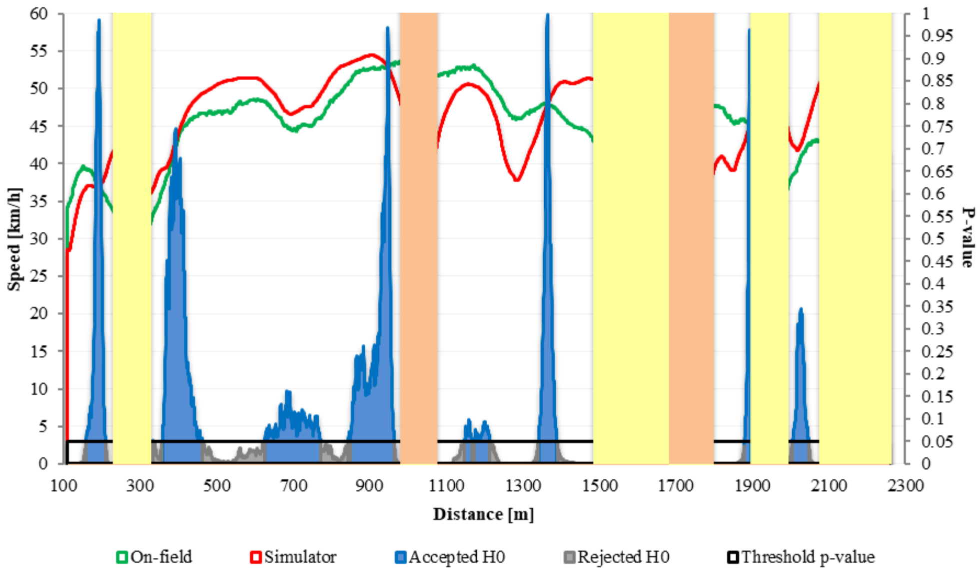

Figure 9: Results of the statistical analysis (p-value estimated each 0.5 m).

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. The results obtained are consistent with the literature, which highlighted that motion-base driving simulators, such as the LaSIS simulator, typically achieve numerical correspondence in the results obtained, especially for speed comparisons (Goodley et al., 2003; Klüver et al., 2016; Mullen et al., 2011). However, according to Törnros (1998), absolute validity is not a compulsory consideration for assessing the driving siulator usefulness as a tool for road design and safety analysis.

3.3 Detailed analysis of the intervention validity

As previously described, one of the most important issues of the on-site experiment was represented by the traffic effect. In Figure 10 all the speed profiles collected in the on-field experiment are represented. The picture allows us to observe the effect of the traffic at the different progressive. Speed reaches zero value (or very close) at different progressive when a traffic light is present as a function of the queues' length. For example, speeds equal to zero km/h were reached at the first signalized intersection in a range of 250-300 m. The same phenomenon is repeated around the progressive 2000 m, where drivers stopped in a range of 350-400 m.

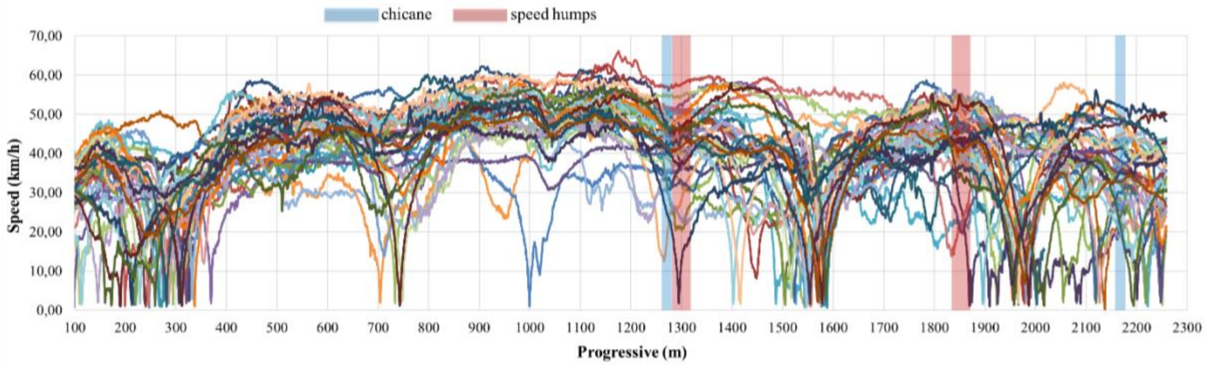

Figure 10: Traffic effect in the all speed profiles collected during the on-field experiment.

The three safety interventions analyzed in detail were depicted in Figure 10 with vertical bars describing also the length of the intervention. In light blue the narrowing from two to one lane and in light red the speed hums (or speed table). In Figure 11 the interventions were qualitatively represented (scenario view without traffic). The two pictures reported include all the three considered interventions (narrowing, speed hums and both).

Figure 11:Ssafety interventions modelled in virtual reality.

The first intervention analyzed (narrowing plus speed table) is located between progressive 1260 and 1320. It is located in a section considered not strongly affected by the traffic queue and congestion. As highlighted in Figure 10 only a couple of participants were infuenced by traffic congestion with speeds decreasong below 20 km/h. In Figure 12 both the average speed profiles (blue and light blue continuous lines) and V85 speed profiles (green and light green dotted lines) are shown.

The comparison between virtual reality and real word allows us to observe the same trend of the speed. Contrary to literature findings (Bella, 2008; Hussain et al., 2019;), the highest values of speed were reached in the real world. However, the two speed profiles both considering the average speed and the V85 speed are very similar. The effect obtained by the intervention that coupled both narrowing and speed table is stronger in the simulation, where the scenario is obviously ideal (for traffic and road maintenance). The speed reduction begins qualitatively at the same distance from the intervention. Moreover, looking at the V85 results, the profiles of virtual simulation and on-field data are almost overlapping.

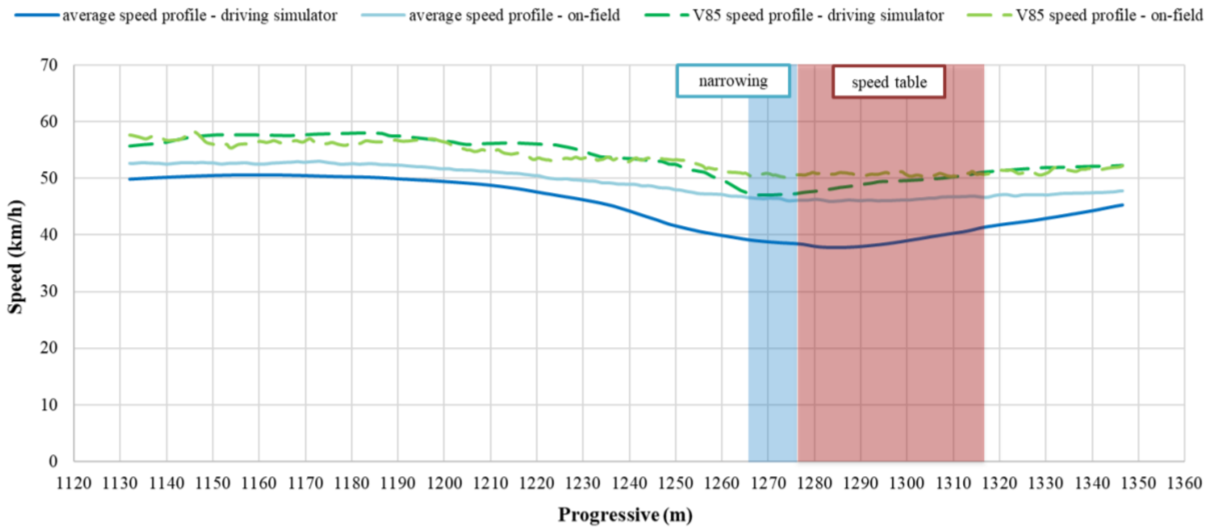

Figure 12: Narrowing + speed table in the intersection.

The statistical analysis conducted in this location showed a non-significative difference between the two speed profiles before the intervention (absolute validity). Then, the difference between speed increase and the statistical analysis defines the difference in speed significative (equal about at 10 km/h somewhere) therefore the absolute validity of the experiment was obtained partially. Because of traffic, although not very strong, the ability of virtual reality to reproduce the real phenomenon was proved confirming the literature finding concerning motion-based driving simulator (Pawar et al., 2022).

In the second intervention analyzed, consisting only in a raised pedestrian crossing (sinusoidal and colored speed humps) the speed profiles showed the same trend but a difference in speed greater than 5 km/h is present. The speed humps analyzed was located immediately after the area not considered in the statistical analysis due to the pedestrian event (the second one). This is the reason for the average speed profile of the driving simulator greater than the speed recorded on-site. The statistical analysis conducted showed a significative difference in speed, and therefore only the relative validity was proved (Figure 13). Even in the research conducted by Auberlet on perceptual interventions, only the relative validity was achieved overall (Auberlet et al., 2012). Similarly, results of the literature revew conducted by Wynne et.al., 2019 and Pawar et al., 2022 confirm the same trends.

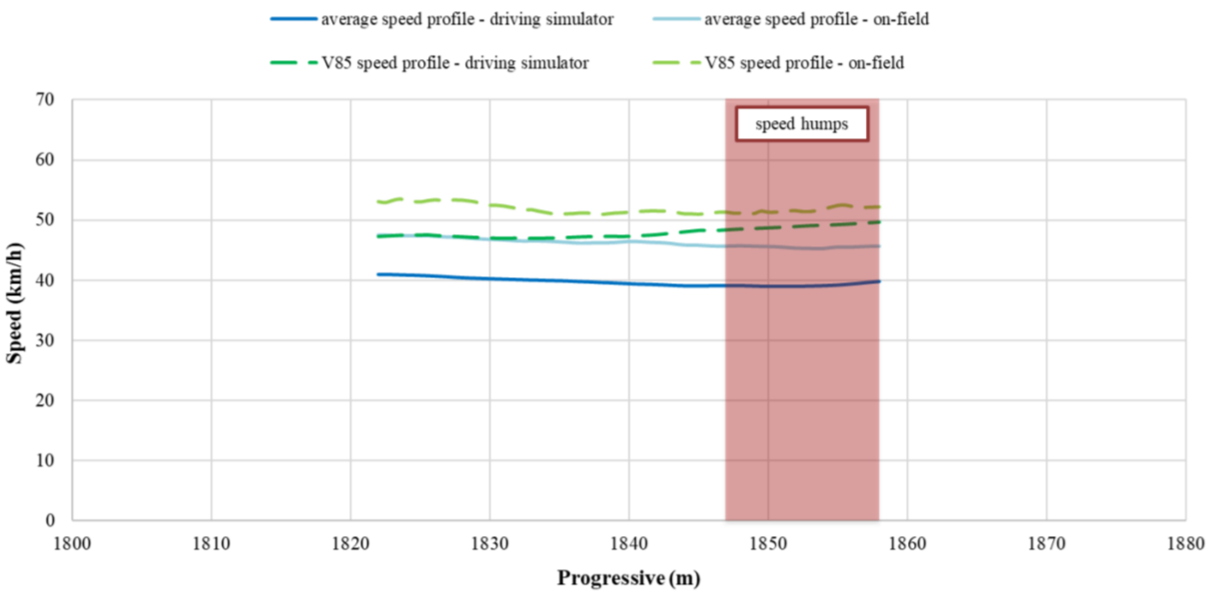

Figure 13: Speed humps.

The last intervention considered is located in the middle of the area congested. In this contingent situation, the traffic effect and the traffic light queues were very strong. The speed profiles, when a narrowing of the number of lanes was proposed, was consistent in trend between virtual reality and on-field experiment (Figure 14). Indeed, the on-site speed was generally lower (more than 10 km/h) than speed recorded in virtual reality but contrarily the decelerations were similar.

The result obtained by the statistical test confirms a significative difference between the two speed profile and only the relative validity was proved according to the reults obtained in the other test already shown.

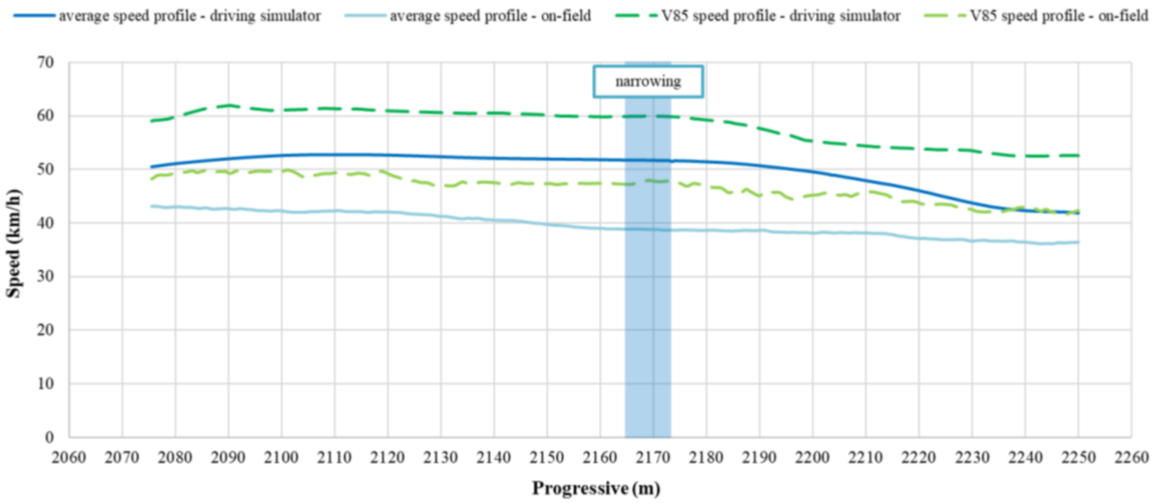

Figure 14: Narrowing.

In conclusion, the detailed analysis conducted shows a great relative validity of the driving simulator analysis where the safety solutions were analyzed. Moreover, absolute validity was demonstrated sometimes improving and demonstrating the quality of some experiments. However, as decsribes in the literature, the absolute validity cannot be considered mandatory to exploit data from the experiment (Törnros, 1998; Pawar et al., 2022).

The main variables that affected the validity are traffic and probably road condition. Indeed, the on-site experiment was conducted during a period in which the safety solutions are damaged (e.g., the pavement color oxidated) and therefore the ability of the driver to perceive the countermeasure reduced to the property of the road itself.

3.4 Regression analysis for validity

Finally, the regression analysis has been carried out. Figure 15 shows the regression result of the overall street. Table 5 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.

Table 5: 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. 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.

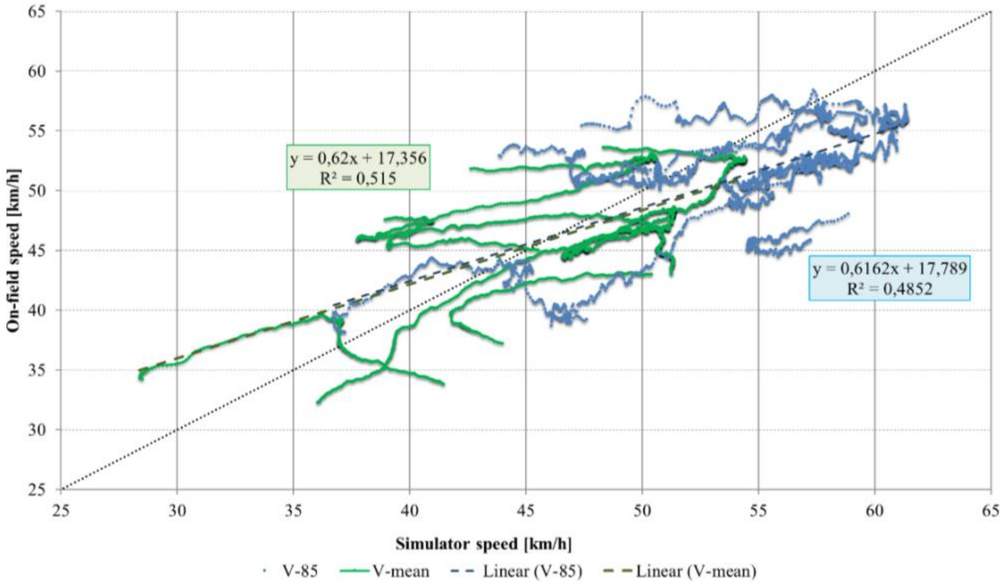

Figure 15: regression analysis for validity (average speed and V85 speed) – overall path.

In Figure 16 the result of the regression analysis conducted for the three interventions detailed are shown. In green, blue and orange respectively the result for speed table and narrowing, speed table only and narrowing only.

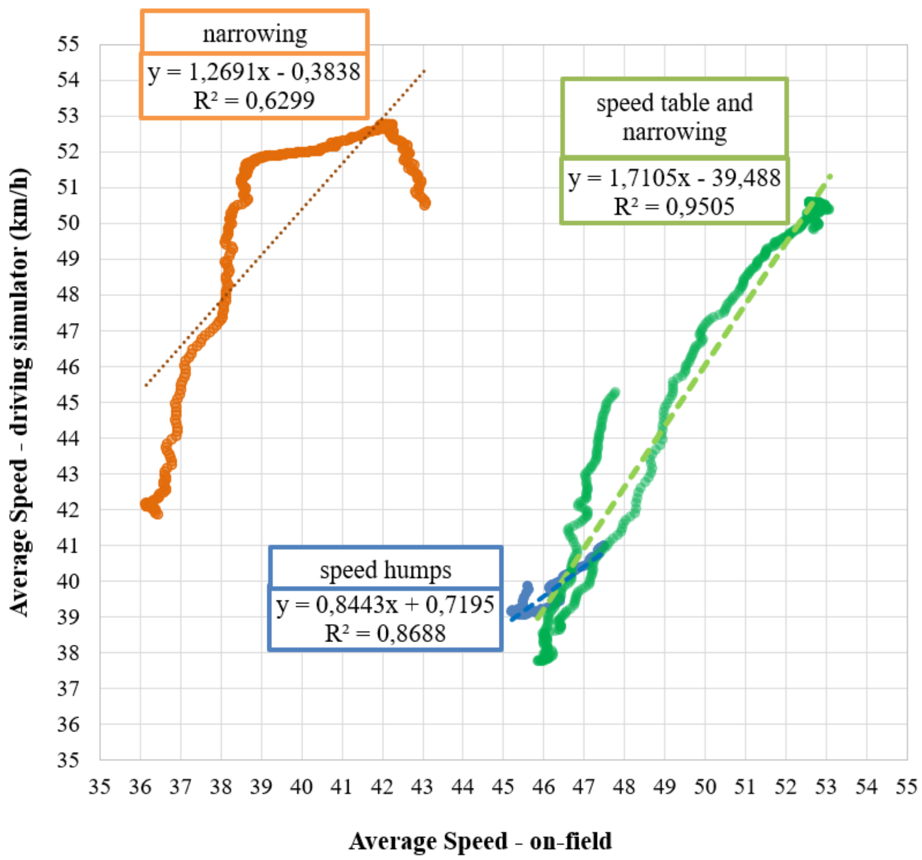

Figure 16: regression analysis on the three intervention.

The graph allows to observe a good correlation between the on-field data and the driving simulator data. The maximum value of the R^2 coefficient was reached for the intervention where the countermeasures were coupled. High values of R^2 were generally reached approaching the intervention confirming relative validity and similar speed profile. The result obtained confirmed those obtained in the statistical analysis.

4. CONCLUSION

Virtual 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. The quality and reliability of the obtained results are strongly related to the driving simulator fidelity and to the experimnet validity. The procedure to exploit the experiment results needs for the application of validation process based on statistical comparison between data recorded in real word and in virtual reality. Usually the validation procedure consists in the comparison between the average speed profiles obtained in the existing configuration of the road, whitout any safety countermeasures implemented (on-site data vs virtual reality data).

In this research, the validation of the existing road configuration was performed in 2017, before the design and implementation of the safety solution in the real road. In this paper a new comparison was described concerning a repetition of the validation procedure after the implementation of the safety countermeasures in order to confirm the effectiveness of the safety solution designed and also the ability of the LaSIS driving simulator to provide reliable results for design safe roads.

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 literature revealed that average speed and speed variation were considered as the most reliable driving behavior parameters in driving simulator validation procedure, therfore, 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. Where the countermeasures were present the consistent of the speed profile was maximum. 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 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 tool and procedure can therefore be proposed as a complementary analysis in the road design process, in order to preliminarily evaluate, if necessary, how drivers respond to road stimuli in different road configurations, with the aim of building ergonomic and safe roads.

The research findings highlights also the need to check the "conditions evaluated" that can be quite different in virtual reality and on-field experiment and affect the real drivers' behavior. Future research will focus on developing new methodologies to create more realistic scenarios aimed at resolving differences in the evaluated conditions. This includes directly importing scenarios from other digital environments, such as mobile mapping, digital twins, or BIM software.

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