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Validation of a Driving Simulator for Road Tunnel Behavioural Studies

Alessandra Lioi[a], Alberto Portera[a], Luca Tefa[a], Abrar Hazoor[a], Marco Bassani[a]*

[a] *Politecnico di Torino, Corso Duca degli Abruzzi, 24, Torino 10129, Italy*

Abstract

Introduction. According to European regulations, road tunnel safety is strategic in the management of national and international road corridors. Although the accident rate is lower in tunnels than on open roads, the severity of crashes in tunnels is higher due to the presence of hard lateral obstacles and limited space in case of lane departure. Driving simulation studies can support design decisions to assess the impact of any safety improvement albeit driving simulators must be validated to understand how the experimental results relate to real driving conditions. *Method.* This study deals with the behavioural validation of the fixed base driving simulator of the RSDS Lab for safety studies for tunnels. Field speed and lateral position data for vehicles were collected by image analysis of video sequences collected from the CCTV cameras in five sections of the Fréjus tunnel (Italy-France). The tunnel was faithfully modelled in the virtual scenario, and the same data were collected by extracting records at the same cameras' stations. Thirty-five participants were involved in a between-subject experiment. Fifteen drivers with Italian B licenses drove a car, and twenty professional drivers with Italian C and/or D licenses drove a heavy truck. *Results and Conclusions.* Normality tests for data distributions and t-tests for the comparison between real and simulated data were conducted. The simulator achieved the relative validation for truck speeds (with values observed in the simulation always lower than those observed in real driving), and absolute validation with regard to truck lateral position. Opposite outcomes were obtained for cars, with absolute validity for speed and relative validity for lateral position. The relative-absolute validation of the driving simulator enables us to establish how experimental outcomes can be generalized to understand the impact of any safety countermeasure.

Keywords: Behavioral validation; Driving simulation; Road safety; Road tunnels.

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1. Introduction

Ever since the tragic accidents in the Mont Blanc (1999) and Gottardo (2001) tunnels more than twenty years ago, there has been an increase in the focus on safety issues in road tunnels (Kirytopoulos et al., 2017). The European Directive for tunnel road safety (European Parliament and Council, 2004) establishes a minimum level of safety for road users in tunnels in the trans-European road network by preventing critical situations that may endanger human life, the environment and the tunnel installations. It applies to all operating, under construction or at the design stage road tunnels. The PIARC Technical Committee (1995) indicates that tunnels are safer (i.e. lower accident frequency) than open roads. However, small curve radii, high longitudinal gradients and bidirectionality are all factors that can lead to more severe accidents than on open roads. Drivers consider a tunnel as an unusual driving environment that might even cause stress (PIARC, 2008). Although the accident rate is lower in tunnels than on open roads, the severity of crashes in tunnels is higher (Caliendo and De Guglielmo, 2012) due to the presence of hard lateral obstacles and limited space in case of lane departure. In particular, Ma et al. (2016) demonstrated that the longer the tunnel, the higher the severity of collisions. The situation becomes even more critical when heavy duty vehicles are considered, because of their gauge and the extent of the damage they can cause.

Driving simulation studies can support design decisions to assess the impact of any improvement on safety. The purpose of a driving simulator is to reproduce a virtual environment that is representative of the real world, safe for users and enables researchers to collect reliable data (Taheri et al., 2017), reducing the risk that human error may generate harmful events. The virtual representation of any scenario can be controlled by acting on the characteristics of the vehicle, the traffic, the route, and the surrounding environment. Although the simulation remains an approximation of reality, it does facilitate an assessment of driver behaviour in dangerous situations that would be difficult to observe in a real-world environment. However, the not always perfect correspondence of some simulator components (e.g., pedals, steering) together with an awareness of the lack of risk may lead the driver to assume a different behaviour from that adopted in real driving.

To generalize the data collected on simulators (i.e., to transfer results to real driving conditions), validation studies must be carried out to affirm whether the data collected in the virtual environment are representative of the behaviours that can be measured through field observations. Hence, before their use, driving simulators must be validated by performing a comparison of data collected in both environments (Shechtman et al., 2009). Results collected in the real environment, which represent the absolute reference, are compared with those collected in the simulation experiment, where vehicle characteristics and environmental conditions replicate real driving conditions. A simulator can be validated by measuring and comparing multiple variables related to (i) the dynamic state of the vehicle needed to achieve a physical validation, or (ii) the driver response to achieve the behavioural validation (Blaauw, 1982). Literature indicates that the behavioural validation is more important than the physical validation (Blaauw, 1982; Gemou, 2013; Klüver et al., 2016).

Behavioural correspondence can lead to (i) absolute validity or (ii) relative validity (Blaauw, 1982). Absolute validity requires that the numerical results for mean and standard deviation obtained in the two driving environments are the same or almost the same. Since the simulator experience does not faithfully replicate the real environment, this type of validity is only rarely achieved (Mullen et al., 2011). Relative validity can be claimed when the difference in corresponding measurements between the real and simulated environment has the same trend and sign at different measurement points. To consider the simulator as a research tool, absolute validity is not essential, while relative validity is necessary (Törnros, 1998).

The aim of this study was the behavioural validation of the fixed-base driving simulator of the Road Safety and Driving Simulation laboratory (RSDS) at Politecnico di Torino (Italy) for driving in road tunnels. The simulator was validated for both car and truck driving, a requirement for a further driving simulation study to assess the impact of the installation of a new ventilation system into the Fréjus tunnel. Longitudinal and transversal drivers' behaviour in the real environment were analysed by video and compared with the behaviour of those involved in the driving simulation experiment. For this purpose, the entire Fréjus tunnel was modelled and used as a road scenario.

2. Method

2.1. Apparatus

The fixed-base driving simulation (AV Simulation, France) of the Road Safety and Driving Simulation (RSDS) Laboratory at Politecnico di Torino was employed (Figure 1a). It was used to model the tunnel, perform the driving simulations, and collect the data. The simulation software includes a module on vehicle dynamics, which enables the user to decide the type of vehicle to be simulated, by changing the calibration setting according to the selected vehicle. A small family car (Figure 1b) and a truck with a semitrailer (Figure 1c) were considered for the validation study. According to Milleville-Pennel, (2008), in fixed-base simulators the vehicle rotation in the simulated environment helps the driver to negotiate curves, understand the road scenario and slow down when the subjective perceived risk is high. The simulator is equipped with a vision system made up of three 32-inch full HD monitors with a 130° field of vision, a steering wheel that returns active force feedback to simulate the rolling motion of wheels, the pavement roughness, and any shocks absorbed. The hardware also includes a manual gearbox, three pedals (including a clutch), and an instrument panel. Vibration pads simulate vehicle vibrations on the seat and pedals. A sound system reproduces the sounds of the engine and the surrounding environment. This simulator had already been subjected to behavioural validation for longitudinal (Bassani et al., 2018; Catani, 2019), transversal (Catani and Bassani, 2019), and passing (Karimi et al., 2020) behaviours along rural highways.

2.2. Scenario

The current layout of the road platform in the G1 Fréjus tunnel, including the external configuration (Figure 2), was faithfully modelled in the virtual scenario. It is a 13 km long, two-lane (one per travel direction) road tunnel that connects Bardonecchia (Italy) to Modane (France) and has lane widths of 371 cm (France-Italy direction) and 373 cm (Italy-France direction). The posted speed limit is 70 km/h. The tunnel is equipped with a closed-circuit camera system and the recordings were used as a reference to extract data for the real driving data.

2.3. Subjects

Thirty-five participants were involved in this validation study. In accordance with the profile of the regular users of the tunnel and the requirements for future studies, fifteen drivers with an Italian category B license drove a car, and twenty professional drivers with an Italian category C and/or D license drove a heavy-duty truck during the driving simulation session. The group with B licenses consisted of 8 males and 7 females, with an average age of 38.8 years (SD = 11.3 years) and an average driving experience of 11,267 km/year (SD = 7,608 km/year). The group with C/D licenses was composed of 20 males, with an average age of 48.4 years (SD = 9.6 years) and an average driving experience of 42,333 km/year (SD = 29,601 km/year). The noticeable differences in age, gender and driving experience between the two groups of drivers is due to the difficulty in finding professional truck drivers.

Fig. 1. (a) Fixed-base driving simulator (Road Safety and Driving Simulation Laboratory, Politecnico di Torino); (b) Simulated car cockpit and engine in the virtual environment; (c) Simulated truck cockpit and engine in the virtual environment.

Fig. 2. Comparison between the real (top of the figure) and the simulated (lower part of the figure) environment, (a) outside and (b) inside the Fréjus tunnel.

2.4. Analysis procedure

A between-subject design, in which people involved in the experiment drove only one of the two experimental conditions, i.e., the simulated environment, was adopted. The measured dependent variables were speed (for longitudinal behaviour) and lateral position (for transversal behaviour). Data from real driving were compared with data collected from the driving simulation experiments. For the measurement of speed and lateral position in the real environment, video sequences collected from the CCTV cameras at specific stations in the Fréjus tunnel (Figure 3) were examined by using the video analysis technique. Kinovea ver. 0.8.27 (Charmant, 2004) allowed us to extract the trajectories of cars and heavy trucks by locating calibrated photogrammetric grids on the road according to the dimensions of the tunnel carriageway. Consequently, the speed relative to each trajectory was evaluated. Only the Italy-France travel direction was considered. For the simulated driving, the simulation software automatically acquired speed and lateral position data for the two drivers' groups (i.e., license type B and license type C/D) at the same stations where real driving data were extracted.

2.5. Protocol

The experimental protocol followed consisted of (i) a pre-drive questionnaire, (ii) a test drive on a trial circuit, (iii) the experimental driving session, and (iv) the post-drive questionnaire.

The pre-drive questionnaire was intended to collect demographic data, driving information, and to assess the general health and physical condition of the test drivers. Subsequently, they were trained to use the simulator vis-à-vis a 5-minute test drive. After a 2-minute break, each participant drove on the entire simulated Fréjus tunnel. The experiment ended with a post-drive questionnaire collecting information on the simulated driving experience and the state of health after completing the driving session.

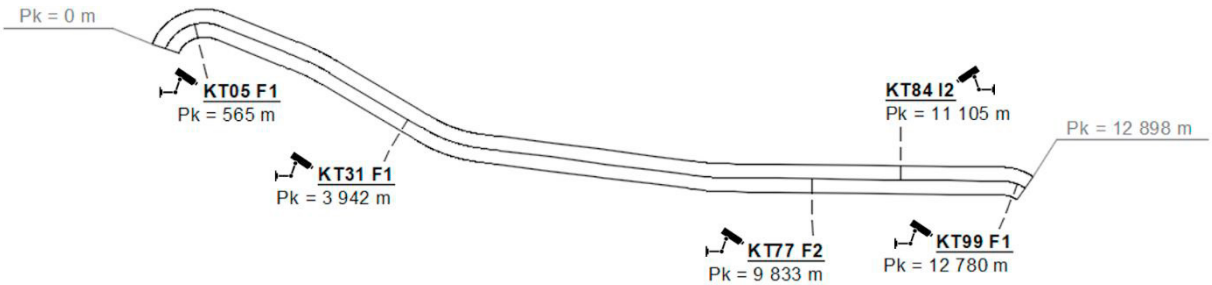

Fig. 3. Horizontal alignment of the Fréjus tunnel. Highlighted here are the camera codes, and relative stations, of the sections considered in the extraction of the videos used for the comparison between real and simulated driving.

2.6. Data Analysis

Before comparing the distribution of speed and lateral position values measured in real driving with those related to the driving simulation, collected data were subjected to the normality test (i.e., KS test) with significance level α set equal to 0.05. Subsequently, the values of speed and lateral position between video analysis and simulation data were compared by means of the Student's t-test.

3. Results

Depending on the availability of video recordings, the measured values of at least 34 cars and 38 heavy vehicles in each section were considered, except for the KT99 F1 section (camera, pk = 12,780 m), where data for only 13 heavy vehicles were collected. In the case of the KT84 I2 camera (pk = 11,105 m), the lateral position was not analysed, since the camera was located on the opposite side of the considered travel direction, with appreciable consequences for the projection errors of the reference points of the photogrammetric grid, used to extract trajectories. Video recordings from the KT31 F1 camera did not contain a sufficient number of cars for analysis and were considered for trucks only.

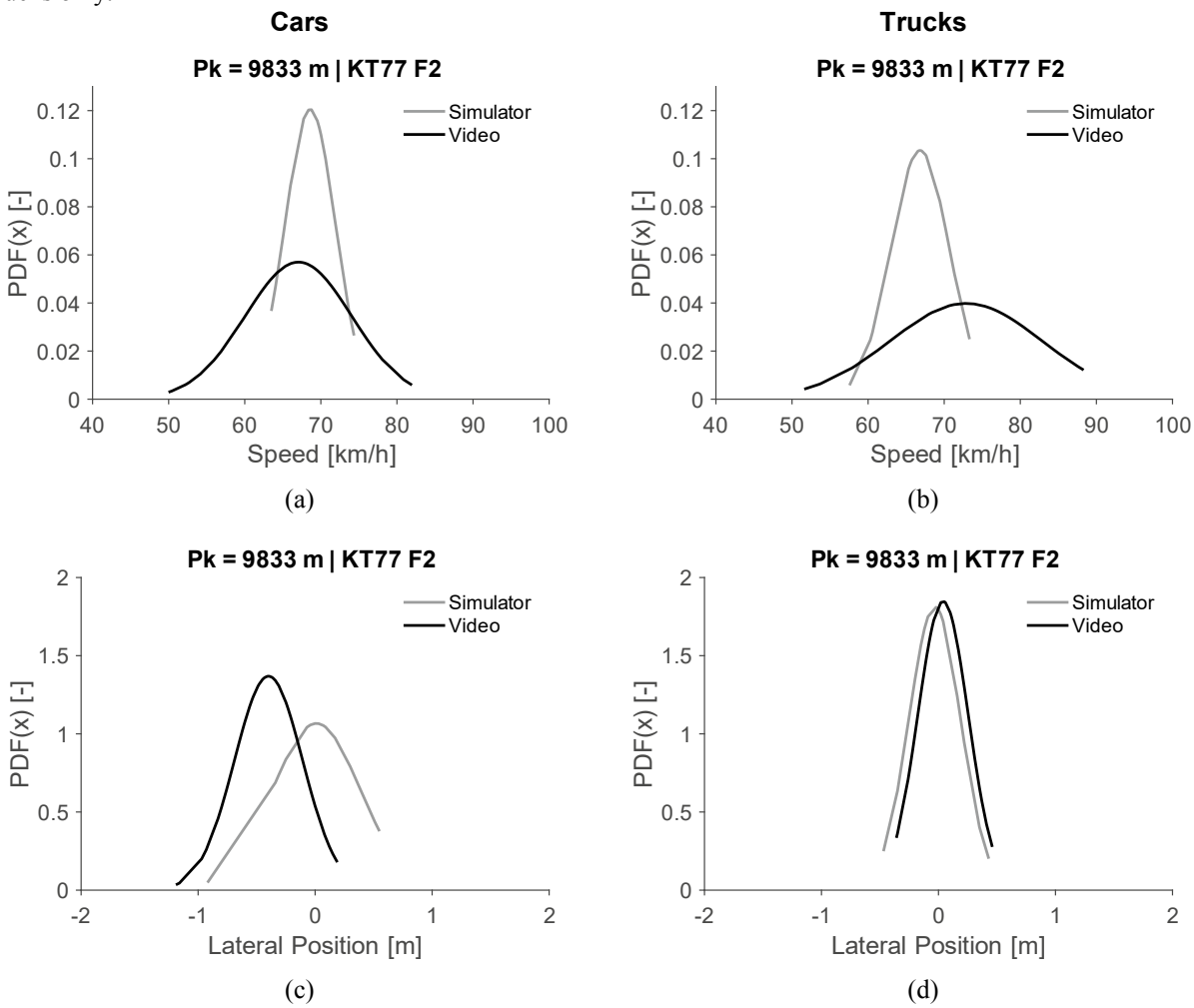

Fig. 4. Probability density functions for speed (*S*) and lateral position (*LP*) in real and simulated environments: (a) *S* for cars, (b) *S* for trucks, (c) *LP* for cars, (d) *LP* for trucks.

KS test p-values on the speed and lateral position data for the real and simulated environments for both cars and trucks resulted in values greater than 0.05 (all p-values between 0.298 and 0.992), thus indicating that all data were normally distributed. Illustrating the KS test results, Figure 4 shows the probability density functions for the collected data at the KT77 F2 camera (pk = 9833 m), for speed (*S*) in Figure 4a and Figure 4b, and lateral position (*LP*) in Figure 4c and Figure 4d. Data related to speed were more dispersed than the lateral position data.

Figure 5 summarizes the results obtained from the video analysis and driving simulations for cars and trucks, with averages and standard deviations of *S* (Figure 5a and Figure 5b) and *LP* (Figure 5c and Figure 5d) in the lane. Regarding the lateral position, the negative value indicates a vehicle centre of gravity to the left side of the lane axis.

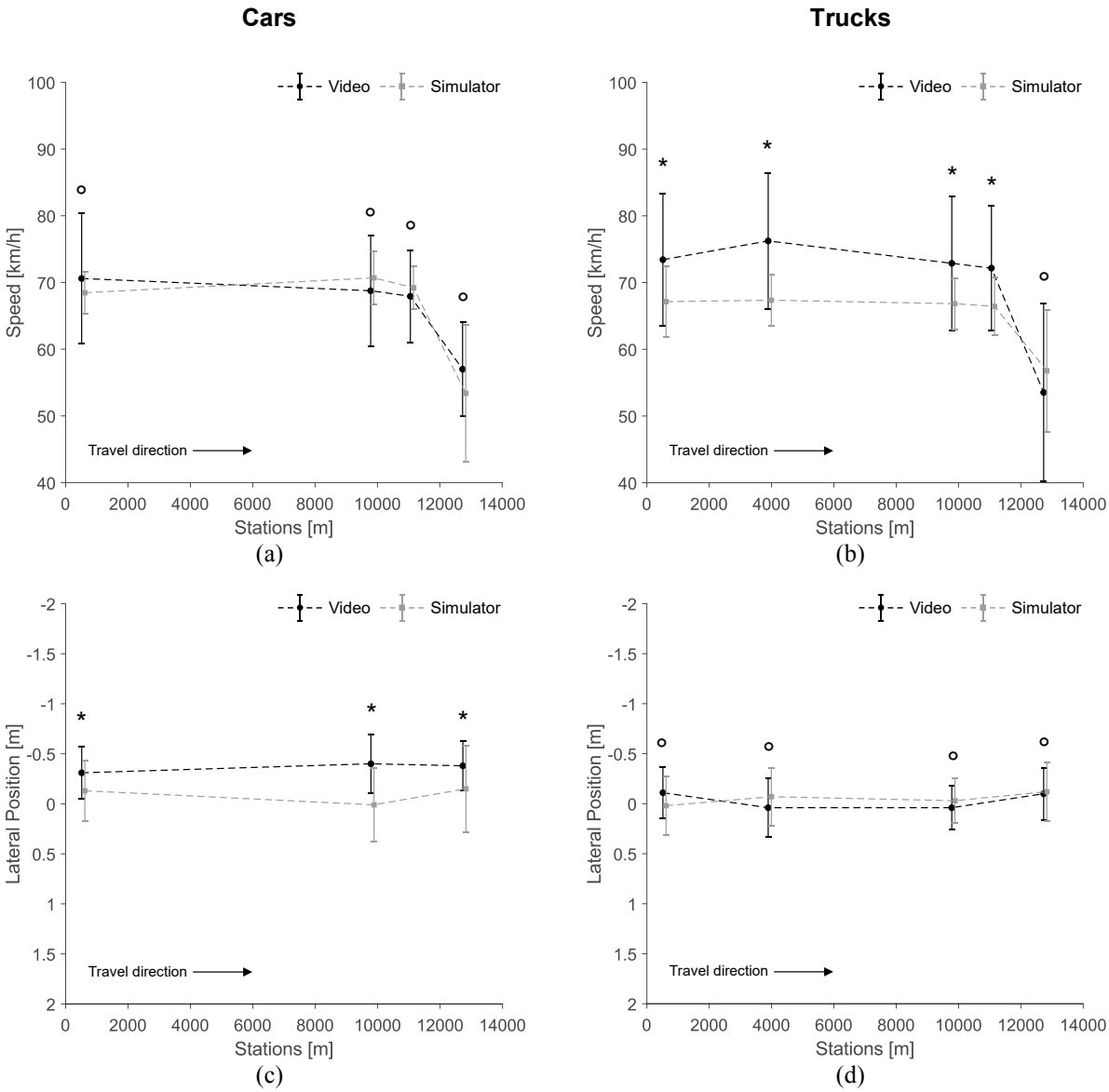

Fig. 5. Average and standard deviation (with error bars) of speed (*S*) and lateral position (*LP*) in real and simulated environments: (a) *S* for cars, (b) *S* for trucks, (c) *LP* for cars, (d) *LP* for trucks. Notes. T-test results: * p-value < 0.05, ° p-value > 0.05.

For car speeds, no significant differences between real and simulated environments were found for any of the investigated sections (p > 0.05). For truck speeds, significant differences were found (p < 0.05) on all sections except

for the last one (KT 99 F1). Professional drivers driving a truck in the real environment adopted a higher speed than truck drivers at the driving simulator (e.g., at KT31 F1, S_{video} = 76.2 km/h vs. $S_{simulator}$ = 67.4 km/h). This tendency is less pronounced among car drivers, where the difference in speed between the real and simulated environment was always around 2 km/h, except for the last camera station (at KT99 F1, S_{video} = 57.0 km/h vs. $S_{simulator}$ = 53.4 km/h).

For car lateral positions, significant differences between real and simulated environment were found in the analysed sections ($p < 0.05$). For truck lateral positions, no significant differences were found ($p > 0.05$). The lateral position for car drivers was more centred in the simulated driving than in real driving. In both cases, drivers kept their trajectory on the left side of the lane centreline, towards the centre of the carriageway. Professional drivers maintained a more centred trajectory than car drivers, and the difference in lateral position between the real and simulated environment was not very pronounced, except at the location of first camera (at KT05 F1, LP_{video} = -0.11 m vs. $LP_{simulator}$ = 0.02 m).

4. Discussion

The speeds for both cars and trucks were lower at the last camera station (i.e., KT99 F1, pk = 12 780 m). This result may be explained by the fact that the drivers were approaching the end of the tunnel and, thus, the end of the driving simulation.

In the case of trucks, the results for lateral positions in the lane indicate no significant differences between the real environment and the simulated scenario. However, for cars there were significant differences in lateral position in the lane between the real environment and simulated scenario. Obviously, heavy duty trucks occupy more space in the lane than cars. The gauge of a heavy truck vehicle is much larger and makes it difficult to weave within the lane. Conversely, a car has sufficient lateral room to correct and vary its trajectory. Moreover, as already mentioned, all the heavy vehicles were driven by professionals with relevant driving experience and, consequently, more control capability. They were all aware of the limited space between the vehicles and the tunnel walls.

The longitudinal behaviour of car drivers was the same in both the simulation drive and in the real drive. The speeds adopted by the professional drivers during the simulated drive were significantly lower than the speeds observed in real driving conditions. It is worth noting that in real driving, professional drivers tend to reduce travel times, driving slightly above the speed limit. In the specific case of the Fréjus tunnel, they also travel at speeds above the 70 km/h limit to compensate for any time lost as a result of customs checks and technical inspections at the border.

5. Conclusions

Considering the outcomes of the Student's t-tests, two different validation results for the RSDS laboratory simulator can be declared for cars and for heavy vehicles in tunnel driving. As regards car driving, the simulator achieved absolute validity for longitudinal behaviour (in terms of speed) and relative validity for lateral behaviour (i.e., lateral position, with the vehicle centre of gravity nearer to the lane centreline). Opposite findings were obtained in the case of truck driving. Relative validity was achieved for speeds, which are always higher in the real environment, while lateral position achieved absolute validity.

The relative-absolute validation of driving simulators enables the authors to extend their experimental results to real operations. The behavioural validation confirms the power of the simulator as a research tool for tunnel driving as well, as already demonstrated for the rural environment, opening up the prospect of new experiments in this field. The validation of driving simulators for tunnel driving is crucial, since safety issues in this environment have to be analysed in order to determine effective countermeasures and reduce the risk of accidents. On the basis of these results, we can interpret behavioural observations inside road tunnels. In particular, a driving simulation experiment was carried out to predict the behavioural effect of the new ventilation system that will be installed in a lateral wall of the Fréjus G1 tunnel.

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