Longitudinal and Transversal Driver Behaviour with Innovative Horizontal Markings Along Curved Motorway On Ramps and Terminals

Longitudinal and Transversal Driver Behaviour with Innovative Horizontal Markings Along Curved Motorway On-Ramps and Terminals

Marco Bassani [1] (*)
(*) = corresponding author
marco.bassani@polito.it
ORCID: 0000-0003-2560-1497

Alberto Portera [1]
alberto.portera@polito.it
ORCID: 0000-0002-6685-4805
https://it.linkedin.com/in/alberto-portera-75a40367

Giorgia Raimondo [1]
giorgia.raimondo@studenti.polito.it
https://it.linkedin.com/in/giorgia-raimondo-484291197

[1] Department of Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino
24, corso Duca degli Abruzzi, Torino, 10129 - Italy.

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ABSTRACT

The manuscript presents a driving simulation study on the effectiveness of two innovative horizontal marking designs (in comparison with the conventional marking) along acceleration ramps and reverse and continue terminals on curved motorway sections. Longitudinal and transversal behavioural data were collected from forty-eight test drivers in response to variations in marking type, lighting conditions, and traffic-flow along the motorway. Although the innovative markings did not have a significant impact on speeds along continue terminals, they did have an impact on the lane gap and the standard deviation of lateral positions. Along the reverse terminal design type, their impact was evident on all the investigated longitudinal and transversal outcomes. This study proved that the perceptual techniques used by drivers engaged in speed and trajectory management along curved terminals are effective in promoting better driving performances.

KEYWORDS: On-ramp terminal, clothoid, driver behaviour, driving simulation, horizontal markings.

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1 INTRODUCTION

Horizontal road markings delimit spaces for the different categories of traffic and promote traffic alignment by obliging road users to follow orderly and common trajectories. They facilitate adherence to the traffic rules and serve to guarantee safe and comfortable conditions for road users (Babić et al., 2020). The markings placed on the road surface are in the form of stripes, symbols, and numbers which serve to convey information to road users. To avoid any confusion, markings must be recognizable and interpretable. For these reasons, road markings are standardized according to national highway codes.

However, ordinary markings may prove ineffectual in situations where the driver is forced to accelerate or decelerate over short distances, or when the driver has to deal with complex road geometries, such as on entry and exit ramp-terminals (Calvi & De Blasiis, 2011; Kondyli & Elefteriadou, 2012). The literature evidences that the ramp-terminal geometry (i.e., type, shape, width, and length) has a significant impact on the operational and safety performance of these facilities (Ahammed et al., 2008, Gu et al., 2019; Reinolsmann et al., 2019). Greater difficulties in trajectory control arise when ramps are connected to curved sections of the motorway, where the connection to the motorway is through road sections with continuously variable curvature (Bassani & Portera, 2020, Portera and Bassani, 2021).

In situations where they have to make significant changes to speed and/or trajectory, drivers may make inappropriate decisions and, consequently, make mistakes (Bassani & Portera, 2020). In such circumstances, drivers should be encouraged to adopt adequate longitudinal and transversal behaviour. In this context, innovative solutions can increase driver awareness when making decisions, and help to ensure adequate safety conditions.

Denton (1980) and Godley et al. (1999) observed that innovative horizontal markings act as perceptive countermeasures which can induce changes in driver behaviour. Innovative markings have been tested and used to reduce the speed at tangents (Ariën et al., 2017), curves (Charlton, 2007; Ariën et al., 2017, Awan et al., 2019; Babić and Brijs, 2021), and transition zones (Hussain et al., 2021). The markings lead to a reduction in speed since they provide drivers with an enhanced perception of their speed. They are used to transmit useful information to drivers which allow them to discriminate between the different road types and, consequently, to select the most appropriate speed (Charlton, et al., 2010).

Not only can horizontal markings influence the perception of speed, but they can also influence the perception of the narrowness of the road through perceptual processing (Montella, et al., 2011). The perceived reduction in the lane width results from the painting of strips on the road surface (Godley, et al., 2004) or by delimiting the width available with shoulder rumble strips (Zaidel, et al., 1986). Perceptual countermeasures are designed to make drivers think that they are travelling at higher speeds than they are. This perception of increased speed leads to a greater sense of danger (perception of risk) and, thereby, encourages the driver to drive more prudently (Fildes, et al., 1993) following the so-called principle of risk homeostasis (Wilde, 1998). These perceptual techniques are already used in other contexts, such as in playrooms and amusement parks, where lights which, initially, flash at a constant frequency, then begin to flash at an accelerated pace, which serves to heighten the sense of movement (Meyer, 2001).

In 1975, Rutley suggested that the perception of speed is based on the rapidity with which objects placed on the side of the road move in the peripheral field of vision. It follows that if the road markings were progressively spaced out along the road, motorists would get a sense of acceleration that they would compensate for by slowing down. In addition to acting on the perception of speed, markings can also act on driver perception of the available lane space ahead within which to manoeuvre the vehicle, and lead to changes in the trajectory of the driven vehicle.

While innovative horizontal markings have been examined for several road components such us intersections, tangents, curves and deceleration ramps (Denton 1980; Godley, et al. 1999; Charlton, 2007; Montella, et al., 2011; Charlton, et al., 2017; Godley, et al., 2004), there are no studies relative to the introduction of these facilities to accelerating transitions zones, such as motorway on-ramps.

On the merging ramp terminals, the driver makes a drastic adjustment to his speed in line with new geometric and operational conditions. On curved on-ramp-terminals, the driver has to manage the vehicle speed when joining the motorway and must also maintain control of the vehicle when changing trajectory. In these sections, entry manoeuvres demand greater control to avoid collisions with fixed installations and other vehicles in the surroundings.

Two different innovative horizontal markings and an ordinary design (i.e., the experimental control condition) were investigated. The research hypothesis was that innovative markings increase the perception of speed and restrict the width of the available road space, both of which may encourage the driver to make better speed decisions (i.e., consistent with the design hypothesis) and maintain superior lateral control of the vehicle.

The data were collected on curved on-ramp-terminals. The experiment was carried out at the fixed-base driving simulator at the Road Safety and Driving Simulation Lab of the Politecnico di Torino. The behaviour of forty-eight licensed participants was evaluated for the three different horizontal markings, two traffic flows (1000 pc/h and 3000 pc/h), and two lighting conditions (day and night). In addition, simulations included driving on two different curved on-ramp terminals, one continue ramp-terminal and one reverse ramp-terminal.

2 METHOD

2.1 Setting

The fixed-base driving simulator (AV Simulation, France) was relatively validated for speed (Catani, 2019, Bassani et al., 2018) and lateral behaviour (Catani & Bassani, 2019). The vision system was made up of three 32-inch full HD covering approximately 130° of the driver field of view. SCANeRStudio™ (AV Simulation, France) was used to design tracks, manage the vehicle parameters, generate the experimental scenarios, run the simulations, collect and extract data.

2.2 Design of road scenarios and horizontal markings

Twelve circuits including direct ramps to connect two-lane rural highways to motorway segments were designed to facilitate the performance of merging manoeuvres. Each circuit consisted of two curved motorway sections with an entry ramp located along each motorway. The first ramp had the same direction as the motorway curve, so a continue ramp-terminal was designed according to Figure 1a. A second ramp in the

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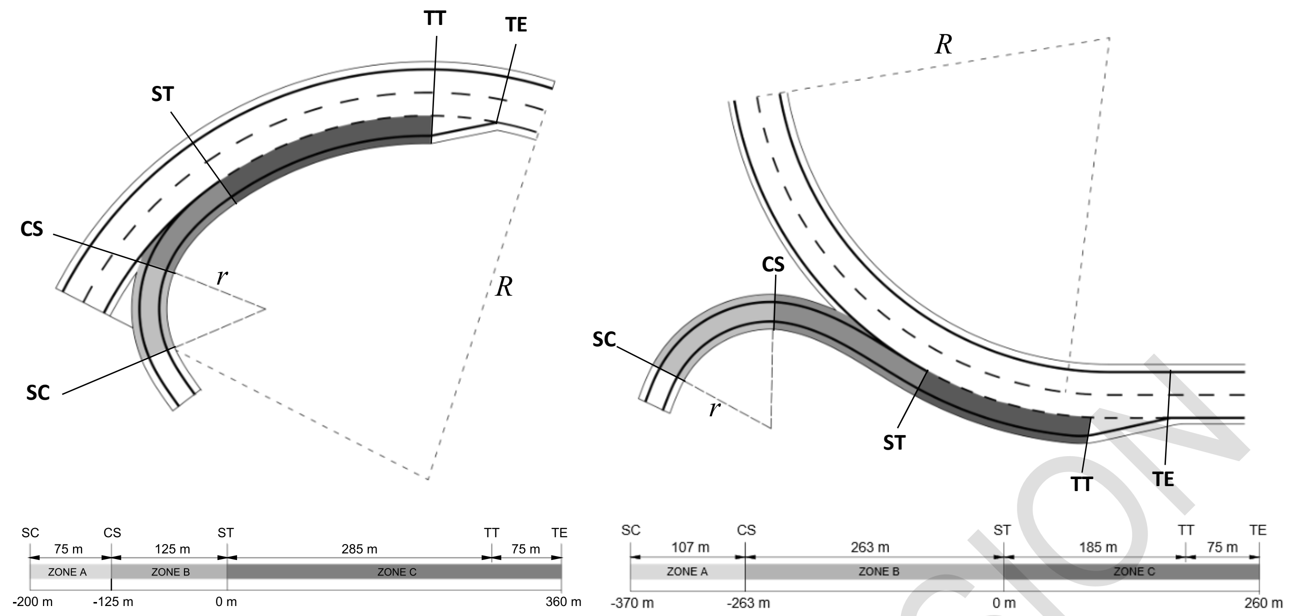
circuit had an opposite curvature to the motorway curve, so a reverse ramp-terminal design was adopted (Figure 1b). Ramps were designed in accordance with the Italian policy for intersection and interchanges (MIT, 2006), with terminal lengths designed according to the Highway Capacity Manual (TRB, 2016) for a level of service corresponding to B. The motorway cross-section presented two lanes per direction, with a lane width of 3.75 m and a right shoulder width of 3 m. According to the Italian Policy (MIT, 2006), the ramp had one 4 m wide lane and two 1.5 m wide shoulders.

Ramp terminals were located along curved sections. The radius of the motorway (R) was set equal to 964 m, which is the minimum radius for the maximum design speed for Italian motorways (140 km/h). The ramp radius was set to r = 150 m with a design speed of 60 km/h. In the case of the continue terminal (Figure 1a), the connection between terminal and ramp was an egg-shaped 125 m long clothoid, and the ramp terminal of 285 m long. In the reverse terminal (Figure 1b), the clothoid was a reverse S-shape design and was 263 m long, and the ramp terminal was 185 m long. The clothoid lengths are different because of their shape despite having the same scale factor (set equal to 150 m). The terminal lengths also differ so as to make it possible for drivers to reach the same design speed at the TT section (120 km/h) under the design acceleration of 1 m/s^2 according to the Italian standard (MIT, 2006). In both cases, the taper was set at a length of 75 m.

The three different horizontal markings were implemented along the entire length of the ramp-terminal system (Figure 2). Each ramp was divided into three zones (Figure 1). Zone A is the circular portion of the ramp which starts at the SC section (spiral-to-curve) and ends at the CS section (curve-to-spiral). Zone B covers the whole clothoid segment of the ramp from CS to ST (spiral-to-terminal). Zone C consists of the circular terminal from ST to TT (terminal-to-taper). The final taper ends 75 m after the TT section (i.e., the TE section). In each zone, the same marking was implemented albeit with different characteristics. In zones A and B, the markings were on both sides (i.e., shoulders) of the lane, while in zone C (i.e., the merging zone from terminal to the motorway through lane) they were only along the right side of the terminal. Conventional road markings, denominated HM1, were considered together with two unconventional horizontal markings HM2 and HM3 (Figure 2).



(a) (b)

Figure 1. Details on the design of non-conventional markings: Zone A circular ramp from SC to CS; Zone B continue clothoid ramp from CS to ST; Zone C circular terminal from ST to TT.

(a - HM2) (b - HM3)

Figure 2. Design details of non-conventional horizontal markings HM2 and HM3 in the three zones of a merging ramp: zone A, ramp with constant radius; zone B, ramp-terminal connection with variable radius; zone C, terminal with constant radius.

The unconventional horizontal markings (HM2 and HM3) proposed in this study were designed with reference to the solutions proposed in Ding et al. (2013). However, the designs of HM2 and HM3 were adapted to the experimental hypothesis as described in details in the following.

HM2 consists of thick bands which are spaced out along the lane. It is assumed that they impact on driver perception of the lane width. The hypothesis is that when the bands are thicker (i.e., the lane appears narrower), the driver exerts a higher degree of lateral vehicle control (i.e., he/she tends to drive closer to the lane centreline). As a secondary but nonetheless important effect, it is assumed that the driver still exerts a superior speed control in the presence of HM2 markings (compared to HM1) despite the sensation of a narrower lane ahead. HM2 marking was designed with bands of variable width in each of the three zones (Figure 2a).

HM3 consists of stripes of equal width but variable spacing, located beyond the lane edge. With this marking, the hypothesis is that it acts on driver speed perception in the peripheral sphere of vision. Despite travelling at a constant speed, the driver has the impression that he is slowing down when the spacing between consecutive stripes increases as the vehicle moves from the ramp to the terminal. This false perception may induce the driver to increase speed and merge onto the motorway at a speed close to that of the vehicles proceeding along the through lanes (i.e., consistent with the design standard hypothesis). For HM3, the spacing between bars was varied in the three zones (Figure 2b).

The second control variable in the experiment was the traffic flow (*TF*) in the motorway through lanes. Traffic-flows and volumes influence the behaviour of road-users, who regulate their speed and trajectory in accordance with the surrounding vehicle density, and the level of conflict in the road (HCM, 2010). Two traffic flows of 1000 and 3000 pc/h were simulated. The traffic was generated following a Gamma probability distribution function, with α (shape) and β (scale) parameters equal to 8.466 and 0.477 respectively for 1000 pc/h, and 3.057 and 0.650 respectively for 3000 pc/h. No traffic was generated along the ramps, i.e. the simulated vehicle was not conditioned by the passage of other vehicles along the ramp and the terminal.

Finally, driving operations were conducted in day-time (Figure 3a) and night-time conditions (Figure 3b). This variable can be decisive when it comes to the control of speed and trajectory, as reduced visibility can be an obstacle to the correct perception of the road geometry indicated by the horizontal markings. No traffic barriers were included in the road scenario (Figure 3) to prevent any behavioural effects that could impact observation data. Barriers alter the perception of safety (Ben-Bassat and Shinar, 2011) and result in a shorter available sight distance (Bassan, 2016), hence they produce effects that are difficult to identify and which are not among the variables of interest in the experiment. These assumptions have been made to ensure a satisfactory level of control in the experiment, and to avoid any additional secondary effects due to the inclusion of other factors in the experiment.

Combining the experimental factors (3 horizontal markings × 2 traffic conditions × 2 environmental lighting conditions), twelve different circuits were created with each one including a continue and a reverse ramp-terminal. Each participant drove on three randomly assigned circuits.

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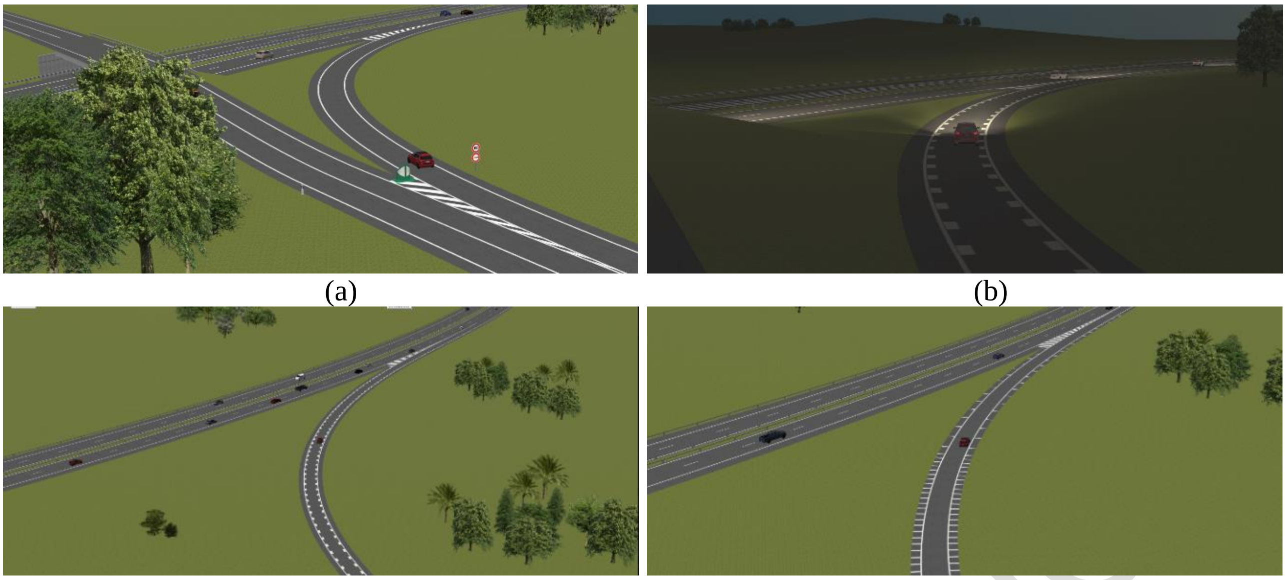

Figure 3. Examples of testing scenarios: (a) continue ramp-terminal daytime condition with HM1, (b) continue ramp-terminal night-time condition with HM2, (c) reverse ramp-terminal daytime condition with HM2, (d) reverse ramp-terminal daytime condition with HM3.

2.3 Participants

Forty-eight licensed drivers (27 males and 21 females) took part in the experiment voluntarily and without any compensation. All those taking part signed a consent form before the beginning of the experiments. The age of the selected drivers ranged from 18 to 64 years with a mean age of 41.4 years. Information on driving licenses on the website of the Ministry of Transport (MIT) was used to ensure that the group of drivers selected was representative of the Italian driver population. Detailed information pertaining to the test drivers' characteristics is provided in Table 1.

Table 1. Characteristics of participants (Mean = Mean value, Min = minimum value, Max = maximum value, SD = standard deviation).

Gender		Male	Female	Total
Participants (number)		27	21	48
Age (years)	Min	19	20	19
	Mean	42.2	41.6	41.4
	Max	61	57	61
Driving Experience [y]	Mean	22.8	22.1	22.5
	SD	13.3	11.6	12.8
Distance Travelled [km/y]	Mean	16,096	9,100	12,615
	SD	11,652	7,643	10,787
Crash Experience [#]	Mean	1.1	1.4	1.2
	SD	1.3	2.3	1.8

2.4 Experiment protocol and data collection

During the experimental phase, each test driver followed the following protocol: (i) completion of a pre-drive questionnaire; (ii) performance of pre-drive cognitive tests (visual and auditory); (iii) driving experience in three scenarios with two-minute rest intervals; (iv) performance of post-drive cognitive tests; and (v) completion of a post-drive questionnaire. The pre-drive questionnaire was used to determine the general health status of the drivers and also to establish whether they had consumed any food and/or substances prior to the experiment; the post-drive questionnaire was related to the virtual environment and the subjective judgment of the driving experience.

Cognitive tests were administered to check for any possible variation in cognitive performance before and after driving. The test was carried out on the available tool on http://cognitivefun.net/. Attentional response times to both visual (visual reaction test) and auditory stimuli (auditory reaction test) were recorded. Cognitive test results showed that the experiment did not induce any significant change(s) in attentional responses. This result was confirmed by the t-test carried out on, before and after data on the visual reaction time (t_{94}= -0.463, p =.64), and the auditory stimuli (t_{94} = 0.087, p = .93). This result confirms that driver performance remained constant during the experiment, and that drivers did not suffer from any excessive mental workload, which might have influenced their performance levels.

The driving task was divided into two sessions. In the first one, drivers drove along a simple urban road to gain familiarity with the simulator. The second session was the real simulation in which data were collected. The second session consisted of three driving scenarios with a rest time of two minutes between each scenario. Data on vehicle positions and driver actions on pedals and the steering wheel were collected at a frequency of 100 Hz. Output factors from driving included longitudinal speed (S), lateral position (LP) of the vehicle centre of gravity (CoG) from the road centreline, and standard deviation of lateral position (SDLP). Negative LP values indicate a CoG on the right side of the terminal lane centreline. SDLP describes the driver's ability to maintain control of the vehicle along a stretch of roadway. Low SDLP values indicate a good level of transversal vehicle control; as the SDLP value increases, the trajectory control capacity decreases. In the present case, this parameter was used to determine whether the markings influence on trajectory control (transversal behaviour).

Since each driver drove on three randomly assigned circuits, there were twelve data available for each output. The simulation outcome data were collected, validated, and processed to get an overview of driving performances and their variability on continue and reverse merging ramp-terminals with different horizontal markings, traffic-flows, and lighting conditions.

2.5 Data analysis and modelling

The Kolmogorov-Smirnov (KS) test for normality was performed on S and LP, with each set of data found to be always normally distributed.

Linear mixed-effect models (LMM) fit with a restricted maximum likelihood (REML) algorithm were calibrated to determine which factors conditioned the driver's longitudinal and transversal behaviour along the investigated road scenarios. LMM include both fixed and random effects and predict the degree to which the experimental outcomes depend on the variables (i.e., horizontal marking type, traffic conditions, lighting conditions, and gender) and covariates (i.e., age and driving experience of participants) as fixed effects, and clustered variables (i.e., test driver ID) which were included as random effects. In LMM, random effects are assumed to be normally distributed with a null mean. Model calibration and all statistical tests (e.g., post-hoc analyses with Holm correction, and simple effect analysis) were carried out through *Jamovi* (ver. 1.8.1.0), with the submodule GAMLj (ver. 2.4.7) (www.jamovi.org/).

3 RESULTS

3.1 Continue ramp-terminal

Longitudinal behaviour has been described through speed data. Figure 4a shows the average speeds recorded along seven significant sections indicated in Figure 1a, with the three different horizontal markings, the two lighting and the two-traffic flow conditions in the through motorway lanes. In Figure 4a, the three zones (A, circular arc in the ramp; B, continue clothoid in the ramp; C, circular arc terminal) are highlighted with a changing background greyscale.

The speeds adopted by drivers were found to be always higher than the design speed (60 km/h). Any difference between the design speed and the speed adopted by drivers always occurs because of the conservative values of the design factors adopted by the reference standard, e.g., curves are designed assuming lateral friction values based on wet pavement conditions. Since the experiments were conducted under dry pavement conditions, most of the drivers adopted a higher operating speed.

In the case of a 1000 pc/h traffic flow in Figures 4a(A) and Figure 4a(B), the lowest speeds were recorded with HM2. Conversely, in the daily case with 3000 pc/h flow, the highest speeds were observed with HM2. Drivers subjected to HM1 and HM3 generated similar speed values; in Figure 4a(D), the average difference between the speeds observed with these two markings (S_{HM1} - S_{HM3}) was 5.7 km/h.

These results are difficult to interpret (at both an individual and collective level) because they are affected by the independent factors and variables included in the experimental design. Furthermore, the results depict the response of a subgroup of drivers only. Hence, the driving style of participants belonging to a specific subgroup may have influenced the data outcomes. Consistent with the indications provided in Section 2.5, the effects associated with driver subjectivity were more correctly interpreted by regarding the test driver ID as a random effect in the LMM.

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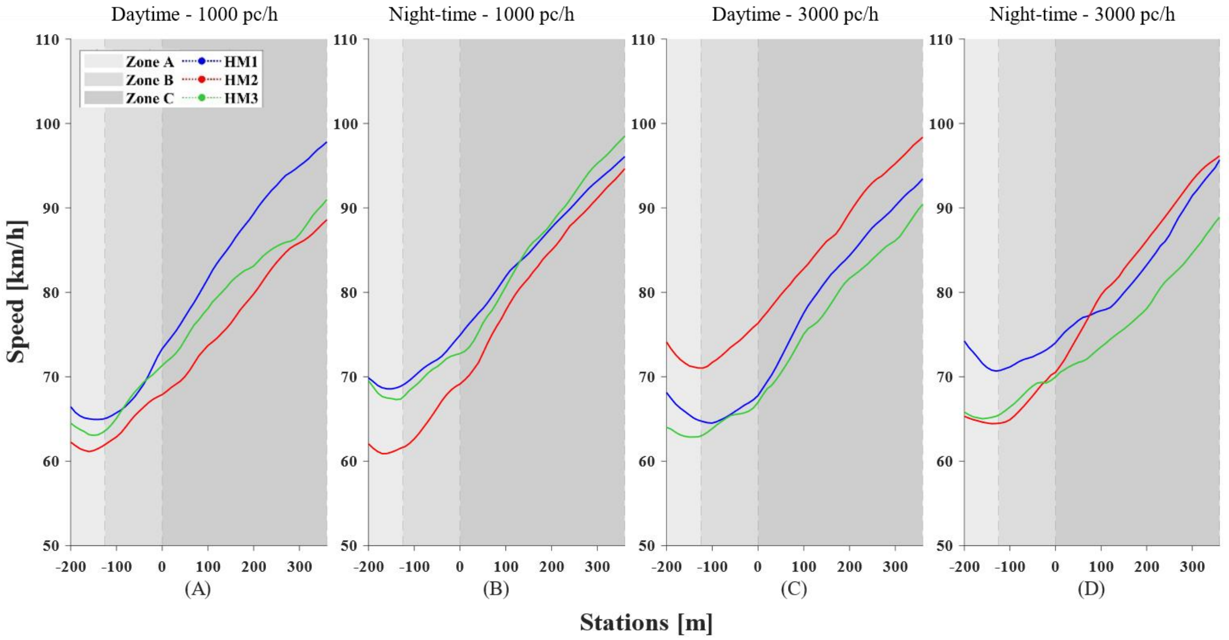
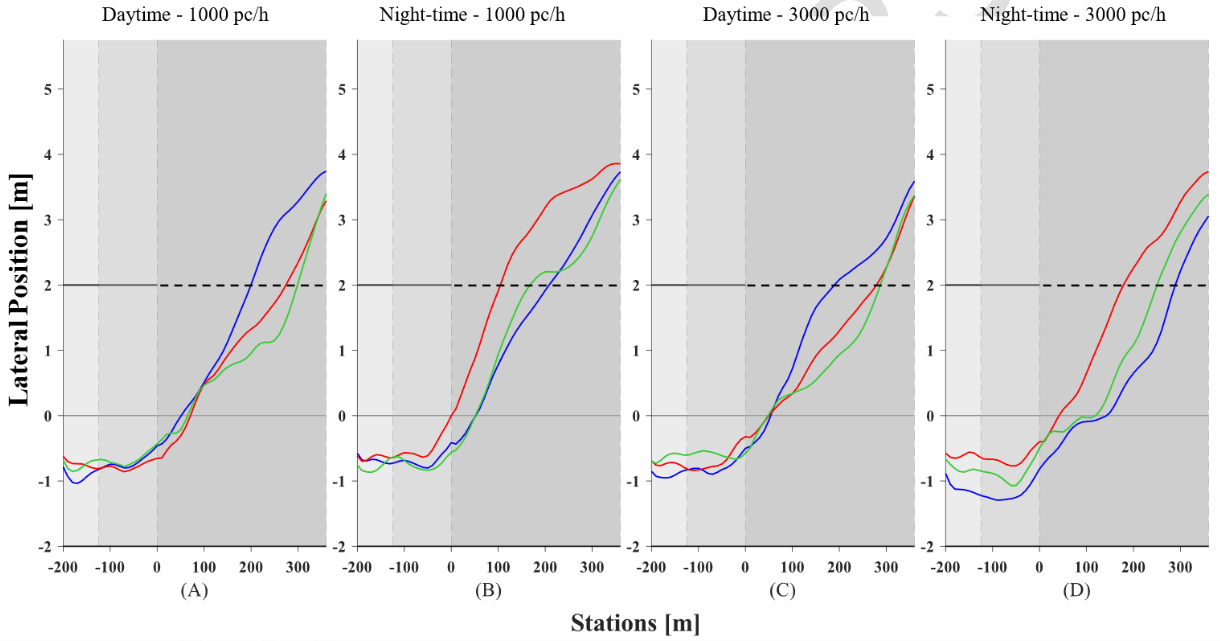


(a)



(b)

Figure 4. (a) Average speeds and (b) average lateral position values observed on a continue ramp-terminal. Each point represents the average of twelve experimental data.

Lateral position (LP) data were also recorded and reported in Figure 4b. LP equal to zero means that the driver is at the centre of the ramp/terminal lane. Positive values indicate that the driver maintained the vehicle on the left side of the lane. In Figure 4b, the two lines for an LP equal to +2 and -2 m indicate the left and right edges of the ramp-terminal lane respectively. In this specific case, data collected in zones A and B refer to the vehicle position in the ramp and in the circular arc (zone A) and clothoid (zone B). In zone C (the circular terminal) the driver can change lanes and merge onto the motorway through lanes. Consequently, at the point of exiting zone B, most of the drivers started moving their vehicle to the left side of the lane, which explains why the recorded values in zone C are generally positive.

As shown in figure 4b, HM2 and HM3 promote a slightly better trajectory control, prompting drivers to maintain more centred trajectories. Specifically, for HM2, in day-time conditions, centred trajectories are more

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evident in zone A, while in night-time conditions this effect also extends to zone B. HM3 had greater effectiveness only in the daytime case with the highest conditioned traffic flow (3000 pc/h).

3.2 Reverse ramp-terminal

Figure 5a shows speeds for the reverse terminal (Figure 1b). In this case, HM2 and HM3 seem to have had a positive effect on longitudinal behaviour prompting drivers to adopt higher speeds than with HM1, which means they reach a merging speed closer to that of vehicles travelling along the motorway through lane (in this experiment simulated vehicles travelled at speeds in the 120-130 km/h range). The only exception observed was in the case of a 1000 pc/h traffic-flow and daytime condition, where HM3 resulted in lower speeds than HM1. HM2 and HM3 both had a positive impact on transversal behaviour during day-time conditions (i.e., the LP values were closer to zero) both on the ramp and on the reverse terminal (Figure 5b). Under night-time conditions, the innovative HM had little to no effect.

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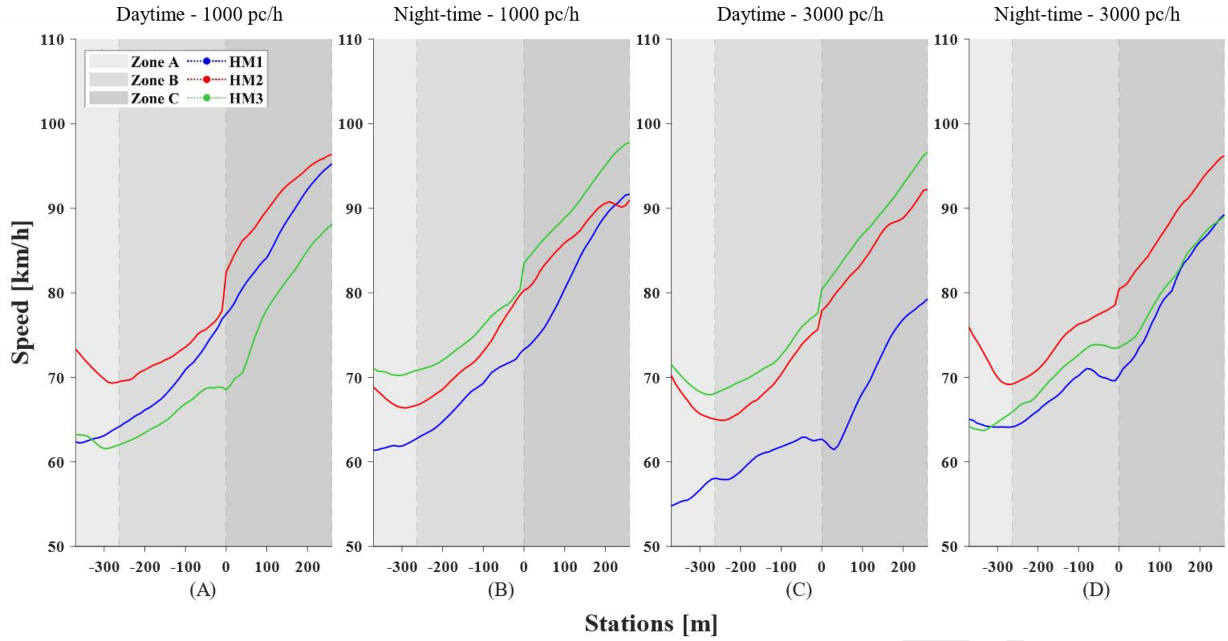
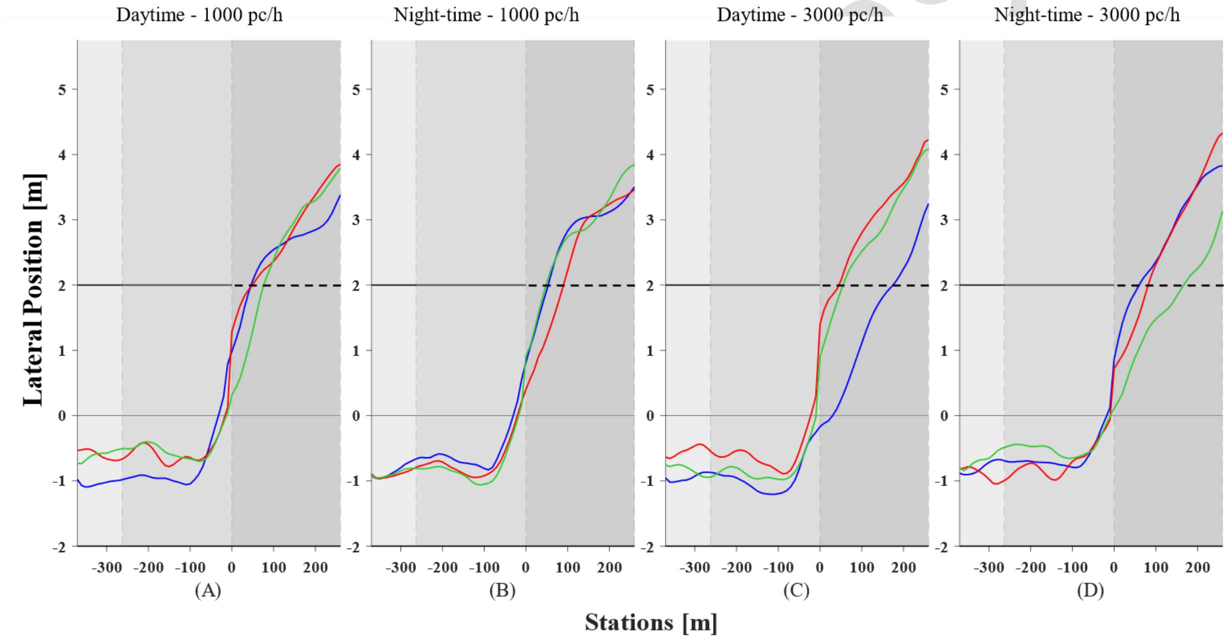


(a)



(b)

Figure 5. (a) Average speeds (b) and average lane gap along reverse ramp-terminals. Each point represents the average of twelve experimental data.

4 ANALYSIS

Based on the data presented in Figure 4 and Figure 5, recorded data were analysed at the specific sites shown in Figure 1. Speed was analysed at the beginning and the end of the terminal, i.e. at the ST (S@ST) and TT (S@TT) sections. Because of the significant number of lane movements observed immediately before the terminal, LP was evaluated at CS (LP@CS) when drivers were moving from the ramp to the variable curvature design connection. Finally, SDLP was evaluated along the connection between the ramp and the terminal (i.e., form CS to ST), which is indicated in Figure 1 and Figure 2 as zone B (SDLP@zone B).

4.1 Continue ramp-terminal

From a calibration of the LMM on speed data, the influence of the innovative HM on speeds proved negligible (S@ST: $F_{106.0} = 0.216$, p = .806; S@TT: $F_{106.9} = 1.1933$, p = .305) as depicted in Table 2. In both models developed for speeds @ST and @TT, the fixed effects associated with participants accounted for more than 22% of the total variance in the model. Gender was considered as a factor and proved significant ($F_{44.7} = 14.966$, p = <.001) with males being faster than females. However, covariates relating to the personal characteristics of participants (driver experience and age) were all found to be irrelevant across all the models. According to the experimental hypothesis, driver speeds in zones B and C featuring HM2 and HM3 were expected to travel at a higher speed than those travelling with HM1, with drivers merging into the motorway at speeds close to that of drivers in the motorway through lanes. However, the LMM outcomes fail to support this hypothesis. This is explained by the fact that the peripheral vision of drivers merging into zone C cannot process the information provided by the additional markings (Figure 2). Finally, no other experimental factors had an impact on the speed decision.

Contrary to what was observed for speeds, LMM indicates that HM type significantly influenced the lateral position of the vehicle. Figure 6 evidences that vehicles subject to the influence of innovative HM remain closer to the ramp centreline than they do in the presence of ordinary HM. When TF = 3000 v/h and during daytime, the difference in LP between HM3 and HM1 is significant ($t_{111} = 2.383$, p = 0.019), as it is during night-time between HM2 and HM1 ($t_{103} = 3.014$, p = .003), and between HM3 and HM1 ($t_{116} = 2.227$, p = .028). Figure 6b also indicates that during night-time, drivers reacted to the higher volume of traffic on the motorway by keeping a larger lateral distance, i.e. maintaining the vehicle closer to the right lane edge. In contrast, drivers approaching the terminal in conditions of lower traffic volumes did not adopt such wide lateral distance values.

Nevertheless, the positive influence of HM2 on transversal behaviour is evident in both Figure 6c and 6d, with drivers maintaining better trajectory control during both daytime and night-time conditions. Surprisingly, HM3 was found to be ineffective on SDLP in daytime conditions (Figure 6c). It is worth noting that the calibrated LMM for SDLP suffers from heteroscedasticity of residuals as indicated by the normal distribution violation as per the KS test ($p < .001$), due to the excessive SDLP values of four of the 48 drivers. It is also worth noting that Schielzeth et al. (2020) observed that LMM are robust enough even when assumption checks are violated.

Traffic volume impacts on the lateral behaviour of drivers as evidenced in Table 2. This effect is explained by the absence of any traffic barriers or sight obstructions restricting the view of oncoming motorway traffic from the ramp. During night-time when TF = 3000 v/h, drivers drove closer to the right lane edge than they did under daytime conditions and in the presence of lower traffic flows. Furthermore, under lower traffic levels in the motorway drivers in the ramp-terminal connection were able to maintain superior transversal vehicle control with respect to scenarios with 3000 v/h on the motorway travelled way.

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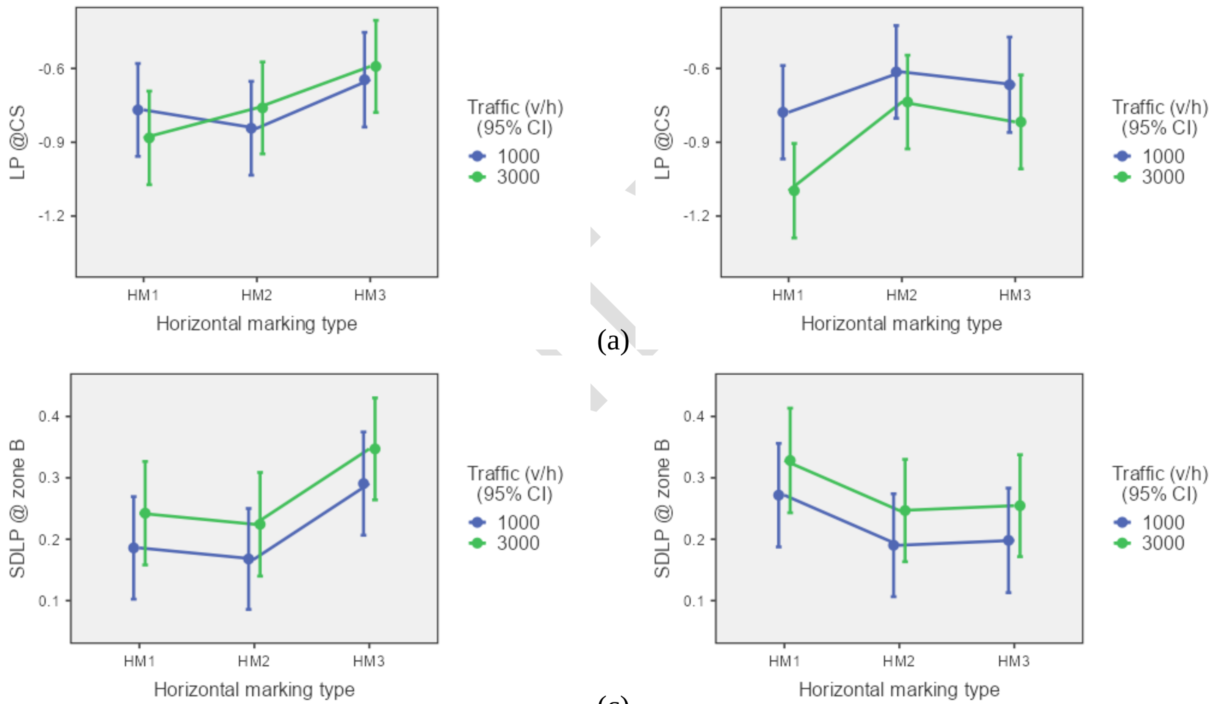
Table 2. LMM outputs on significant factors affecting speeds, LP and SDLP along continue terminals (HM = horizontal markings type, TF = traffic flow, LC = lighting conditions)

		Estimated model coefficients (p-value)			
Variables	**Effect**	**S @ ST**	**S @ TT**	**LP @ CS**	**SDLP @ Zone B**
Intercept		70.616 (<.001)	93.498 (<.001)	-0.7668 (<.001)	0.2457 (<.001)
FE: HM	(HM2-HM1)	-	-	0.1429 (.039)	-
	(HM3-HM1)	-	-	0.2012 (.006)	-
TF		-	-	-	0.0565 (.077)
LC * TF		-	-	-0.2052 (.060)	-
HM * LC	(HM2-HM1)	-	-	-	-
	(HM3-HM1)	-	-	-	-0.1784 (.021)
Gender		10.842 (<.001)	11.863 (<.001)	-	-
RE: Test driver ID		(<.001)	(<.001)	(<.001)	(.245)
Summary statistics					
AIC		1078.8	1118.1	135.9	-55.029
BIC		1089.5	1108.1	230.9	39.197
R^2 marginal		.227	.238	.135	.106
R^2 conditional		.664	.571	.464	.210
Observations				144	
Participants				48	
Observations/participants				3	
KS test on residual (p-value)		.995	.670	.754	<.001



(a) (b) (c) (d)

Figure 6. (a, b) Lateral position @CS and (c, d) standard deviation of lateral position along zone B (the ramp-terminal connection) during day (a, c) and night-time (b, d) lighting conditions for the continue ramp-terminal

4.2 Reverse ramp-terminal

In the case of the reverse ramp-terminal, the interrelation between the innovative horizontal markings and longitudinal and transversal user behaviour is more complex. Interactions between HM type and lighting conditions were captured by the LMM (Table 3). Along the ST section during daytime conditions and low traffic volumes, HM2 ($t_{99.8}$ = 3.187, p = .002) results in drivers travelling at higher speeds than with HM1, while speeds at the highest traffic volumes for both HM2 ($t_{101.7}$ = 2.413, p = .018) and HM3 ($t_{96.6}$ = 2.577, p = .011) were found to be significantly higher than speeds with baseline conditions (i.e., HM1). Similar trends were observed with the TT section. This outcome differs from that of the continue case, because the reverse clothoid used for this ramp-terminal connection is longer than that used in the continue connection. A longer ramp-terminal connection ensures that drivers are exposed to the innovative marking for a longer time before merging into the motorway. It is worth noting that the higher the speed of merging vehicles along the terminal, the less disruptive the interaction between motorway through traffic and merging vehicles.

As expected, the lateral position was significantly influenced by the innovative HM. HM2 (t_{119} = 3.081, p = .003) and HM3 (t_{116} = 3.199, p = .002) resulted in trajectories which were significantly closer to the lane centreline than was the case with conventional HM irrespective of traffic volumes. HM2 always induces drivers to maintain a more central trajectory in the lane.

Slightly lower values for SDLP were recorded in the case of HM2 and night-time conditions (Figure 7). In night-time conditions, no significant differences were observed between the three horizontal markings. In daytime conditions and for low traffic levels, significant reductions in SDLP values under HM3 (t_{112} = -2.976, p = .004) and non-significant reductions under HM2 (t_{116} = -1.613, p = .110) were observed with respect to conventional HM.

Finally, the calibrated LMM for reverse terminals passed the violation check carried out with the KS test (p < .001)

Table 3. LMM outputs on significant factors affecting speeds, LP and SDLP along reverse terminals (HM = horizontal markings type, TF = traffic flow, LC = lighting conditions)

		Estimated model coefficients (p-value)			
Variables	**Effect**	**S @ ST**	**S @ TT**	**LP @ CS**	**SDLP @ Zone B**
Intercept		75.215 (<.001)	91.236 (<.001)	-0.6620 (<.001)	0.4223 (<.001)
FE: HM	(HM2-HM1)	6.968 (.003)	-	0.2174 (.007)	-
	(HM3-HM1)	-	-	0.1713 (.035)	-0.0612 (.068)
HM * LC	(HM2-HM1)	-10.889 (.011)	-12.177 (.006)	-0.4413 (.004)	-
	(HM3-HM1)	-	-	-0.3257 (.033)	-
HM * LC * TF	(HM3-HM1)	-	-	0.6613 (.036)	-0.3733 (.004)
HM * Gender	(HM3-HM1)	-12.112 (.011)	-24.421 (.009)	-	-
Gender		11.223 (.003)	10.279 (.004)	-	-
Driving experience (y)		-.289 (.048)	-	-	-
RE: Test driver ID		(<.001)	(<.001)	(.001)	(<.001)
Summary statistics					
AIC		1145.2	1146.3	157.4	-94.834
BIC		1138.0	1135.3	236.2	6.932
R^2 marginal		.258	.191	.158	.088
R^2 conditional		.702	.630	.410	.420
Observations				144	
Participants				48	
Observations/participants				3	
KS test on residual (p-value)		.620	.500	.764	.427

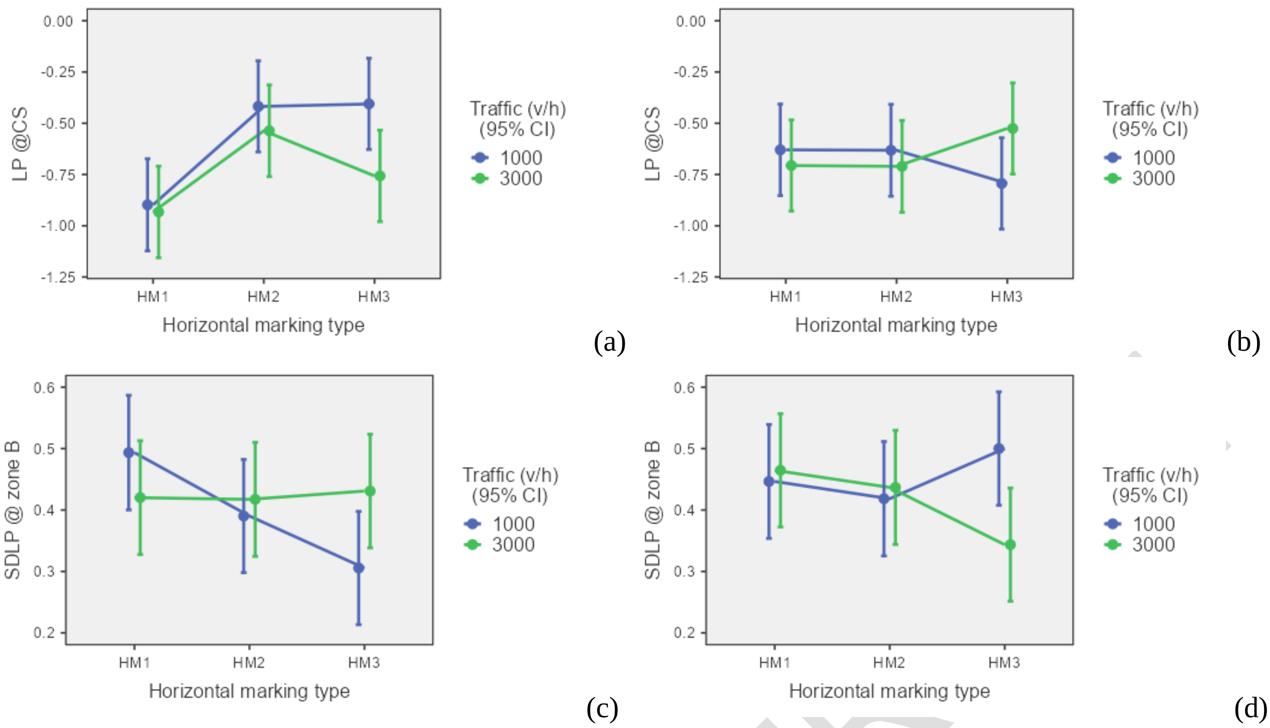


Figure 7. (a, b) Lateral position @CS and (c, d) standard deviation of lateral position along zone B (the ramp-terminal connection) during day (a, c) and night-time (b, d) lighting conditions for the reverse ramp-terminal

5 DISCUSSION AND CONCLUSIONS

Alternative horizontal markings (HM2 and HM3) were put in place with the hypothesis that an alternative marking design might lead to improved longitudinal and transversal driving control along transitional elements such as merging motorway terminals. The HM2 design with its use of interior bands (Figure 2a) acts on the drivers' perception of the lane width causing them to sense a lateral constraint and maintain a more central trajectory. Moving from the ramp to the terminal, the bands become progressively smaller such that the drivers perceive a lower level of lateral control and are confident enough to increase their speed before merging onto the motorway through lane. HM3 (Figure 2b) is intended to work mainly on speed perception (longitudinal behaviour). The distance between the external bands are progressively extended, causing drivers to think they are reducing their speed. In this case, the hypothesis is that drivers react to this perception by increasing their speed to levels that are generally higher than those typically observed with ordinary markings.

The results of this experimental study indicate that innovative horizontal markings designed to increase speed and positively influence lane width perception are not always effective on curved on-ramp terminals. A different effect was observed between the only two possible solutions for ramp-terminal connections: the continue (egg-shaped) and the reverse (S-shaped) designs. Although innovative markings do not have a significant impact on speeds in the first terminal type, they were found to have a significant impact on lane gap and standard deviation of lateral positions; in the second terminal type a positive impact was evident for all the investigated longitudinal and transversal outcomes. A possible explanation for this may be the difference in length between the two connection types, with the continue connection being significantly shorter than the reverse one.

Of the different marking designs investigated and compared with the conventional type, it is the HM2 rather than the HM3 which seems to have a more positive effect on lateral vehicle control. This is due to the perception of a narrower path which prompts the driver to select a more central trajectory than that adopted in response to the other designs. The effect of a perceived increment in lane width when the driver passes from the ramp to the terminal is also extended to speeds, which are frequently higher in the case of the alternative design investigated here independent of the particular traffic and environmental lighting conditions. Under daytime conditions, innovative markings delivered better results than they did under night-time lighting conditions. Aggregating the results from both ramp-terminal connection types, traffic, and lighting conditions, HM2 produced lower SDLP values which is indicative of good lateral vehicle control. With such complex results, the experimental hypothesis can only be partially confirmed.

In conclusion, this research demonstrates the effectiveness of the perceptual techniques used in these specific areas of road design, where drivers are engaged in speed and trajectory management of their vehicles in very dynamic and fluid scenarios. The study shows that even though speed results are not as expected for the continue ramp-terminal connection, the use of innovative markings which influence both lateral perception of the lane and speed may improve driver performances and, as a consequence, the safety of merging operations.

The work carried out has limitations as it focused on the influence of a few specific variables while excluding others from consideration. Examples of variables not considered are the motorway radius and other environmental factors that may affect driver visibility. The presence of traffic along the ramp is another factor that was not considered in this experiment, and which should be the subject of future study. To overcome these limitations, future investigations will analyse the effect of innovative horizontal markings when safety barriers are located along ramps.

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