POLITECNICO DI TORINO
Repository ISTITUZIONALE

Driver behaviour assessment due to changes in the geometric layout to integrate lateral jet fans in long road tunnels

Original
Driver behaviour assessment due to changes in the geometric layout to integrate lateral jet fans in long road tunnels / Lioi, A.; Portera, A.; Hazoor, A.; Tefa, L.; Karimi, A.; Bassani, M.. - In: TRANSPORTATION RESEARCH INTERDISCIPLINARY PERSPECTIVES. - ISSN 2590-1982. - 26:(2024), pp. 1-11. [10.1016/j.trip.2024.101137]

Availability:
This version is available at: 11583/2990770 since: 2024-07-14T15:08:16Z

Publisher:
Elsevier

Published
DOI:10.1016/j.trip.2024.101137

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

06 May 2026

Transportation Research Interdisciplinary Perspectives 26 (2024) 101137

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.sciencedirect.com/journal/transportation-research-interdisciplinary-perspectives

Driver behaviour assessment due to changes in the geometric layout to integrate lateral jet fans in long road tunnels

A. Lioi[a], A. Portera[a], A. Hazoor[b], L. Tefa[a], A. Karimi[a], M. Bassani[a,*]

[a] *Department of Environment, Land, and Infrastructure Engineering (DIATI), Politecnico di Torino, Corso Duca degli Abruzzi, 24, Torino 10129, Italy*
[b] *Road Traffic Research Division, NORD University, Wessels veg 75, Stjørdal 7502, Norway*

ARTICLE INFO

Keywords:
Road tunnel
Jet fans
Lighting conditions
Driving simulation
Driver behaviour
Truck drivers

ABSTRACT

This driving simulation study is aimed at evaluating the effects on the longitudinal and transversal behaviour of drivers attributable to layout changes in an existing long tunnel caused by the introduction of jet fans along the tunnel walls. Furthermore, the effects of two different levels of light intensity capable of revealing or masking the presence of jet fans, thus manipulating the vision of participants, were also evaluated. Forty drivers were involved in this multi–level mixed-factorial experiment, in which twenty car and twenty truck drivers drove on three different layouts of a two–way two-lane long tunnel. Two different pairwise analyses were carried out to assess the effects of these two within-subject factors. The presence of oncoming traffic was also considered as a factor in the study.

The presence of jet fans led to lower speeds and affected the transversal behaviour of car and truck drivers in different ways. In the presence of the jet fans trucks reduced the lateral distance to the tunnel wall, while car trajectories were always closer to it. All drivers showed better lateral control when facing the jet fans and when meeting oncoming vehicles. When the light intensity was reduced, truck drivers adopted lower speeds, while with higher light intensity they drove closer to the tunnel wall, thus reducing the risk of collision with any oncoming traffic.

1. Introduction

Long tunnels facilitate traffic mobility in mountainous and otherwise almost inaccessible environments. While the number of long new tunnels has increased in recent years, many older ones are still in service and need safety interventions (Amundsen, 1994; Commission Internationale de l'Éclairage, 2004). Statistics confirm that crashes in tunnels are less frequent than on open roads (Bassan, 2016) and the longer the tunnel, the lower the frequency of crashes per unit length, but the higher the probability of more severe consequences (Kirytopoulos et al., 2017; Lemke, 2000; Ma et al., 2016). The accidents at Mont Blanc (1999), Gotthard (2001) and Fréjus (2005) tunnels demonstrated that tunnel safety is strongly influenced by the driver behaviour and the presence of safety-related infrastructures (PIARC, 2008; Kirytopoulos et al., 2017).

1.1. Literature review

Crashes in road tunnels follow a different dynamic with respect to those on open roads due to the influence of behavioural, geometric, and traffic-related factors (Caliendo & De Guglielmo, 2012). Along tunnels, drivers travel at lower speeds and tend to shift more laterally towards the centre of the lane than they do on open roads (Calvi and D'Amico, 2013; Calvi et al., 2012), increasing the risk of colliding with oncoming traffic. Moreover, the difficulty in adapting to the change in lighting when entering and exiting the tunnel can impair driving performance (Caliendo et al., 2013). Furthermore, narrow tunnels with sharp curves and long alignments are more dangerous, with the presence of heavy vehicles and two–way traffic increasing the risk of collision (Salvisberg et al., 2004).

Driving simulation studies have demonstrated that the wider the lane the higher the speed, especially on roads with a hard shoulder (Liu et al., 2016). Narrow shoulders result in vehicles driving closer to the tunnel wall, thus inducing stress in drivers which in turn increases their mental workload (Shimojo et al., 1995). Moreover, the ability to maintain concentration while driving tends to deteriorate in long tunnels with a transit time exceeding ten minutes (Hirata, 2006).

---

* Corresponding author.
E-mail addresses: alessandra.lioi@polito.it (A. Lioi), alberto.portera@polito.it (A. Portera), abrar.hazoor@nord.no (A. Hazoor), luca.tefa@polito.it (L. Tefa), arastoo.karimi@polito.it (A. Karimi), marco.bassani@polito.it (M. Bassani).

https://doi.org/10.1016/j.trip.2024.101137
Received 12 February 2024; Received in revised form 29 May 2024; Accepted 31 May 2024
Available online 29 June 2024
2590-1982/© 2024 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

A survey among drivers in Singapore highlighted the negative perception (of familiar and non-familiar drivers alike) associated with driving inside expressway tunnels, and it also demonstrated that lighting is a factor that influences and can enhance the quality of driving (Yeung et al., 2013). In fact, driving in tunnels is stressful for drivers because of (i) the objective risk conditions due to the enclosed environment and the short lateral distances to rigid obstacles, and (ii) the subjective perception of risk experienced by drivers which is amplified in long tunnels, and which conditions their behaviour. To compensate for such risks, the Commission Internationale de l'Éclairage (2004) provides recommendations for the design and installation of lighting systems in tunnels. This guide emphasizes safety and driving comfort, while describing design criteria, lighting techniques, light sources, control systems, emergency lighting, and maintenance procedures. Peña-García (2018) investigated the flicker effect, one of the main problems related to lighting systems in very long underground roads, and the possible solutions. With a driving simulation experiment, Domenichini et al. (2017) revealed that LED lighting systems were superior to high-pressure sodium vapor ones, in terms of their impact on driver behaviour and driving comfort. Kircher and Ahlstrom (2012) confirmed that different lighting levels as well as the colour of the walls influence driver behaviour. Other studies demonstrated that the different colours and visual patterns of tunnel walls can affect driving behaviour, especially speed perception (Manser & Hancock, 2007) and visual information (Qin et al., 2020).

1.2. Problem statement and study objective

To comply with current safety regulations (EU Directive 2004/54/EC, 2004), in the event of a fire the ventilation systems must provide fresh air to those people still inside the tunnel and curtail smoke propagation by ensuring the full length of the tunnel is sufficiently illuminated for the purposes of evacuation and rescue (Barbato et al., 2014; Maevski, 2017). Furthermore, following the recent, tragic road accidents in Alpine tunnels, some management authorities are considering the installation of additional longitudinal ventilation systems to maintain a suitable environment for the evacuation of tunnel users. However, since most of the existing long tunnels do not comply with the current standards on minimum vertical and lateral clearance, new installations require the adoption of unconventional solutions. In such cases, any new cross-section layout must avoid creating additional risks for road users. Therefore, any decisions regarding the inclusion of new installations should also take their influence on driver behaviour and fire evacuation procedures into consideration. To the best of our knowledge, no previous study has investigated the effects of installing jet fans along the tunnel wall under different lighting conditions.

The aim of this multi-level mixed–factorial driving simulation experiment was to evaluate the impact of installing jet fans on the walls of a long tunnel on the behaviour of both car and truck drivers, with the latter having a more elevated position while driving and thus a different viewpoint. Furthermore, to counterbalance the possible visual impact of the jet fans, we also investigated the effect of adopting a different light intensity in the tunnel. This research study was conducted to support decision–makers in modifying the tunnel's geometric layout in scenarios where jet fans can only be installed along the tunnel wall.

Two separate analyses were conducted to evaluate driver behaviour before and after the installation of the jet fans, and with drivers also subjected to two different light intensities able to highlight or mask the jet fans. Both car and truck drivers were involved to ensure a range of different driving styles, abilities, and experiences. Prior to this study, the driving simulator was behaviourally validated by comparing data on speed and lateral position with those collected in the real tunnel as documented in Lioi et al. (2023).

2. Method

2.1. Scenarios

This assessment of driver behaviour resulting from changes in the geometric layout of a road tunnel due to the installation of jet fans has been inspired by the case study of the G1 tunnel of the Fréjus tunnel connecting Italy (Bardonecchia) to France (Modane). In 2020, the tunnel operator GEIE-GEF commissioned the Politecnico di Torino to study and evaluate the impact of jet fans, to be installed approximately 250 m apart on the tunnel wall, on traffic operations. The Fréjus tunnel is approximately 13 km long, with current lane widths in the two directions of 3.73 and 3.71 m for the Italy-France and France-Italy directions, respectively (see Fig. 1, Layout 0, Scenario 0). In the tunnel, the posted speed limit is 70 km/h, and blue LED lights are installed at intervals of 150 m along the walls to encourage drivers to maintain a safe distance from the vehicle in front.

It should be noted that the installation of wall-mounted jet fans might be the only possible solution where there is insufficient space in the obstacle-free area above the carriageway, the size of which is established through national road design policies (AASHTO, 2018; Ministero delle Infrastrutture e dei Trasporti, 2001). Therefore, this study could be pertinent for those existing tunnels that still need to be updated to satisfy current fire safety prescriptions (EU Directive 2004/54/EC, 2004). Relevant examples of wall–mounted jet fans come from French roads (e.g., Fourvière and Brotteaux-Servient tunnels in Lyon, Tunnel de Prado Sud in Marseille) and motorways (e.g., Queillau and Tilleuls along the L2 beltway in Marseille, the Tunnel d'Orelle along the A43).

Due to the vertical limitations in the cross–section of the Fréjus tunnel (see Fig. 1), the jet fans were designed to be installed at a height of 2.30 m along the tunnel wall. This decision required an increment in the insurmountable lateral sidewalk width in the Italy-France direction from 0.5 to 1.2 m to guarantee a lateral clearance of 0.3 m from the carriageway, and the reduction of lane, median and shoulder width (see Fig. 1, Layout 1 – high light intensity, Scenario 1). Furthermore, no guardrails were erected between the jet fans and the carriageway as they might hinder the evacuation of vehicle occupants in an emergency.

Based on these decisions, we surmised that the presence of jet fans might lead drivers travelling in the Italy–France direction to shift laterally away from the tunnel wall, thus increasing the risk of collision with oncoming traffic (Analysis 1). To counter this risk, we also hypothesized that a lower intensity of light on the tunnel wall renders the jet fans less visible (see Fig. 1, Layout 1 – low light intensity, Scenario 2, Analysis 2). As a result, we posited a second experimental hypothesis that a reduced light intensity to mask the presence of jet fans along the tunnel wall would enhance the longitudinal and transversal behaviour of drivers. It is worth noting that the luminance of illuminated tunnel roads falls within the mesopic region of human vision (Viikari et al., 2008), and that a minimum luminance of the carriageway 0.5–1 cd·m^{-2} is required, with tunnel walls having at least 60 % of the pavement luminance (Ente Nazionale Italiano di Normazione, 2011). With a low light intensity, these minimum thresholds must guarantee the ability of drivers to distinguish colours and details in the foveal region, with just a reduced resolution (Boyce, 2008). Conversely, a higher light intensity activates human vision closer to the boundary between the photopic and mesopic states, ensuring that drivers are fully capable of discerning colours and the details of traffic, pavement, and road equipment (Mussone, 2023).

2.2. Experimental design

Based on the case study, the experimental design included the effects of two main within-subjects factors: (i) the different layouts (the existing layout and the new one with the jet fans) and, following the installation of jet fans, (ii) the light intensity. Combining the two cross sections depicted in Fig. 1 (Layouts 0 and 1) and the two different light intensities

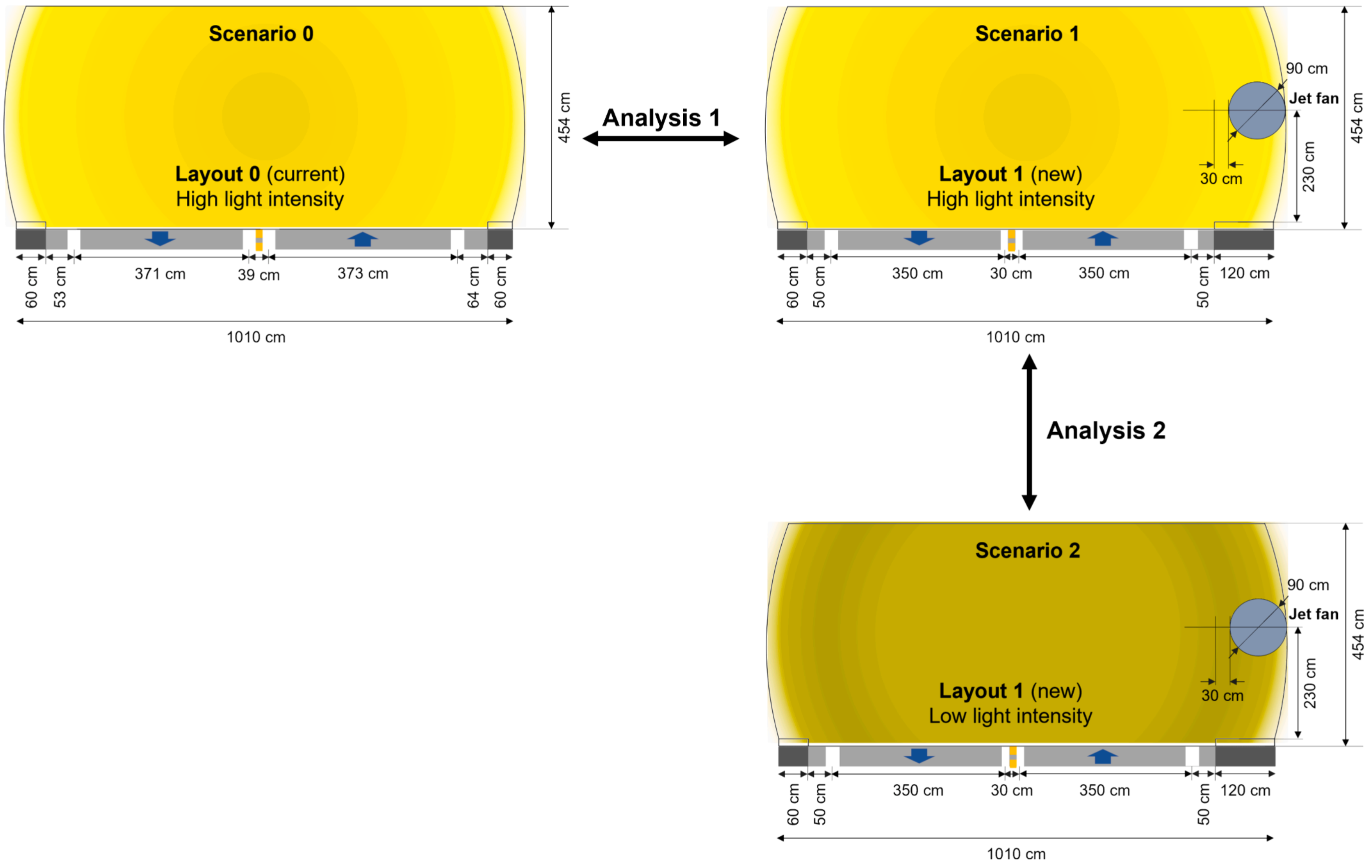


Fig. 1. Experimental scenarios with pairwise analyses to evaluate the effect of the presence of jet fans (Analysis 1, Scenario 0 vs. Scenario 1), and the effect of different light intensities used in an attempt to mask the presence of the jet fans along the tunnel walls (Analysis 2, Scenario 1 vs. Scenario 2).

(Layouts 1 – high light intensity and 1 – low light intensity), the three scenarios depicted in Fig. 1 were considered. A comparison between the behavioural outcomes of Layouts 0 and 1 allowed us to evaluate the effects of the jet fans and the change in the geometric characteristics of the cross section under mesopic/photopic adaptation (Analysis 1, Scenario 0 vs. Scenario 1). The behavioural outcomes between Layout 1

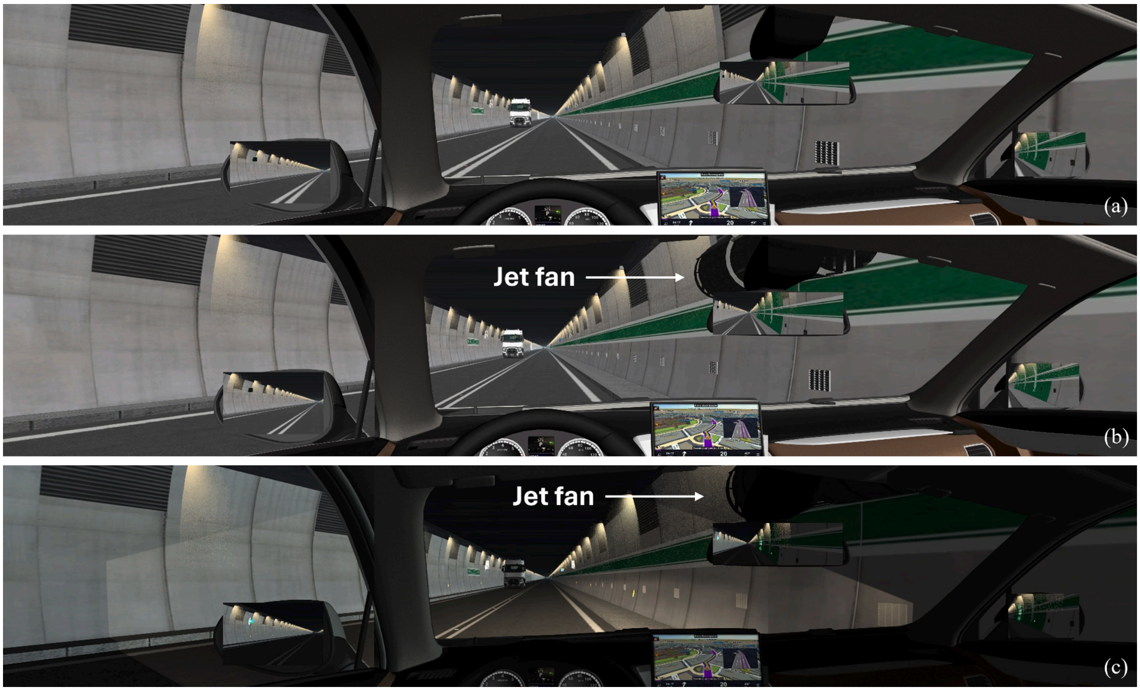


Fig. 2. Simulated car cockpit and engine in the virtual environment for (a) Scenario 0, (b) Scenario 1 and (c) Scenario 2.

with high light intensity and the same Layout 1 but with a lower light intensity were analysed to evaluate the effects attributable to different light conditions and their ability (or failure) to mask the presence of jet fans along the tunnel walls (Analysis 2, Scenario 1 vs. Scenario 2) as clearly depicted in both Fig. 2 and Fig. 3.

We also considered two vehicle types (cars and trucks) to account for any differences attributable to the driver's vantage point. Figs. 2 and 3 show the different viewpoints of car and truck drivers, positioned at 1.35 m and 2.70 m above the pavement respectively, in the three scenarios (Fig. 1).

In the simulation, the driven vehicles operated under free-flow conditions in the investigated travel direction (from Italy to France). In the opposite direction (from France to Italy), a flow of simulated cars and trucks was programmed to maintain a relative distance of at least 150 m, and to meet the driven vehicles in front of 20 out of 55 jet fans, as shown in Fig. 4a. In the other 35 sections, the simulated ego-vehicle did not meet any vehicle in the opposite direction as depicted in Fig. 4b. The programmed interaction between the driven (ego) and other simulated vehicles aimed to evaluate the behavioural effects caused by the contextual conditioning of traffic and jet fans, which is a challenging situation in tunnel driving particularly for truck drivers.

Table 1 lists the independent factors based on their role in the experiment (between- vs. within-subject) for Analysis 1 and Analysis 2, respectively.

2.3. Participants and experimental protocol

The experiment was conducted in a manner consistent with the Code of Ethics of the World Medical Association (2018). Forty participants, twenty professional drivers with C and/or D European driving licence (truck drivers), and twenty drivers holding a B licence (car drivers), were involved. C and D licence holders drove the truck, while B licence holders drove the car. A summary of test drivers' characteristics is shown in Table 2. Only male truck drivers participated due to the difficulty in inviting and involving professional female drivers. As confirmed in previous studies, the percentage of women among truck drivers is very low, i.e., 6–10 % (Reed & Cronin, 2003; Makuto et al., 2023). The drivers were selected from a list of more than 400 individuals who had previously participated in other simulation experiments as volunteers. No participants received compensation for their involvement in the experiment. The age range of the car drivers was wider (22–58 years) than that of the truck drivers (36–62 years). Given their status, professional truck drivers had driven more kilometres per year than B-licence holders.

Data collection took place between February and May 2021. The following experimental protocol was adopted. First, participants filled out a 5-minute pre-drive questionnaire to collect general demographic data. Then, they drove for five minutes on a different scenario to get familiar with the simulator.

After the trial, six different sequences were designed to include the three scenarios (0, 1 and 2, see Fig. 1) and assigned to six drivers following two different Latin square designs, ensuring that each condition occurred exactly once within each order and that all conditions were equally spaced.

Each driving scenario lasted approximately 12 min. Participants were asked to drive as they normally would while also respecting the speed limits in operation inside the tunnel. A post-drive questionnaire was finally dispensed to get information on their driving experience, with an additional oral interview.

2.4. Equipment

The study was performed at the Road Safety and Driving Simulation Laboratory (Politecnico di Torino, Italy). A fixed-base driving simulator equipped with three 32-inch full HD monitors with a 130° field of vision was used. The simulator was equipped with both manual transmission for cars, and automatic transmission for trucks. Scenarios were built with SCANeR Studio® (AV Simulation, France), which allows for simulations with both car and truck cockpits with realistic rear–view mirrors. The steering wheel had a force-feedback and was animated on the screen as well as the on–board instruments (e.g., speedometer, rev counter, levels, indicators). During the experiment, the vehicle dynamics module was activated to reproduce the typical pitch and roll movements of vehicles on the screen.

Our previous research on the validation of driving simulators for tunnel driving (Lioi et al., 2023) has shown that the simulator can yield

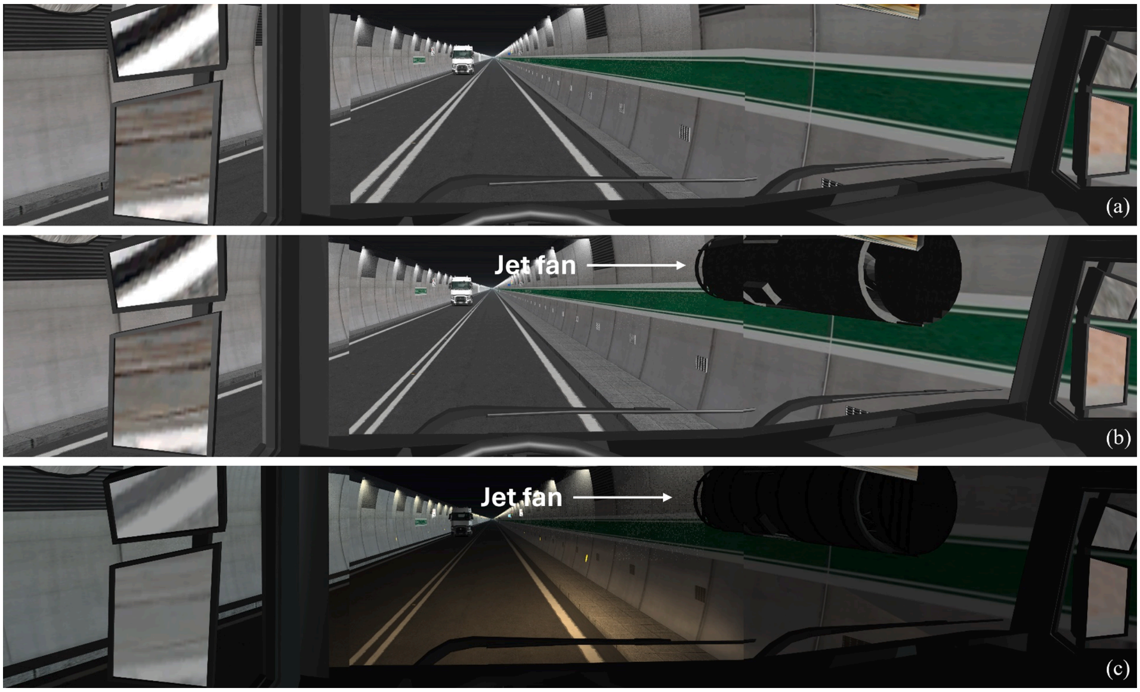


Fig. 3. Simulated truck cockpit and engine in the virtual environment for (a) Scenario 0, (b) Scenario 1 and (c) Scenario 2.

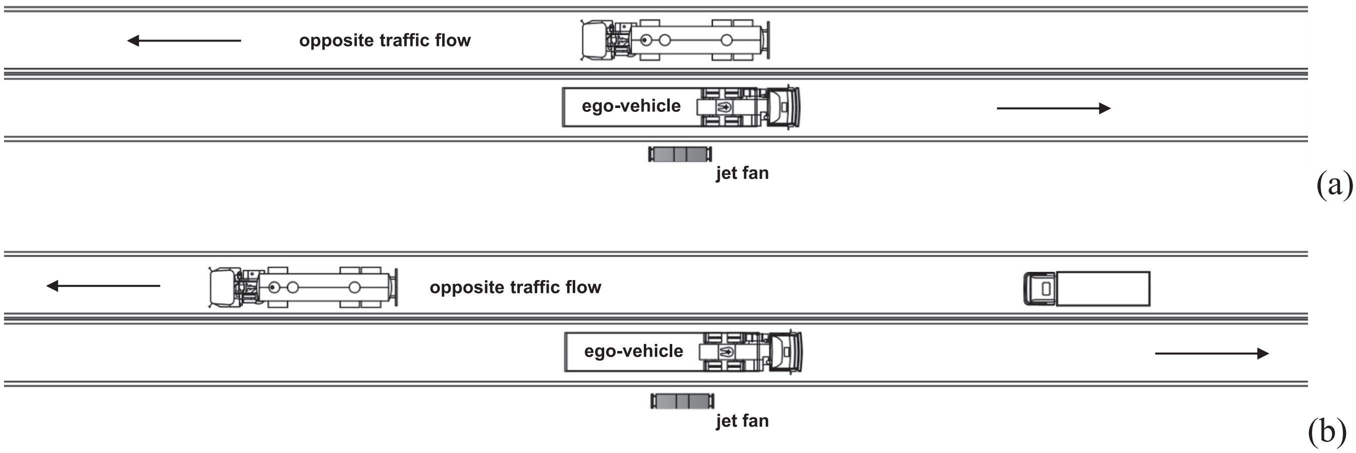


Fig. 4. (a) Illustration of interaction between ego-vehicle (e.g., heavy vehicle) and simulated vehicle (e.g., heavy vehicle) travelling in the opposite direction in the proximity of the jet fan; and (b) illustration of non–interaction between ego-vehicle and simulated vehicle travelling in the opposite direction in the proximity of the jet fan.

Table 1
Experimental factors for Analyses 1 and 2.

Analysis	Scenarios	Factors			
		Within-subject			Between-subject
		Layout	Light intensity	Oncoming traffic	Type of vehicle
1	0	0	High	No/Yes	Car/Truck
	1	1	High	No/Yes	Car/Truck
2	1	1	High	No/Yes	Car/Truck
	2	1	Low	No/Yes	Car/Truck

results that are transferable to real-world scenarios. The study revealed absolute validity for speed and relative validity for lateral position in the case of cars. Conversely, relative validity for speeds and absolute validity for lateral position were achieved for trucks. These findings highlight the potential of the simulator as a valuable research tool for studying driver behaviour in tunnels (Törnros, 1998). The absolute validity achieved confirms the ability of the simulator to accurately reproduce real-world behaviour, and the obtained relative validity enables us to effectively capture and differentiate variations in driving behaviour, providing valuable insights into the relative effects of different factors on driving performance within the simulator.

2.5. Data analysis

Speed and lateral position data were collected along the full length of the tunnel at a frequency of 10 Hz. Data was filtered by excluding the first and the last 500 m as the data relating to these sections would be influenced by speed changes associated with entering and exiting the tunnel. To avoid the effects of the curvature on driver behaviour, only the 42 straight sections (out of the total of 55 in the tunnel) were considered.

Three behavioural variables were analysed in both pairwise analyses: (i) the speed (*S*) at the sections where jet fans were located, (ii) the lateral position (*LP*) at the same locations, and (iii) the standard deviation of the lateral position (*SDLP*) over the 100 m stretches, 50 m before and 50 m after the position of every jet fan. Therefore, 3360 (=40 drivers × 42 sections × 2 scenarios) observations per analysis were considered. A negative value for *LP* indicates a vehicle centre of gravity value (CoG) on the left side of the lane centreline.

Linear mixed effects models (LMMs) were used to assess the effect of the independent factors on the three driving behaviour variables, taking into account the effects of the predictor variables while accounting for individual differences. They offer several advantages over traditional linear models, particularly when dealing with complex data structures (e.g., repeated measures within-subjects designs), including both fixed and random effects. Traditional linear models assume the independence of observations, whereas LMMs deal skilfully with correlated data and the non-independence of errors through the inclusion of random effects. This feature is particularly beneficial when the data consist of repeated measurements on the same subjects, allowing LMMs to account for individual differences that cannot be explained by the fixed effects alone. They can also handle missing data and provide a more robust analysis of the data by using likelihood-based estimation techniques such as restricted maximum likelihood (REML).

LMMs were estimated by using R Statistical Software ver. 4.2.2 (R Core Team, 2022), with the *lme4* package (Bates et al., 2015). Factors to be included were selected according to (i) the backward elimination technique and (ii) comparisons of the model performances, e.g., AIC, BIC, likelihood. Estimated marginal means were calculated by using the *emmeans* package (Lenth, 2023) and results were graphically reproduced with the *ggplot2* package (Wickham, 2016). The significance level was set at 5 %. Post-hoc tests with Bonferroni correction were performed for statistically significant interactions.

Table 2
Descriptive statistics of participants' characteristics (mean and standard deviation between brackets).

Type of vehicle (Driving licence)	Gender	Age	Number of drivers	Driving experience		Number of crashes
				years	km/years	
Car (B)	M	37.2 (12.4)	11	17.3 (11.1)	11 273 (8 380)	0.6 (0.8)
	F	32.7 (15.4)	9	15.8 (11.3)	8 365 (10 294)	0.2 (0.4)
Truck (C and D)	M	50.2 (6.6)	20	24.7 (7.6)	44 842 (28 066)	1.45 (2.2)

3. Results and discussion

3.1. *Analysis 1 – Effect of the layout*

Table 3 provides descriptive statistics of the outcomes for Analysis 1, according to the layout, the oncoming traffic flow and the type of vehicle. Gender was not considered as an experimental factor due to the lack of professional female drivers. Results indicate that (i) all drivers respected the speed limit of 70 km/h, which is also the value adopted in the real tunnel as indicated in Lioi et al. (2023), and (ii) car speeds were slightly higher than those of heavy vehicles. Differences in *LP* values were minimal. Passenger cars tended to occupy a position in the lane closer to the tunnel wall than heavy vehicles, which, in contrast, tended to follow the lane centreline. Even the difference in *SDLP* between passenger cars and trucks was relatively small, with truck drivers maintaining greater trajectory control with lower average *SDLP* values than car drivers.

3.1.1. *LMMs estimations*

The new ($lo = 1$) or the current ($lo = 0$) layout (*lo*), the presence ($ot =$ yes) or the absence ($ot =$ no) of oncoming traffic (*ot*) were included as categorical factors, while the test driver ID was considered a random effect. LMM outcomes are shown in Table 4.

Table 4 shows the proportion of variance attributable to the fixed factors only (marginal R^2) and the proportion explained by both fixed and random effects (conditional R^2) in the models for Analysis 1. For *S*, approximately 72 % of the variance in the data is explained by the model, only 1.5 % of which is attributable to fixed effects. Around 54 % of the total variance of the models for *LP* is explained, while the variance explained by the fixed factors alone is around 11 % of the total. Only 9.5 % of the variance of the model for *SDLP* is fully explained by the model, mostly by random effects (marginal $R^2 = 0.008$). LRT tests for random effects demonstrate the strong significance of the random component for all the considered variables.

With regard to speeds, most of the model variance is explained by random effects. As demonstrated by the large intraclass correlation coefficient (ICC) value for random components, the influence of individual attitudes was found to be extremely significant. While the statistical analysis revealed a significant speed difference between Layout 1 and Layout 0 in the presence of jet fans ($S_{lo\,=\,1} - S_{lo\,=\,0} = –0.35$ km/h, $t_{3319} = –3.046$, $p = 0.002$), it is important to note that this observed difference, though statistically significant, may not have practical significance in real-world driving conditions. No significant differences in speeds were attributable to the type of vehicle, but this factor improved the goodness of the model.

Differences in layout and type of vehicle had a significant effect on *LP*.

Table 3
Descriptive statistics of the outcomes of Analysis 1 (mean and standard deviation between brackets).

Layout	Opposing traffic	Vehicle type	*S* (km/h)	*LP* (m)	*SDLP* (m)
Layout 0	No	Car	70.59 (5.55)	0.074 (0.284)	0.063 (0.046)
		Truck	69.55 (6.56)	−0.063 (0.270)	0.059 (0.046)
	Yes	Car	70.48 (5.44)	0.129 (0.269)	0.061 (0.040)
		Truck	69.34 (6.71)	−0.013 (0.257)	0.053 (0.045)
Layout 1	No	Car	70.42 (5.60)	0.070 (0.261)	0.056 (0.037)
		Truck	69.04 (6.21)	−0.031 (0.248)	0.051 (0.035)
	Yes	Car	70.24 (5.98)	0.120 (0.248)	0.053 (0.035)
		Truck	68.87 (6.22)	0.036 (0.241)	0.051 (0.033)

Table 4
Significant factors and summary statistics of LMM for Analysis 1.

Variables	Effect	Estimate (significance)		
		S **(km/h)**	***LP*** **(m)**	***SDLP*** **(m)**
Fixed Effects *(main factors and interactions)*				
Intercept		70.6315 (***)	0.0739 (.)	0.0606 (***)
Layout (*lo*)	1 – 0	−0.3464 (**)	−0.0057 (–)	−0.0068 (***)
Oncoming traffic (*ot*)	Yes – No	–	0.0557 (***)	−0.0030 (*)
Vehicle type	Truck – Car	−1.2277 (–)	−0.1389 (*)	–
Vehicle type * Layout	(Truck – Car) * (1 – 0)	–	0.0438 (***)	–
Random effects				
Participant ID – LRT test		(***)	(***)	(***)
Summary statistics				
AIC		17769.095	−1582.138	−12204.349
BIC		17799.694	−1539.300	−12173.751
Log- Likelihood		−8879.548	798.069	6107.175
Marginal R^2		0.011	0.058	0.008
Conditional R^2		0.715	0.541	0.095
ICC for random components		0.712	0.513	0.087
Observations		3360		
Drivers		40		
Observations/driver		84		

Notes. "." for $p < 0.1$, "*" for $p < 0.05$, "**" for $p < 0.01$, and "***" for $p < 0.001$, symbol "-" means not statistically significant at a significance level of 0.05.

Post–hoc tests with Bonferroni correction demonstrated that truck drivers tended to deviate more from the centreline to the tunnel wall in Layout 1 with respect to Layout 0 (for trucks, $LP_{lo\,=\,1} - LP_{lo\,=\,0} = 0.038$ m, $t_{3317} = 4.223$, $p < 0.001$). Furthermore, car drivers deviated more from the centreline of the lane towards the tunnel wall than truck drivers did ($LP_{\text{truck}} - LP_{\text{car}} = –0.117$ m, $t_{38} = \text{-}2.286$, $p = 0.028$). When passing an oncoming vehicle, drivers tended to move laterally toward the right side to increase the distance between the two vehicles ($LP_{ot\,=\,\text{yes}} - LP_{ot\,=\,\text{no}} = 0.056$ m, $t_{3317} = 8.219$, $p < 0.001$).

Independent variables explained a small portion of the *SDLP* variance in the LMM, with random effects proving significant statistically, i.e., the driving style and ability of participants. Drivers exhibited better lateral control when using the new layout of the tunnel ($SDLP_{lo\,=\,1} - SDLP_{lo\,=\,0} = –0.007$ m, $t_{3318} = \text{-}5.072$, $p < 0.001$) and also when they passed oncoming vehicles in front of the jet fan ($SDLP_{ot\,=\,\text{yes}} - SDLP_{ot\,=\,\text{no}} = \text{-}0.003$ m, $t_{3318} = \text{-}2.124$, $p = 0.034$).

3.1.2. *Discussion*

Analysis 1 aimed at evaluating the effect of the new layout on driver behaviour. Layouts 0 and 1 differ both in the cross section (lane, median, shoulder and sidewalk width) and in the presence or absence of jet fans.

When comparing the two layouts, a statistically significant decrease in speed was observed in Layout 1 (Fig. 5), while the effects of the vehicle type were found to be statistically insignificant. This outcome is consistent with those from Liu et al. (2016) who observed a significant speed reduction associated with a reduction in the lane width, a fact that has also been observed on roads outside tunnels (Lamm et al., 1990; Godley et al., 2004). While the statistical analysis revealed a small but statistically significant reduction in speed (0.35 km/h on average) due to the layout change, it is essential to address the practical significance of this finding. In the context of real-world driving, a 0.35 km/h difference in speed is relatively minor and may not substantially impact traffic flow, driver safety, or overall road performance. The use of a large dataset and the application of a LMM allowed us to detect even subtle variations in response to the layout changes. However, it is crucial to consider the broader context and potential real-world implications, which may prove to be minor or negligible in this case. When vehicles travelling in opposite directions were closer to each other, we believe

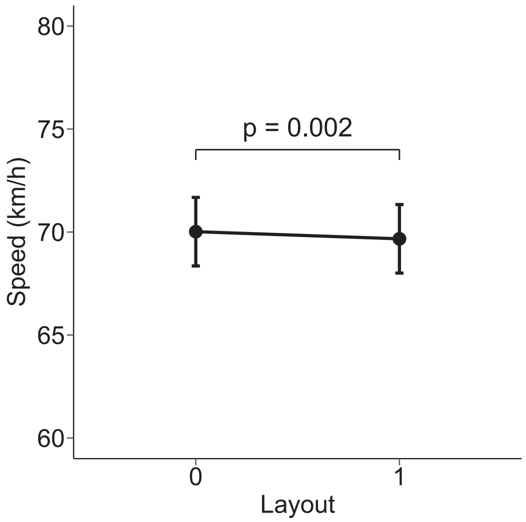


Fig. 5. Effect plot for speed in Analysis 1: influence of the Layout.

that drivers reduced their speed to limit the risk of collision with a lateral obstacle (i.e., oncoming vehicles and the tunnel wall). We also believe that the proximity to a jet fan did not influence the longitudinal behaviour of truck drivers, as they themselves claimed in their post-driving session oral interview in which they declared that they had sufficient experience and awareness to maintain speed levels on lanes with a width equal to the legal size (i.e., 2.55 m).

LMM results indicate that the CoG of cars were closer to the right side of the lane and the tunnel wall than truck drivers, even in the presence of jet fans with narrower lanes of Layout 1 (Fig. 6a). This behaviour is explained by the vantage point of car drivers being lower than the jet fans (installed at a height of 75 cm), which is why car drivers kept their trajectory closer to the lateral hard obstacles (i.e., jet fans and tunnel wall), as confirmed by the effect plot of Fig. 6b. Conversely, the truck driver's viewpoint was at the same elevation as the jet fans, so they had to maintain the vehicle centred in the lane to remain equidistant from fixed hazardous installations and oncoming traffic. However, Layout 1 influenced driver behaviour with a statistically significant lateral change behaviour with respect to the current layout (Layout 0) as indicated in Fig. 6b. This experiment confirms that truck drivers performed better than car drivers in adopting compensatory strategies to limit the risk of collision. Their higher level of driving proficiency allowed them to maintain better lateral control confirming what Chen et al. (2021) observed with mid–aged and old professional and non-professional drivers. In this study, truck drivers demonstrated an excellent ability to control the lateral position of the vehicle. Therefore, based on this result, the first hypothesis regarding the negative effects of jet fans in the tunnel wall is rejected. Finally, the presence of oncoming traffic also proved to be a significant factor in the lateral control of participants in the study, with drivers moving laterally towards the tunnel wall to avoid a possible head-on collision with the opposite vehicle in both section layouts (Fig. 6c).

Based on model results (Table 4), the new layout caused a statistically significant reduction in *SDLP*. Therefore, higher and more precise levels of lateral control were observed in the layout with narrower lanes and median and in the presence of jet fans (Fig. 7a). The presence of hard lateral obstacles on the two sides and narrower lanes brings the driver's attention back to the driving task, increasing the control capability with lower *SDLP* (Mecheri et al., 2017). Increased driving focus may also be the reason why significantly lower *SDLP* values were found in the presence of oncoming traffic (Fig. 7b). This result indicates that riskier driving situations induce drivers to exercise greater lateral control similar to the way they do in other hazardous driving scenarios such as driving in foggy conditions (Saffarian et al., 2012).

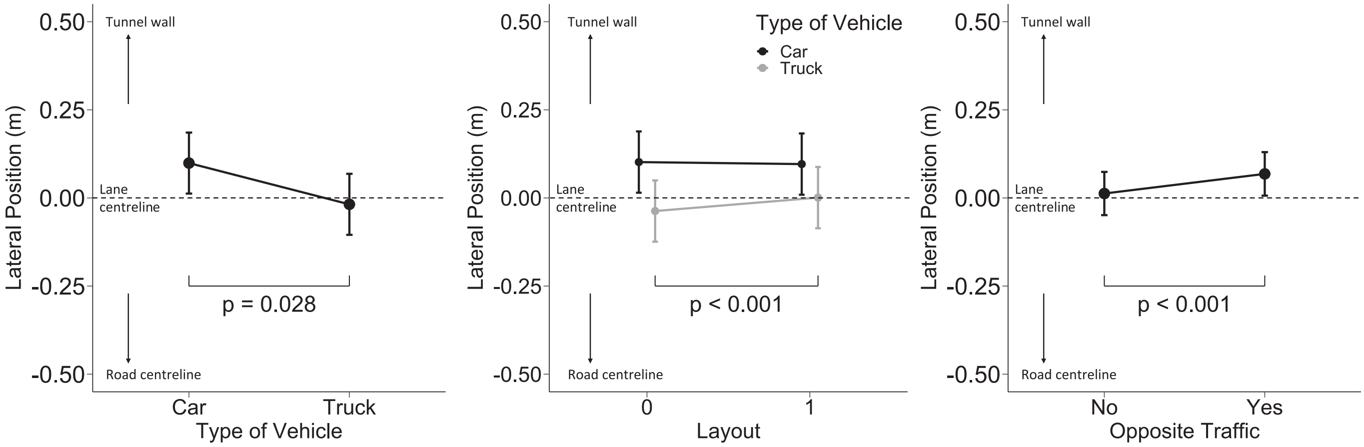
3.2. Analysis 2 – Effect of the lighting conditions

Table 5 summarizes the results of the second analysis, where we evaluated the effect(s) of the different light intensities in the new tunnel layout on driver behaviour. Again, gender was not considered as an experimental factor. Average passenger car speeds were slightly higher than those for heavy vehicles. The influence of independent factors on driving behavioural outcomes is explored in the following sections.

3.2.1. LMMs estimations

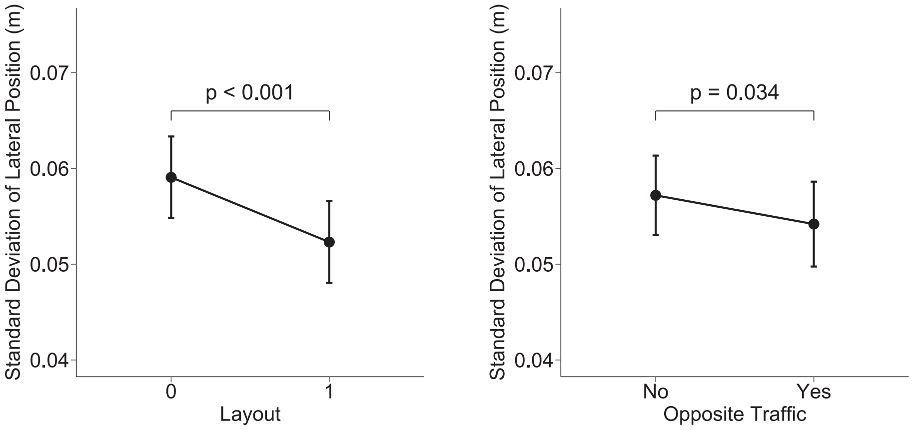
Speed, lateral position and standard deviation of lateral position were dependent variables in the LMM, with the light intensity (*li*), the presence (*ot* = yes) and the absence (*ot* = no) of opposing traffic (*ot*) and the vehicle type (car vs. truck) included as fixed effects, while the test driver ID was included as a random effect.

As reported in Table 6, both fixed and random factors accounted for circa 70 % of the speed variance in the LMM, albeit only 3 % of this was



(a) (b) (c)

Fig. 6. Effect plots for lateral position in Analysis 1: influence of (a) the type of vehicle, (b) the type of vehicle in interaction with the layout, and (c) the oncoming traffic (Notes: positive values of *LP* indicate the vehicle CoG on the right side of the lane, near the tunnel wall).



(a) (b)

Fig. 7. Effect plots for standard deviation of lateral position in Analysis 1: influence of (a) the layout and (b) the opposing traffic.

attributable to fixed effects. Also in Analysis 2, the strong significance of the subjective driver trait on speed is highlighted by the high value of ICC and the strong significance of the LRT test. Light intensity in interaction with vehicle type influenced the longitudinal behaviour of drivers. Post–hoc tests with Bonferroni corrections showed that truck drivers reduced their speed under low light intensity (for heavy vehicles, $S_{li=2} - S_{li=1}$ = -0.58 km/h, t_{3318} = -3.627, p = 0.001), when jet fans were less visible, while car drivers were not affected by the different light intensity (for cars, $S_{li=2} - S_{li=1}$ = 0.14 km/h, t_{3318} = 0.891, p = 1.000). The passage of oncoming vehicles in front of jet fans did not affect speeds.

The significant factors in the LMM explained around 49 % of the variance in lateral position, with random effects making a significant contribution (92 % of the total variance is explained by the model). The magnitude of the effect of light intensity on the transversal behaviour of drivers depended on the type of vehicle. Passenger car drivers maintained a lateral position closer to the jet fans when these were clearly visible, as demonstrated by post-hoc tests with Bonferroni correction (for cars, $LP_{li=2} - LP_{li=1}$ = -0.051 m, t_{3317} = -5.862, p < 0.001). This did not

Table 5
Descriptive statistics of the outcomes of Analysis 2 (mean and standard deviation between brackets).

Light intensity	Opposite traffic	Vehicle type	*S* (km/h)	*LP* (m)	*SDLP* (m)
High	No	Car	70.42 (5.60)	0.070 (0.261)	0.056 (0.037)
		Truck	69.04 (6.21)	−0.031 (0.248)	0.051 (0.035)
	Yes	Car	70.24 (5.98)	0.120 (0.248)	0.053 (0.035)
		Truck	68.87 (6.22)	0.036 (0.241)	0.051 (0.033)
Low	No	Car	70.55 (5.45)	0.020 (0.235)	0.060 (0.040)
		Truck	68.45 (6.99)	−0.038 (0.232)	0.054 (0.039)
	Yes	Car	70.42 (5.41)	0.068 (0.235)	0.058 (0.037)
		Truck	68.32 (7.24)	0.008 (0.220)	0.056 (0.039)

Table 6
Significant factors and summary statistics of LMM for Analysis 2.

Variables	Effect	Estimate (significance)		
		S **(km/h)**	***LP*** **(m)**	***SDLP*** **(m)**
Fixed Effects *(main factors and interactions)*				
Intercept		70.3611 (***)	0.0693 (.)	0.0528 (***)
Light intensity (*li*)	Low – High	0.1413 (–)	−0.0509 (***)	0.0042 (***)
Oncoming traffic (*ot*)	Yes – No	–	0.0526 (***)	–
Type of vehicle	Truck – Car	−1.3798 (–)	−0.0951 (.)	–
Type of vehicle * Light intensity	(Truck – Car) * (Low – High)	−0.7163 (**)	0.0366 (**)	–
Random effects				
Participant ID – LRT test		(***)	(***)	(***)
Summary statistics				
AIC		17678.688	−1846.596	−12721.882
BIC		17715.406	−1803.759	−12697.403
Log- Likelihood		−8833.344	930.298	6364.941
Marginal R^2		0.020	0.039	0.003
Conditional R^2		0.736	0.489	0.067
ICC for random components		0.730	0.469	0.064
Observations		3360		
Drivers		40		
Observations/driver		84		

Notes. "." for $p < 0.1$, "*" for $p < 0.05$, "**" for $p < 0.01$, and "***" for $p < 0.001$, symbol "-" means not statistically significant at a significance level of 0.05.

happen with truck drivers (for trucks, $LP_{li=2} - LP_{li=1}$ = -0.014 m, $t_{3317} = -1.650$, $p = 0.396$). In the presence of oncoming traffic, drivers drove more on the right side of the lane, near the tunnel wall ($LP_{ot=yes} - LP_{ot=no} = 0.053$ m, $t_{3317} = 8.066$, $p = 0.003$).

Finally, only 6.7 % of the variance is explained by the LMM for *SDLP*, highlighting the significance of random effects with the low marginal R^2. According to the coefficients estimates, in conditions of high light intensity the lateral control capability of drivers improved, i.e., lower *SDLP* ($SDLP_{li=2} - SDLP_{li=1} = 0.004$ m, $t_{3319} = 3.406$, $p < 0.001$).

3.2.2. Discussion

The objective of the second analysis was to evaluate the effect of different light intensities in the tunnel at the points where jet fans were installed. Therefore, Layout 1 was considered, in the first version promoting a photopic vision with clearly visible jet fans and in the second inducing a scotopic vision to mask them.

An analysis of the longitudinal behaviour of drivers revealed that truck drivers tended to reduce their speed under scotopic vision (Scenario 2, low light intensity, Fig. 8). The low-intensity lighting may trigger a sense of danger in drivers, who consequently react by reducing their speed. The professional experience of truck drivers makes them more familiar with driving along different types of tunnels, and hence able to recognize dangerous situations. Car drivers, in contrast, did not adjust their speed in conditions of low-intensity lighting.

On examination of the LMM outcomes, the effect of the different light intensities on lateral driver performance is also evident. Analyses show that drivers drove closer to the tunnel wall and the jet fans in conditions of high-intensity illumination. Thus, the experimental hypothesis for light intensity is rejected. If drivers are not able to clearly perceive the obstacle, as in the case of low light intensity, the presence of the obstacle induces the driver to move toward the left, as a risk compensation reaction (Wilde, 1982; Wilde, 1998).

We also observed that car drivers tended to travel more to the left side of the lane in the presence of low-intensity illumination (Fig. 9a), a behaviour not adopted by truck drivers. As assumed in the first experiment, the different results for cars and trucks in terms of lateral performance can also be explained by the difference in their relative sizes.

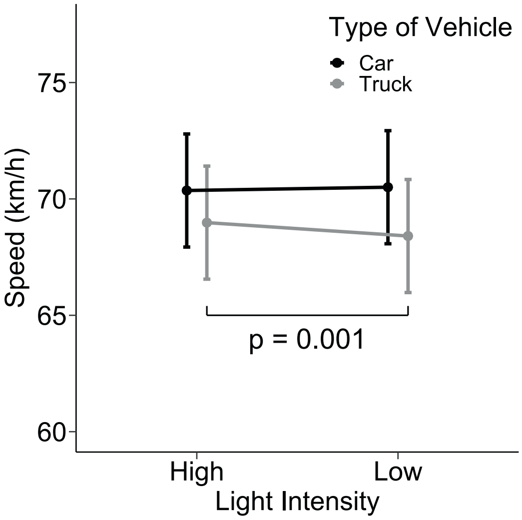


Fig. 8. Effect plot for speed in Analysis 2: influence of the light intensity in interaction with the type of vehicle (High light intensity = Scenario 1, Low light intensity = Scenario 2).

The lateral gauge of the car is smaller than that of the heavy vehicle, allowing them more lateral movement within the lane. Finally, Fig. 9b shows that in the presence of oncoming traffic, drivers moved toward the wall to avoid the risk of a head-on collision with oncoming vehicles.

It is known that different light intensities in tunnels can lead to different visual loads for drivers, thus altering their driving performances (He et al., 2017). We observed that the high-intensity illumination led to a better lateral control capability as clearly indicated in Fig. 10. This confirms what Zang et al. (2023) stated about the effects of light intensity on driver behaviour.

4. Final remarks and conclusions

In this section, the final remarks and conclusions are presented, highlighting the impact of various factors on driver behaviour in a tunnel environment. The effects of tunnel layout type and degree of light intensity on driver speed, behaviour and lateral control were evaluated, providing valuable insights into the measures needed to enhance tunnel safety. The key findings obtained from the analyses are as follows:

- a new tunnel layout with narrower lanes and median widths and the presence of jet fans, led to a statistically albeit not practically significant reduction in driver speed. In addition, drivers exhibited a tendency to reduce speed in response to the presence of lateral obstacles, such as oncoming vehicles;
- car drivers exhibited more lateral movement within the lane than truck drivers and their trajectories were closer to the tunnel wall, perhaps due to the smaller size of their vehicles; however, truck drivers demonstrated better lateral control (i.e., low values of SDLP), probably due to their higher level of driving proficiency together with a better field of vision along the tunnel;
- the sight of an obstacle on the side (e.g., jet fans and oncoming vehicles) helped to bring the driver's attention back to the driving task, increasing the control capability;
- light intensity played a significant role in driver behaviour, affecting both longitudinal and lateral performance;
- low light intensity resulted in reduced speed among truck drivers, likely due to a heightened sense of danger;
- high-intensity illumination influenced both driver lateral behaviour and positioning; drivers tended to move their vehicles closer to the tunnel walls under high-intensity lighting conditions, suggesting that increased visibility prompts drivers to maintain a closer proximity to fixed obstacles in the tunnel environment;
- the increased visibility provided by high-intensity lighting enhanced the driver's lateral control capability, resulting in more precise and stable vehicle positioning within the lane.

In conclusion, this study has provided insights into the impact of various factors on driver behaviour in a tunnel environment. The findings have demonstrated how driver speed and lateral control are influenced by both the installation of jet fans on tunnel walls and the adoption of two different light intensities to mask or highlight their presence.

When evaluated as a whole, the results indicate excellent driver adaptation to the new layout with jet fans installed along the tunnel wall. The new layout resulted in a slight reduction in speeds, due to the increased proximity to both fixed installations and oncoming traffic. Meanwhile, the new layout did not adversely affect the lateral behaviour of truck drivers, who showed greater control to compensate for the reduced space available. The second analysis also evaluated the effect of a different tunnel lighting strategy. When jet fans are highlighted by interior light, truck drivers showed better lateral control by driving closer to the tunnel wall. In general, lower light intensity resulted in a slight decrease in drivers' lateral behaviour and negligible changes in speed.

The results obtained here can be transferred to the real world thanks

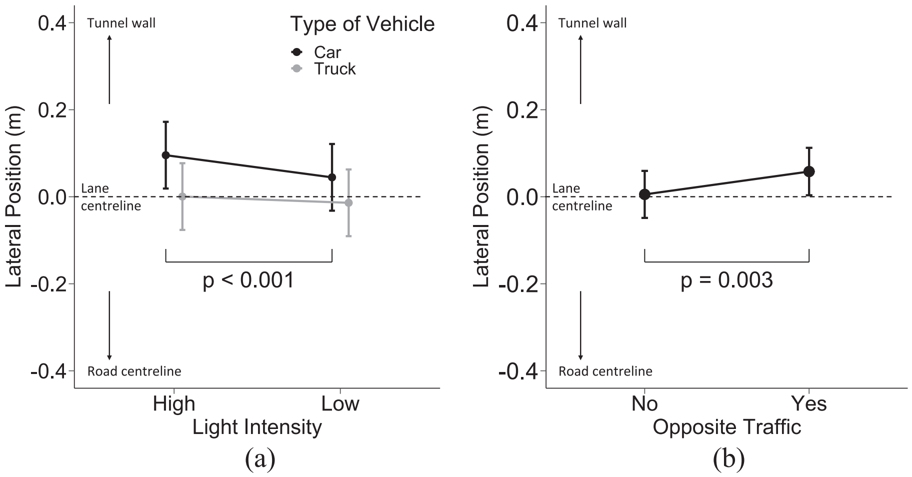


Fig. 9. Effect plots for lateral position in Analysis 2: influence of (a) the type of vehicle in interaction with the light intensity and (b) the opposite traffic (Notes: positive values of *LP* indicate the vehicle CoG on the right side of the lane, near the tunnel wall).

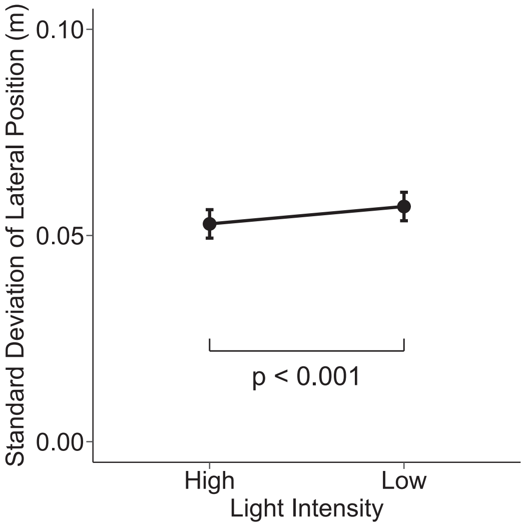


Fig. 10. Effect plot for standard deviation of lateral position in Analysis 2: influence of the light intensity (High light intensity = Scenario 1, Low light intensity = Scenario 2).

to the validation experiment which preceded the study (Lioi et al., 2023). While absolute validity was achieved for certain variables, relative validity was also observed for others. Given that the driving simulator utilized the same tunnel layout as that in real-world conditions, the relative validity of the observed behaviours can be considered sufficient to allow the findings to be generalized. Therefore, we expect that the trends and influences of the independent factors investigated in this experiment will most likely be reproduced in the corresponding values achieved in real driving conditions.

Driving simulation software struggles to replicate the light intensity and luminance of real road environments. However, in our validation study (Lioi et al., 2023), we confirmed both relative and absolute validity for vehicle speed and lateral position under high light intensity in a simulated tunnel environment, parallel to real conditions in the Fréjus tunnel. Driving behaviour changed at lower light intensities, which suggests that driver behaviour is also affected by changes in light levels. However, the limitation of the study lies in its single lighting condition. Nevertheless, previous validations (Bassani et al., 2018; Catani & Bassani, 2019) under daylight conditions support the simulator's ability to reproduce driving behaviour under different lighting scenarios, although further research is needed for comprehensive validation.

Other limitations of this work should be acknowledged. The analysis focused on a specific tunnel layout and lighting conditions, limiting the scope to generalize our findings across other tunnel configurations. Additionally, while efforts were made to minimize confounding factors, there may still be variables unaccounted for such as individual driver characteristics, psychological factors, and sensory cues (e.g., noise and air quality) that could have influenced driver behaviour. LMMs are robust statistical tools but have limitations, including the assumption of normal residuals, the need for large sample sizes to estimate parameters accurately, and high computational demands, especially for large datasets.

It is also worth noting that only male truck drivers were involved in the study, a fact that impacts on our ability to generalise our findings to both women and men truck drivers. Future research should consider a wider range of tunnel configurations, lighting conditions, and driving scenarios to deepen our understanding of driver behaviour in tunnels. Despite these limitations, the findings of this study provide valuable knowledge that could be used for improvements in design, lighting strategies, and safety in tunnel environments.

In reviewing the results of the study, it is clear that the geometry of a tunnel, including its width and the introduction of jet fans, has a significant impact on driver behaviour. In particular, the presence of jet fans along the tunnel walls resulted in reduced speeds and changed lateral distances to the tunnel walls for both car and truck drivers, improving lateral control. These changes highlight the critical role of tunnel design in ensuring driver safety. By carefully considering tunnel geometry and layout, including the strategic placement of jet fans and varying lighting conditions, engineers and policy makers can effectively mitigate potential risks and promote a safer driving environment in tunnels.

Funding

This research received funds from GEIE-GEF, the French-Italian public company that manages the Fréjus tunnel. A special thanks goes to all participants who supported us without any compensation. All activities were carried out in the Laboratory of Road Safety and Driving Simulation (RSDS Lab) at the Department of Environment, Land and Infrastructure Engineering (Politecnico di Torino).

CRediT authorship contribution statement

A. Lioi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **A. Portera:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **A. Hazoor:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **L. Tefa:** Writing – review & editing, Writing – original draft, Methodology. **A. Karimi:** Writing – review & editing, Writing – original draft, Methodology. **M. Bassani:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Aashto, 2018. A Policy on Geometric Design of Highways and Streets, 7th Edition. American Association of State Highway, and Transportation Officials, Washington, D.C.

Amundsen, F.H., 1994. Studies of driver behaviour in Norwegian road tunnels. Tunn. Undergr. Space Technol. 9 (1), 9–15. https://doi.org/10.1016/0886-7798(94)90004-3.

Barbato, L., Cascetta, F., Musto, M., Rotondo, G., 2014. Fire safety investigation for road tunnel ventilation systems–an overview. Tunn. Undergr. Space Technol. 43, 253–265. https://doi.org/10.1016/j.tust.2014.05.012.

Bassan, S., 2016. Overview of traffic safety aspects and design in road tunnels. IATSS Research 40 (1), 35–46. https://doi.org/10.1016/j.iatssr.2016.02.002.

Bassani, M., Catani, L., Ignazzi, A., & Piras, M. (2018). Validation of a fixed-base driving simulator to assess behavioural effects of road geometrics. In: Driving Simulation Conference Europe 2018 VR, Antibes, 2018.

Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67 (1), 1–48. https://doi.org/10.18637/jss.v067.i01.

Boyce, P.R., 2008. Lighting for driving: roads, vehicles, signs, and signals. CRC Press.

Caliendo, C., De Guglielmo, M.L., 2012. Accident rates in road tunnels and social cost evaluation. Procedia Soc. Behav. Sci. 53, 166–177. https://doi.org/10.1016/j.sbspro.2012.09.870.

Caliendo, C., De Guglielmo, M.L., Guida, M., 2013. A crash-prediction model for road tunnels. Accid. Anal. Prev. 55, 107–115. https://doi.org/10.1016/j.aap.2013.02.024.

Calvi, A., & D'Amico, F. (2013). A study of the effects of road tunnel on driver behavior and road safety using driving simulator. *Advances in Transportation Studies*, (30).

Calvi, A., De Blasiis, M.R., Guattari, C., 2012. An empirical study of the effects of road tunnel on driving *performance*. Procedia Soc. Behav. Sci. 53, 1098–1108. https://doi.org/10.1016/j.sbspro.2012.09.959.

Catani, L., Bassani, M. (2019). Anticipatory distance, curvature, and curvature change rate in compound curve negotiation: a comparison between real and simulated driving. In: 98th TRB Annual Meeting, Washington DC, 2019.

Chen, T., Sze, N.N., Newnam, S., Bai, L., 2021. Effectiveness of the compensatory strategy adopted by older drivers: Difference between professional and non-professional drivers. Transport. Res. F: Traffic Psychol. Behav. 77, 168–180. https://doi.org/10.1016/j.trf.2021.01.006.

Commission Internationale de l'Éclairage (2004). *Guide for the lighting of road tunnels and underpasses*. CIE Publ. 88, Vienna.

Domenichini, L., La Torre, F., Vangi, D., Virga, A., Branzi, V., 2017. Influence of the lighting system on the driver's behavior in road tunnels: A driving simulator study. J. Transp. Safety Security 9 (2), 216–238. https://doi.org/10.1080/19439962.2016.1173155.

Ente Nazionale Italiano di Normazione (2011). *Illuminazione delle Gallerie Stradali* (in Italian), UNI 11095:2011.

EU Directive 2004/54/EC (2004). *Minimum safety requirements for tunnels in the Trans-European Road Network*. Official Journal of the European Union (29th April 2004).

Godley, S.T., Triggs, T.J., Fildes, B.N., 2004. Perceptual lane width, wide perceptual road centre markings and driving speeds. Ergonomics 47 (3), 237–256. https://doi.org/10.1080/00140130310001629711.

He, S., Liang, B., Pan, G., Wang, F., Cui, L., 2017. Influence of dynamic highway tunnel lighting environment on driving safety based on eye movement parameters of the driver. Tunn. Undergr. Space Technol. 67, 52–60. https://doi.org/10.1016/j.tust.2017.04.020.

Hirata, T. (2006). Traffic safety analysis in underground urban expressway using driving simulation system MOVIC-T4 (No. 06-2184).

Kircher, K., Ahlstrom, C., 2012. The impact of tunnel design and lighting on the performance of attentive and visually distracted drivers. Accid. Anal. Prev. 47, 153–161. https://doi.org/10.1016/j.aap.2012.01.019.

Kirytopoulos, K., Kazaras, K., Papapavlou, P., Ntzeremes, P., Tatsiopoulos, I., 2017. Exploring driving habits and safety critical behavioural intentions among road tunnel users: A questionnaire survey in Greece. Tunn. Undergr. Space Technol. 63, 244–251. https://doi.org/10.1016/j.tust.2016.12.002.

Lamm, R., Choueiri, E.M., Mailaender, T., 1990. Comparison of operating speeds on dry and wet pavements of two-lane rural highways. Transp. Res. Rec. 1280 (8), 199–207.

Lemke, K., 2000. Road safety in tunnels. Transp. Res. Rec. 1740 (1), 170–174. https://doi.org/10.3141/1740-22.

Lenth R. (2023)._emmeans: Estimated Marginal Means, aka Least-Squares Means_. R package version 1.8.4-1. https://CRAN.R-project.org/package=emmeans.

Lioi, A., Portera, A., Tefa, L., Hazoor, A., Bassani, M., 2023. Validation of a Driving Simulator for Road Tunnel Behavioural Studies. Transp. Res. Procedia 69, 352–359. https://doi.org/10.1016/j.trpro.2023.02.182.

Liu, S., Wang, J., Fu, T., 2016. Effects of lane width, lane position and edge shoulder width on driving behavior in underground urban expressways: a driving simulator study. Int. J. Environ. Res. Public Health 13 (10), 1010. https://doi.org/10.3390/ijerph13101010.

Ma, Z., Steven, I., Chien, J., Dong, C., Hu, D., Xu, T., 2016. Exploring factors affecting injury severity of crashes in freeway tunnels. Tunn. Undergr. Space Technol. 59, 100–104. https://doi.org/10.1016/j.tust.2016.06.013.

Maevski, I., 2017. Guidelines for emergency ventilation smoke control in roadway tunnels. NCHRP Research Report, 836, 1–81.

Makuto, N., Kristman, V., Bigelow, P., Bedard, M., 2023. Factors associated with depressive symptoms in long-haul truck drivers. Transp. Res. Interdisciplinary Perspectives 21, 100851. https://doi.org/10.1016/j.trip.2023.100851.

Manser, M.P., Hancock, P.A., 2007. The influence of perceptual speed regulation on speed perception, choice, and control: Tunnel wall characteristics and influences. Accid. Anal. Prev. 39 (1), 69–78. https://doi.org/10.1016/j.aap.2006.06.005.

Mecheri, S., Rosey, F., Lobjois, R., 2017. The effects of lane width, shoulder width, and road cross-sectional reallocation on drivers' behavioral adaptations. Accid. Anal. Prev. 104, 65–73. https://doi.org/10.1016/j.aap.2017.04.019.

Ministero delle Infrastrutture e dei Trasporti (2001). *Norme funzionali e geometriche per la costruzione delle strade* (in Italian). D.M. no. 6792 of November 5th.

Mussone, L., 2023. Assessing the effects of road geometry and fidelity on driver behaviour in driving simulator experiments. Transp. Res. Interdisciplinary Perspectives 20, 100835. https://doi.org/10.1016/j.trip.2023.100835.

Peña-García, A., 2018. The impact of lighting on drivers well-being and safety in very long underground roads: New challenges for new infrastructures. Tunn. Undergr. Space Technol. 80, 38–43. https://doi.org/10.1016/j.tust.2018.06.005.

PIARC (2008). *Human factors and road tunnel safety regarding users*. PIARC Technical Committee C3.3, Road Tunnel Operation, Report R17, Paris.

Qin, X., Zhang, N., Zhang, W., Meitner, M., 2020. How does tunnel interior color environment influence driving behavior? Quantitative analysis and assessment experiment. Tunn. Undergr. Space Technol. 98, 103320 https://doi.org/10.1016/j.tust.2020.103320.

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Reed, D.B., Cronin, J.S., 2003. Health on the road: issues faced by female truck drivers. AAOHN J. 51 (3), 120–125. https://doi.org/10.1177/216507990305100305.

Saffarian, M., Happee, R., Winter, J.D., 2012. Why do drivers maintain short headways in fog? A driving-simulator study evaluating feeling of risk and lateral control during automated and manual car following. Ergonomics 55 (9), 971–985. https://doi.org/10.1080/00140139.2012.691993.

Salvisberg, U., Allenbach, R., Cavegn, M., Hubacher, M., & Siegrist, S. (2004). *Verkehrssicherheit in Autobahn-und Autostrassentunneln des Nationalstrassennetzes* (No. 51).

Shimojo, A., Takagi, H., & Onuma, H. (1995, July). A simulation study of driving performance in long tunnel. *In Pacific Rim TransTech Conference. 1995 Vehicle Navigation and Information Systems Conference Proceedings. 6th International VNIS. A Ride into the Future* (pp. 96-103). IEEE. 10.1109/VNIS.1995.518824.

Törnros, J., 1998. Driving behaviour in a real and a simulated road tunnel—a validation study. Accid. Anal. Prev. 30 (4), 497–503. https://doi.org/10.1016/S0001-4575(97)00099-7.

Viikari, M., Ekrias, A., Eloholma, M., Halonen, L., 2008. Modeling spectral sensitivity at low light levels based on mesopic visual performance. Clin. Ophthalmol. 2 (1), 173–185. https://doi.org/10.2147/opth.s2414.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York.

Wilde, G.J., 1982. The theory of risk homeostasis: implications for safety and health. Risk Anal. 2 (4), 209–225. https://doi.org/10.1111/j.1539-6924.1982.tb01384.x.

Wilde, G.J., 1998. Risk homeostasis theory: an overview. Inj. Prev. 4 (2), 89–91. https://doi.org/10.1136/ip.4.2.89.

World Medical Association, 2018. WMA Declaration of Helsinki–Ethical Principles for Medical Research Involving Human Subjects, 9 July 2018. https://www.wma.net/what-we-do/medical-ethics/declaration-of-helsinki/.

Yeung, J.S., Wong, Y.D., Xu, H., 2013. Driver perspectives of open and tunnel expressways. J. Environ. Psychol. 36, 248–256. https://doi.org/10.1016/j.jenvp.2013.09.002.

Zang, Y., Yan, Z., Wu, H., Gan, P., Hu, M., Wu, W., Liu, P., He, G., Xiao, J., 2023. An evaluation of the effect of urban tunnel lighting on driving comfort: a driving simulation study. In: International Conference on Green Intelligent Transportation System and Safety. Springer, Singapore, pp. 481–492.