Alternative Horizontal Markings along Curved Exit Ramp Terminals to Improve Driver-Safety-Related Performance

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ABSTRACT

Previous investigation revealed that diverging maneuvers along curved terminals lead to a deterioration in the longitudinal and transversal performances of drivers with respect to linear ones. As a countermeasure, innovative horizontal markings (HMs) may be used to compel drivers to drive more prudently and maintain better vehicle control.

In this driving simulation study, the behavioral effects of alternative HMs along curved exit ramp terminals were investigated. Forty-eight voluntary participants drove along randomly assigned exit ramp terminals, the design of which involved combinations of the following input variables: (i) horizontal markings (standard HM1, HM2 with internal lane bands, HM3 with external zebra stripes); (ii) lighting conditions (day and night); (iii) traffic flow in the motorway (1000 pc/h and 3000 pc/h), and (iv) ramp terminal connection type (continuous and reverse). Longitudinal (i.e., speed) and transversal (i.e., lateral position and diverging abscissa) behavioral data were collected.

HM2 leads to greater improvements in the level of road safety thanks to better longitudinal and transversal driver behavior. However, drivers did delay their exit from the motorway with respect to the baseline condition (HM1) independently of the connection type. No relevant improvements were observed with HM3, apart from speed reductions at the end of the terminal and more centered trajectories when approaching the ramp. Results also show that drivers tended to enter the reverse terminal later than the continuous one (where drivers correctly used the taper), thus revealing that the use of the innovative HMs was not able to compensate for this inappropriate behavior adopted along reverse terminals.

Keywords

Horizontal markings, exiting terminal, diverging maneuver, driving simulation, driver behavior, statistical data modelling.

INTRODUCTION

Interchange ramp terminals are intended to facilitate the smooth and safe transition and change in speed of vehicles entering and exiting the motorway (*1*). However, on these road facilities a number of conflicts among vehicles occur, resulting in a relevant crash frequency rate (*2*, 3). Ramp terminals are specialized lanes on which drivers contextually change speed and lateral position, so their geometric characteristics should be carefully designed to guarantee safe and efficient operations. Literature reveals that exit-ramps are more dangerous than entry ones i.e., they have a higher crash frequency rate (*4*-*6*). Lane-changing maneuvers, fluctuations in speed, and decision-making actions all contribute to an increase in the inherent risk of exit ramps (*7*, 8).

Some studies have identified inconsistencies between the design criteria of ramp terminals and real driving operations. Kinematic models used at the design stage assume uniform deceleration during diverging maneuvers (*9*-*11*), while in a simulation-based investigation, Calvi et al. (*12*) showed that drivers approaching exit ramps start reducing speed before the deceleration lane, thus slowing down the general traffic flow along the motorway. Furthermore, Lyu et al. (*13*) found that in diverging maneuvers drivers adopt speeds which are significantly higher than the posted speed limit when approaching exit ramp terminals.

Several naturalistic and driving simulator-based studies have also investigated the factors affecting the safety of linear deceleration terminals along tangent sections of mainline motorways. The volume of traffic is one of the most critical factors determining safety at interchanges (*14*, *15*) as well as the terminal layout (*16*-*18*). During the deceleration operation, factors affecting driver behavior include the length of the deceleration lane (*19*, *20*), the number of lanes (*21*), the type of deceleration lane (parallel or tapered) (*22*, *23*), and the ramp geometry (*5*, *6*).

Problem statement

Recently, Portera and Bassani (*24*) investigated driver behavior along the curved diverging terminals of exit ramps. They found that the direction of the exit ramp curve with respect to the curvature of the motorway has a strong impact on longitudinal and transversal driver behavior. Along continuous ramp terminals (**Figure 1d**), i.e., ramps which have the same curvature as that of the motorway, drivers behave similarly to the way they would along straight terminals. Conversely, along reverse ramp terminals (**Figure 1g**), i.e., ramps which have a different curvature to that of the motorway, drivers do not always select appropriate speeds and lane change positions, thus highlighting critical driving situations that need to be considered when adopting appropriate safety countermeasures at the design stage.

Road markings are generally regarded as a low-cost and effective measure for improving longitudinal and transversal behavior along horizontal curves (*25*-*27*). In the past, different types of perceptual road markings were proposed as a means to reduce speed and improve lateral position in hazardous locations (*28*, *29*). Several studies have demonstrated the effectiveness of perceptual horizontal markings (HMs), i.e., transverse strips, colored median, herringbone patterns, etc. in speed reduction (*30*-*33*). Perceptual treatments are specifically designed to enhance the perception of speed in drivers (*34*), with this higher perception of risk being unconsciously induced in accordance with the risk homeostasis theory (*35*). The majority of these studies focused on curved sections of rural roads (*36*-*39*), where any miscalculations in speed and perception of curvature tend to be reflected in a higher incidence of crashes (*31*). In motorway interchanges, Gu et al. (*8*) suggested the use of more efficient HMs as a safety improvement.

Road markings can also affect the perception of lane width thus improving the lateral position of the vehicle within the lane (*28*, *31*). Rumble strips were found to be useful in decreasing the standard deviation of lateral position (SDLP) of drivers travelling along a curve on a two-lane road section (*40*). Awan et al. (*37*) observed that drivers followed a safe path along a curve when herringbone pattern markings were present. They pointed out that this kind of perceptual marking can help to reduce the number of head-on crashes along curves where drivers tend to adopt inappropriate lateral positions.

When considering exit ramps, the before-after observational study of Retting et al. (*41*) indicated that the installation of lateral pavement marking patterns narrowing the lane width led to an effective reduction in average speeds. In contrast, Hunter et al. (*42*) observed that the use of chevron pavement markings had only a moderate influence on driver speeds. They argued that these markings are only effective for a limited time following their installation but then their impact declines as drivers become familiar with them.

Study objective

In this driving simulation study, the effects of innovative horizontal markings along curved exit ramp terminals were investigated. The main hypothesis is that HMs designed to have an impact on perceptual lane width and speed may improve the lateral and longitudinal control of drivers as they exit from motorways. The experiment involved forty-eight volunteers. Four main factors were considered in the experimental design: (i) the HM layout (standard vs. innovative), (ii) the traffic flow along the motorway (1000 vs. 3000 pc/h/lane), (iii) the terminal geometry (continuous vs. reverse), and (iv) the environmental lighting conditions (i.e., day vs. night). Speeds and lateral positions at specific sections and the diverging abscissa i.e., the point at which drivers changed lane when moving from the motorway to the terminal, were taken into account in the analysis. Generalized Linear and Linear Mixed-Effects models were used to interpret the collected data and identify the factors influencing driver behaviour.

METHODS

Scenarios, design of the experiment, and independent factors

The virtual road scenarios consisted of two-lane highway and motorway segments and were designed in accordance with the prescribed Italian standard (*43*). Segments of these two road categories were linked through direct deceleration ramps (**Figure 1**) with a horizontal radius R_r = 150 m (*44*). A ramp with the same curvature as the curved motorway, i.e., a continuous transition (**Figure 1d**), was included together with a ramp with the opposite curvature sign to that of the curved motorway segment, i.e., a reverse transition (**Figure 1g**).

The circuit was developed with no longitudinal slope. The motorway segments included two 3.75 m wide lanes per direction, while the highway segments had two 3.75 m wide lanes (one per direction). The motorway ramps included one 4.00 m wide lane, with shoulders of 1.00 m in width. The exit lane included a taper and a terminal. Both were curved and parallel to the adjacent through lanes as indicated in **Figure 1**. The deceleration length was calculated using the following equation:

$$L_{d,u} = \frac{{v_1}^2 - {v_2}^2}{2a} \tag{1}$$

where v_1 (m/s) is the entry speed into the deceleration terminal (140 km/h), v_2 (m/s) is the exit speed at the end of the deceleration segment (60 km/h), and a is the deceleration rate assumed equal to 3 m/s^2. Following these design rules, the deceleration length was 205 m. The taper length was set at 90 m according to the Italian standard (*44*).

Experimental independent factors included: (i) the horizontal marking (HM), i.e., conventional (HM1), alternative type 2 (HM2), and alternative type 3 (HM3); (ii) the connection type (CT) between terminal and ramp, i.e., continuous or reverse; (iii) the traffic flow (TF) in the motorway through lanes, i.e., 1000 and 3000 pc/h/lane; and (iv) the lighting conditions (LC), i.e., day and night.

FIGURE 1. Images showing the three HMs and the two ramp terminal connection types (continuous and reverse). Vision of the three HMs from the driver point of view: (a) HM1 (baseline), (b) HM2 (type 2), and (c) HM3 (type 3). Plan view of the three layouts: (d) HM1 continuous ramp terminal, (e) HM2 continuous e ramp terminal, (f) HM3 continuous ramp terminals, (g) HM1 reverse ramp terminals, (h) HM2 reverse ramp terminals, and (i) HM3 reverse ramp terminals (TB = taper begin, TT = taper-to-terminal, TS = terminal-to-spiral, SC = spiral-to-curve, CE = curve end).

Each circuit was composed of two exit ramp terminals, one with the continuous design and the other with the reverse design. For each scenario, a random combination of HM (3 levels), TF (2 levels) and LC (2 levels) was assumed. Considering all possible combinations, a total of twelve (= 3×2×2) circuits were generated.

HM2 (**Figure 1b**) consisted of internal white spaced bands of variable thickness placed inside the lane of the exit ramp terminal. These internal bands widen along the ramp terminal, hence reducing the perception of available lane width. The longitudinal size and spacing of the white bands, 0.70 m and 2.5 m respectively, were maintained constant along the entire length of the exit ramp terminals. The thickness of the bands changed at specific stations: between the taper-to-terminal (TT) and the terminal-to-spiral (TS) sections it was 0.25 m, with the bands located on the right side of the lane only. From the TS to the spiral-to-curve (SC) sections the thickness was equal to 0.40 m, while between SC and the ramp curve end (CE) it was set equal to 0.55 m. The hypothesis with the use of HM2 is that drivers maintain better control of their lateral position inside the ramp terminal lane (i.e., more centered trajectories in the lane), as observed by Katz et al. (*33*) and Charlton (*31*).

HM3 consisted of stripes with variable longitudinal spacing placed on the shoulders only. In this case, the hypothesis is that markings act on driver peripheral field of vision to increase the perception of speed during deceleration (*45*). **Figure 1c** shows that HM3 has a spacing with stripes 0.15 m thick and 1.0 m long along the entire exit ramp terminal. Their spacing changed between TT and TS (10.0 m), TS and SC (5.0 m), and SC and CE (2.5 m). When travelling at a constant speed, the shorter distance between consecutive stripes leads drivers to believe that they are travelling at a higher speed than they actually are. This perception should prompt drivers to reduce their speed during the maneuver, thereby adopting speeds closer to those assumed at the design stage of the terminal (*31*, *41*).

The third variable in the experiment was the rate of traffic flow along the motorway. In this experiment, the same traffic conditions used by Portera and Bassani (*46*) were adopted. Specifically, (i) high-volume traffic conditions (Level of Service, LOS C, with a flow of 3000 pc/h), and (ii) low-volume traffic conditions (LOS A, 1000 pc/h flow) were used. These flows refer to pc/h per the whole travelled way in the investigated direction. Finally, test drivers were subjected to both daytime and night-time driving conditions. Since reduced visibility can make it difficult for drivers to clearly see the markings, this variable can be decisive in the control of speed and trajectory.

Participants and equipment

The study was conducted in line with the Code of Ethics of the World Medical Association included in the Declaration of Helsinki (*47*). Forty-eight licensed drivers took part in the experiment on a voluntary basis without any remuneration. The sample set of participants was constructed to be representative of the general Italian driving population (full driving license holders) in terms of gender and age (21 females and 27 males divided into three classes: < 25 years old; 25-44 years old; 45-64 years old). Before participating in the experiment, test drivers signed a privacy consent form as required by Italian law. **Table 1** summarizes the aggregated information on participants in the experiment by age group.

The fixed-base simulator (AV Simulation, France) available at the Road Safety and Driving Simulation laboratory (RSDS Lab) of Politecnico di Torino was employed. The system was relatively validated for longitudinal, lateral, and passing behavior (*48-50*). The apparatus consists of three 32-inch screens that provide an angle of view of 130°, a true force steering wheel, pedals, and gearbox. The resolution of the visual scene is 1920×1080 pixel, and the refresh rate is 60 Hz. The simulator also includes equipment to reproduce the sounds of both the engine and the surrounding environment. The recording system acquired all data with a frequency of 100 Hz.

TABLE 1. Information on the sample of drivers (mean values and standard deviation between brackets).

Participant characteristics	< 25 years	25-44 years	45-64 years	Total Sample
Total number (females)	5 (2)	20 (9)	23 (10)	48 (21)
Age (years)	21.4 (1.7)	33.2 (6.1)	53.8 (4.0)	41.4 (12.9)
Driving Experience (years)	3.0 (2.0)	15.0 (6.3)	34.8 (4.6)	22.8 (12.8)
Distance travelled (km/year)	5,000 (3,082)	11,500 (10,000)	15,635 (11,890)	12,615 (10,790)
Number of accidents	0.20 (0.45)	0.60 (0.75)	1.81 (2.34)	1.11 (1.77)

Experimental protocol

Before starting the driving session, test drivers were asked to fill in a pre-drive questionnaire to evaluate their physical condition and health. Then, all drivers performed visual and auditory cognitive tests (available at: www.cognitivefun.net) to measure their reaction times to stimuli and detect any possible changes in their cognitive performances due to impairments resulting from the driving test. Reaction times were found to be normally distributed as per the Kolmogorov-Smirnov test (pre-drive visual reaction: $D_{48} = 0.08$, $p = .847$; pre-drive auditory reaction: $D_{48} = 0.14$, $p = .228$; post-drive visual reaction: $D_{48} = 0.12$, $p = .435$; post-drive auditory reaction: $D_{48} = 0.17$, $p = .102$). The duration of reactions to visual stimuli were evidently longer than those to auditory stimuli because of the difference in time needed to process and react to the signal received, which is longer in the case of visual stimuli (*51*). These results are consistent with previous observations from Thompson et al. (*52*) and Pain and Hibbs (*53*). Test results before and after the driving task for both visual ($F_{47,47} = 0.728$, $p = .140$; $t_{94} = 0.463$, $p = .644$) and auditory ($F_{47,47} = 1.018$, $p = .475$; $t_{94} = 0.087$, $p = .930$) reaction times were not found to be statistically different. Hence, the auditory and visual performances of participants were not altered by the experimental protocol adopted.

Prior to the experiment, each participant drove on a trial test track to gain familiarity with the simulator. Then, each participant drove on three circuits which were randomly assigned from the twelve possible. In addition, the age and gender of the drivers assigned to each circuit was proportionate to the age and gender makeup of the total sample of drivers. After the experimental drive, the participants performed the same two cognitive tests and completed a post-drive questionnaire.

The post-drive questionnaire was designed to elicit information from drivers on their experience of the driving simulation and to determine whether the alternative HMs represented a disturbance or distraction for them during the driving session. The questionnaires revealed that during the simulation 25% of participants experienced very minor ailments like visual fatigue, and blurred vision. These discomforts, being very mild in intensity, were deemed acceptable for the purpose of the experiment. Only one driver experienced a level of simulation sickness which prevented him from completing the driving task. Hence, he was replaced with another driver of the same age and gender. The decision to consider all the data collected valid was corroborated by the cognitive responses before and after the driving test.

Observed variables, data collection, and manipulation

Data on speed (*S*), lateral position in the lane (*LP*) and diverging abscissa (*DA*, the position where drivers changed lane to leave the motorway) were collected for each driver along the ramp terminal systems at a number of specific sections. The outcomes for *S* and *LP* were used to calibrate Linear Mixed-Effects models (*LMM*) which integrate both fixed and random effects and are suitable for the interpretation of experimental design with repeated measurements. The four experimental factors (HM type, rate of traffic flow, lighting conditions and connection type) and the covariates (age and driving experience) were accounted for as fixed effects, with the identification code of the driver regarded as a random effect (i.e., the cluster variable in the experiment). The *LMM* was calibrated by adopting the backward elimination technique. Data for *LMM* were extracted at TT, TS and SC sections for speeds, and at TS and SC sections for lateral position models. Finally, diverging abscissa data were used to calibrate a Generalized Linear Model (*glm*). Statistical data analyses and modelling were carried out with *Jamovi* ver. 1.8.1.0, with the three modules *GAMLj* ver. 2.4.5, *Moretests* ver. 0.9.3, and *Scatr* ver. 1.2.0. Significance levels were always set at 0.05.

RESULTS

Figure 2 for speeds (*S*), **Figure 3** for lateral position (*LP*), and **Figure 4** for the diverging abscissa (*DA*) provide a summary of the results. They have been sub-divided by rate of traffic flow (i.e., 1000 pc/h and 3000 pc/h), lighting conditions (i.e., day and night), and connection type (i.e., continuous and reverse). In each graph, the results obtained when drivers negotiated ramp terminals with different horizontal markings (i.e., HM1, HM2, and HM3) are presented. Each line represents the average speed value or lateral position resulting from 12 data from station 0 m (section TB, taper beginning), 450 m (section TS, terminal-to-spiral) and 640 m (section SC, spiral-to-curve).

Figure 3 provides the LP of the vehicle center of gravity (CoG) with respect to the deceleration lane centerline. Negative average values indicate that the vehicular CoG was located on the left side of the lane centerline. The lateral position does not appear to be strongly influenced by *HM* during the diverging maneuver, from the beginning of the taper (section TB), until the end of the deceleration lane (section TS).

FIGURE 2. Longitudinal (speed) behavior along curved deceleration ramp terminals with a range of experimental factor combinations (TB = taper begin, TT = taper-to-terminal, TS = terminal-to-spiral, SC = spiral-to-curve, CE = curve end).

FIGURE 3. Transversal (lateral position) behavior along curved deceleration ramp terminals with variable experimental factor combinations (TB = taper begin, TT = taper-to-terminal, TS = terminal-to-spiral, SC = spiral-to-curve, CE = curve end).

FIGURE 4. Boxplots of diverging abscissa for three HM designs in continuous and reverse ramp terminals.

ANALYSIS AND DISCUSSION

Statistical model outcomes

The Linear Mixed-Effects (*LMM*) and Generalized Linear Model (*glm*) outcomes are fully reported in **Table 2**. In *LMM*, the R^2 conditional value describes the variance attributable to fixed and random effects, while the R^2 marginal is determined by fixed effects only. Higher R^2 conditional values were found for speed data (i.e., > 70%) with a relatively small marginal R^2. This suggests that most of the variance in the model may be explained by random effects, i.e., the subjective characteristics of drivers, rather than the experimental factors. In the case of *LP*, the variance is attributable in equal measure to fixed and random factors.

Speeds

The speed outcomes from *LMM* (**Table 2** and **Figure 5**) indicate that HM2 significantly reduces speeds (i.e., the estimated model coefficient is negative) at the TT ($p = .015$), TS ($p < .001$) and SC sections ($p = .025$) with respect to the baseline condition (HM1). This outcome evidences that HM2 had a secondary effect on longitudinal behavior, albeit it was originally conceived to improve lateral control (*35*). This is explained by the fact that the perception of a narrower lane compels drivers to adopt lower speeds as a compensatory reaction. Although HM3 was intended to act on longitudinal driver behavior, *LMM* does not reveal any significant difference between speeds observed under the influence of HM3 and HM1 at SC ($S_{SC,HM3} - S_{SC,HM1} = -1.19$ km/h, $p = .288$) and TT ($S_{TT,HM3} - S_{TT,HM1} = -1.20$ km/h, $p = .372$) sections. The effects of HM3 are relevant at the terminal end ($S_{TS,HM3} - S_{TS,HM1} = -3.93$ km/h, $p = .002$) where they worked according to the hypothesis.

Gender was statistically significant in the *LMM* (**Table 2**). **Figure 5** shows that female (F) drivers drove at lower speeds than males (M) ($S_{TT,F} - S_{TT,M} = -11.58$ km/h, $p = .003$; $S_{TS,F} - S_{TS,M} = -10.43$ km/h, $p = .009$; $S_{SC,F} - S_{SC,M} = -8.63$ km/h, $p = .009$). This result is in line with the findings of Portera and Bassani

(*24*) and Oltedal and Rundmo (*54*), who stated that male drivers are more willing to take risks than female drivers.

TABLE 2. Estimated model coefficients (p-value) on significant factors affecting speeds (S), lateral position (LP) and diverging abscissa (DA) along ramp terminals (HM = horizontal markings type, TF = traffic flow, LC = lighting conditions, CT = connection type, R = reverse, C = continuous, F = female, M = male, N = night, D = day, “ - ” = not statistically significant, N/A = not available). Significance level for p-value: *** < .001; ** < 0.01; * < .05

Model type		**LMM**					**glm**
Variables		$\boldsymbol{S_{TT}}$	$\boldsymbol{S_{TS}}$	$\boldsymbol{S_{SC}}$	$\boldsymbol{LP_{TS}}$	$\boldsymbol{LP_{SC}}$	$\boldsymbol{DA}$
Fixed Effects:							
Intercept		98.35 ***	84.41 ***	74.03 ***	-0.117 *	0.650 ***	68.881 ***
HM	*HM2 - HM1*	-3.27 *	-4.34 ***	-2.51 *	-0.150	-0.413 ***	11.760 *
	HM3 - HM1	-	-3.93 **	-	-	-0.198 ***	-
TF	*3000 – 1000 (pc/h)*	-1.85	-2.05 *	-	-	0.075 *	-
CT	*R – C*	-	5.72 ***	1.47	-0.516 ***	-0.399 ***	30.634 ***
Gender	*F – M*	-11.58 **	-10.14 **	-8.63 **	-	-	-
Gender * LC	*(F – M) * (N – D)*	-	-	-	-0.30 5*	-0.221 **	-
Gender * CT	*(F – M) * (R – C)*	-	-	-	-	-0.170 *	-
CT * LC	*(R – C) * (N – D)*	-	-	-	0.312 **	-	-
CT * HM	*(R – C) * (HM1 – HM2)*	-	-	-	-	0.230 *	-
Experience (y)		-	-	-	-	-	3.691 **
Age		-	-	-	-	-	-3.385 **
Random Effects:							
Test driver ID (p-value only)		***	***	***	***	***	N/A
Summary statistics:							
AIC		2183.7	2160.0	2088.1	494.1	245.0	2952.7
BIC		2197.8	2173.0	2105.0	568.3	349.0	2978.4
R^2 marginal		0.166	0.160	0.118	0.211	0.326	N/A
R^2 (conditional)		0.735	0.756	0.717	0.383	0.608	0.179
Observations		288					
Participants		48					
Observations/participants		6					
KS test on residual (p-value)		(.695)	(.905)	(.623)	(.136)	(.956)	N/A

LMM in **Table 2** also revealed significant differences in speed along the two ramp terminal connection types (i.e., continuous vs. reverse). The geometric difference between the two CTs influenced driver longitudinal behaviors as confirmed by Portera and Bassani (*24*). This factor significantly affects speed at the TS (terminal end) section with the reverse design where drivers arrived at a higher speed than they did on a continuous one ($S_{TS,R}$ - $S_{TS,C}$ = 5.72 km/h, $p < .001$). A higher speed, albeit less significant in magnitude, is also evident at the SC section ($S_{SC,R}$ - $S_{SC,C}$ = 1.47 km/h, $p = .082$).

Speeds at the end of the deceleration lane (TS section) were only slightly affected by traffic volume ($S_{TS,3000}$ - $S_{TS,1000}$ = 2.05 km/h, $p = .031$), in contrast to results observed on linear terminals by Calvi et al. (*12*). The same trend was detected at the taper end (TT) with a lower level of significance ($S_{TT,3000}$ - $S_{TT,1000}$ = -1.85 km/h, $p = .061$). Finally, the traffic flow had no significant bearing on speeds at the SC section, i.e., the beginning of the curved ramp ($S_{SC,3000}$ - $S_{SC,1000}$ = -1.31 km/h, $p = .120$).

FIGURE 5. Speeds (*S*) for horizontal markings designs at TT (a, d), TS (b, e) and SC (c, f) sections. (a), (b) and (c) plots refer to male drivers, while (d), (e) and (f) refer to female drivers.

Lateral positions

LMM outcomes indicate that *LP* was significantly influenced by innovative HMs (**Table 2** and **Figure 6**). In particular, HM2 had a considerable impact on the lateral position maintained by drivers. At the SC section, the trajectory of drivers travelling in the ramp terminal with HM2 was significantly closer to the lane centerline, a result in keeping with the experimental hypothesis ($LP_{SC,HM2}$ - $LP_{SC,HM1}$ = -0.413 m, $p < .001$). However, this difference is only marginally significant at the end of the terminal

($LP_{TS,HM2}$ - $LP_{TS,HM1}$ = -0.150 m, p = .055). In the case of HM3, the results at the SC section indicate that drivers stayed closer to the lane centerline with respect to the conventional marking HM1 ($LP_{SC,HM3}$ - $LP_{SC,HM1}$ = 0.198 m, p < .001), albeit no significant differences (p < .556) were found at the terminal end (TS section).

The effect of the connection type (*CT*) on lateral position was significant for both sections (TS and SC). At the TS section, drivers maintained their position on the right side of the lane in the continuous connection type but failed to do so on the reverse one ($LP_{TS,R}$ - $LP_{TS,C}$ = -0.516 m, p < .001). At the beginning of the ramp (SC), results show that drivers tended to drive closer to the lane centerline in the reverse connection type ($LP_{SC,R}$ - $LP_{SC,C}$ = -0.399 m, p < .001). While traffic volume did have a slight impact on the lateral behavior of drivers, it was only at the beginning of the ramp curve (SC) as evidenced in **Table 2** ($LP_{SC,3000}$ - $LP_{SC,1000}$ = 0.075 m, p = .042). The results are in line with those obtained by Portera and Bassani (*24*): traffic volume on the motorway has no impact on the lateral position of the vehicle at the end of the terminal (TS).

FIGURE 6. Plots of lateral position (*LP*), for the three horizontal markings designs at (a) TS and (b) SC sections.

Figure 6 shows the effect of the interaction between *HM* and connection type on lateral positions at TS and SC sections. In **Figure 6a**, similar trends for both connection types with different HMs are depicted. Although no statistically significant differences were found at the TS section, Figure 6a indicates that HM2 led to an improved LP (LP close to 0) with respect to HM1 and HM3 in continuous ramp-terminal connections. Conversely, HM2 increased the distance between the vehicle CoG and the lane centerline in reverse connections. Significant effects on the lateral position at the beginning of the ramp (SC section) were found for both continuous and reverse ramp designs (**Figure 6b**). At the TS section, the HM2 was on the right side of the lane only (see Figure 1e and Figure 1h), and thus the perception of a narrowing lane was not as strong. Conversely, at the SC section, the HM2 is on both sides and, therefore, has a greater impact on driver perception. A post-hoc test with Bonferroni correction indicates a significant difference between HM1 and HM2 ($LP_{SC,R,HM1}$ - $LP_{SC,R,HM2}$ = 0.298 m, t_{257} = 4.17, p < .001). Similar outcomes were found for the continuous connection type ($LP_{SC,C,HM1}$ - $LP_{SC,C,HM2}$ = 0.528 m, t_{243} = 7.80, p < .001). In this case, the differences between HM1 and HM3 were also significant ($LP_{SC,C,HM3}$ - $LP_{SC,C,HM1}$ = 0.292 m, t_{260} = 4.05, p = .001).

Diverging abscissa

The *LMM* for the diverging abscissa produced poor quality results, with residuals that were not normally distributed (p < .001). A Shapiro-Wilk test revealed that 7 out of the 24 groups of *DA* data split into the four experimental factors (HM, connection type, lighting conditions, and traffic volume, levels: 3×2×2×2=24) were not normally distributed. As a result, the *glm* was used to interpret this set of experimental data.

glm outputs (**Table 2**) indicate that innovative HMs impacted on *DA* in different ways: drivers responded to HM2 by adopting a longer *DA* than they did with HM1, conversely HM3 did not significantly reduce the *DA* in comparison to HM1. A post-hoc test with Bonferroni correction confirmed this outcome (DA_{HM1} - DA_{HM3} = 3.04 m, z = 0.51, p = .605). Furthermore, according to the data in **Figure 4**, the connection type had a relevant impact for reverse ramp terminal connections exhibiting larger values of *DA* than those observed along continuous ones (DA_C - DA_R = -30.63 m, z = -6.47, p < .001). Driver experience and age also had a relevant effect on *DA*, with more experienced drivers tending to enter the terminal at higher *DA* values than less experienced ones, and older drivers tending to initiate the diverging maneuver into the terminal sooner than younger drivers. These trends are in line with previous studies which observed a different attitude to risk taking among drivers of different ages (*55*) and with different levels of experience (*56*).

CONCLUSIONS

This study investigated the hypothesis that innovative horizontal markings (HMs) might result in longitudinal and transversal driving performances along diverging ramp terminals superior to those achieved with conventional markings. In this experiment, horizontal marking of type 2 (HM2) was designed to act on the driver's perception of the lane width. The sense of lateral constraint would encourage the driver to maintain a centered trajectory in the lane. Horizontal marking of type 3 (HM3) was intended to work mainly on speed perception by acting on driver peripheral vision (i.e., the distance between the external bands was progressively reduced), leading drivers to believe they were increasing speed. With HM3, the hypothesis is that drivers react to this perception by reducing their speed to values lower than those observed with conventional markings (HM1).

The experimental outcomes revealed that both alternative HM types (i.e., HM2 and HM3) had a positive effect on the behavior of drivers involved in this maneuver. In particular, exposure to HM2 resulted in a clear improvement in lateral behavior as hypothesized with drivers closer to the continuous terminal centerline when approaching the ramp (section SC, spiral-to-curve). 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 standard design (HM1). HM2 also had a significant impact on speeds, which were lower than in cases where drivers interacted with HM1. In fact, the effect of a perceived reduction in lane width is also extended to speeds, which were lower in all the considered sections in the case of the alternative design HM2 independently of the traffic and environmental lighting conditions. Similarly, and in line with the hypothesis, HM3 had a significant effect on speed, resulting in improved driver longitudinal control at the end of the terminal (section TS, terminal-to-spiral). Nevertheless, it promoted better lateral behavior only when the driver was close to the ramp. In those specific sections, the ramp shoulders were indicated by the markings with the result that the lane contours were clearly visible making it easier for drivers to position their vehicles in the center.

In this study, the geometric difference between the two types of connection joining the curved terminal to the ramp was considered. With the continuous connection type, HM2 had a significant positive impact on longitudinal and transversal driver response. HM3, in contrast, had a lower and, indeed, in some cases negligible impact on both speed and lateral position. With the reverse design, drivers merged into the terminal and arrived at the ramp at a higher speed than they did with the continuous design. However, the innovative markings contributed more than conventional one to a reduction in speeds. The connection type also impacted on the driver position in the lane along the same connection, with HM2 allowing drivers to maintain a trajectory which was mostly centered in the lane. However, innovative HMs were not able to contrast the tendency of some drivers to change lane at the end of the reverse terminal when exiting from same. As a result, in this specific case, it is necessary to contrast this inappropriate behavior with the use of alternative countermeasures.

This research confirms the effectiveness of the perceptual techniques used in these specific areas of road design, where drivers are engaged in maneuvers involving changes to speed and/or trajectory. The study demonstrated that innovative markings influence both lateral and longitudinal perceptions leading to improved driver performances and, consequently, contribute in part to an increase in the safety of diverging operations as drivers move from the motorway to the ramp.

The work carried out has limitations as it focused on the influence of a limited number of independent variables, while excluding others from active consideration. The effects of the motorway radius, traffic barriers, and surrounding vehicles in the terminal are all variables which merit investigation in future studies.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: M. Bassani, G. Raimondo, A. Portera; data collection: A. Portera, G. Raimondo; analysis and interpretation of results: M. Bassani, A. Portera, L. Tefa, A. Lioi, A. Hazoor; draft manuscript preparation: M. Bassani, A. Portera, L. Tefa, A. Lioi, A. Hazoor. All authors reviewed the results and approved the final version of the manuscript.

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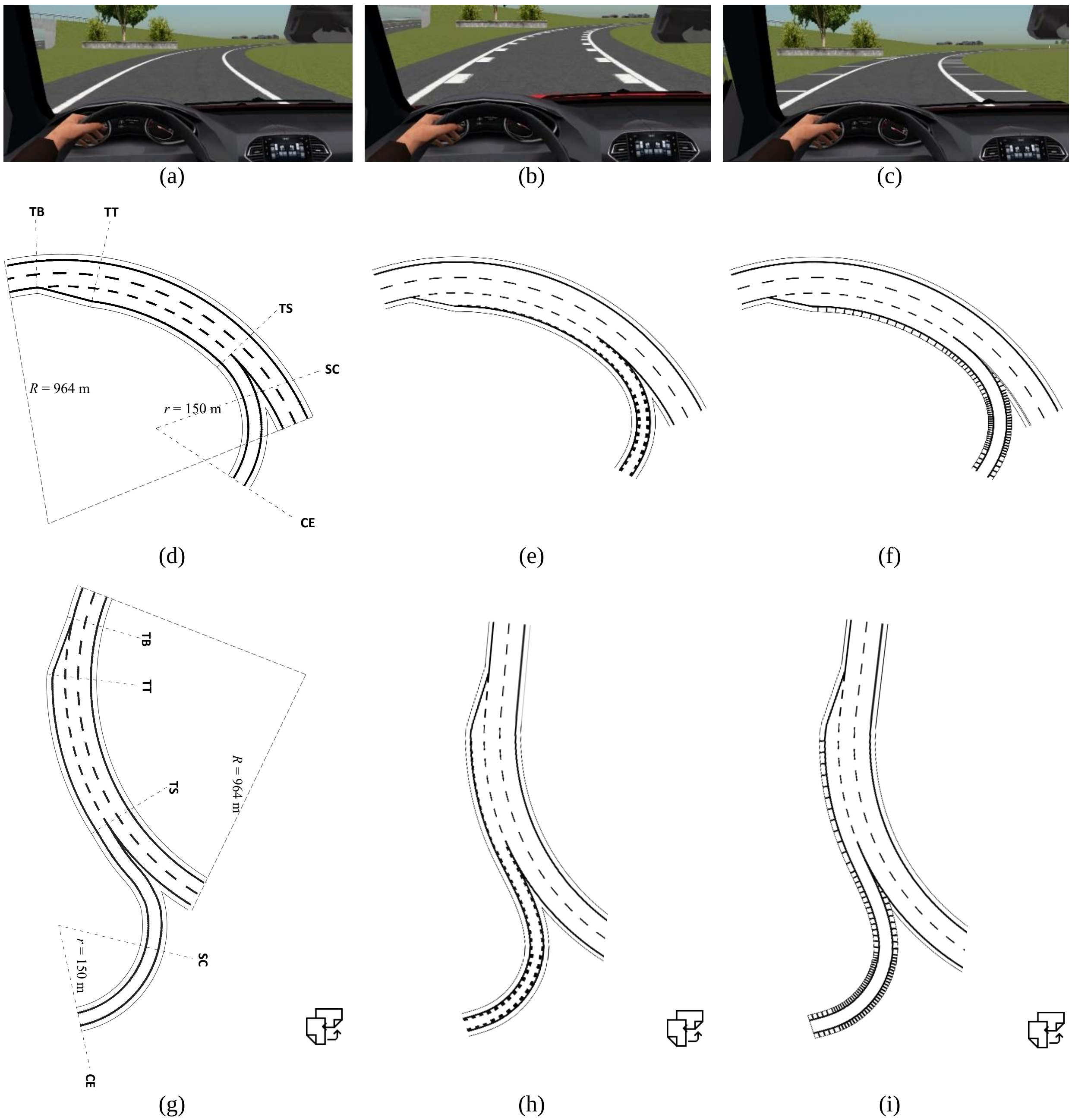


FIGURE 1. Images showing the three HMs and the two ramp terminal connection types (continuous and reverse). Vision of the three HMs from the driver point of view: (a) HM1 (baseline), (b) HM2 (type 2), and (c) HM3 (type 3). Plan view of the three layouts: (d) HM1 continuous ramp terminal, (e) HM2 continuous e ramp terminal, (f) HM3 continuous ramp terminals, (g) HM1 reverse ramp terminals, (h) HM2 reverse ramp terminals, and (i) HM3 reverse ramp terminals (TB = taper begin, TT = taper-to-terminal, TS = terminal-to-spiral, SC = spiral-to-curve, CE = curve end).

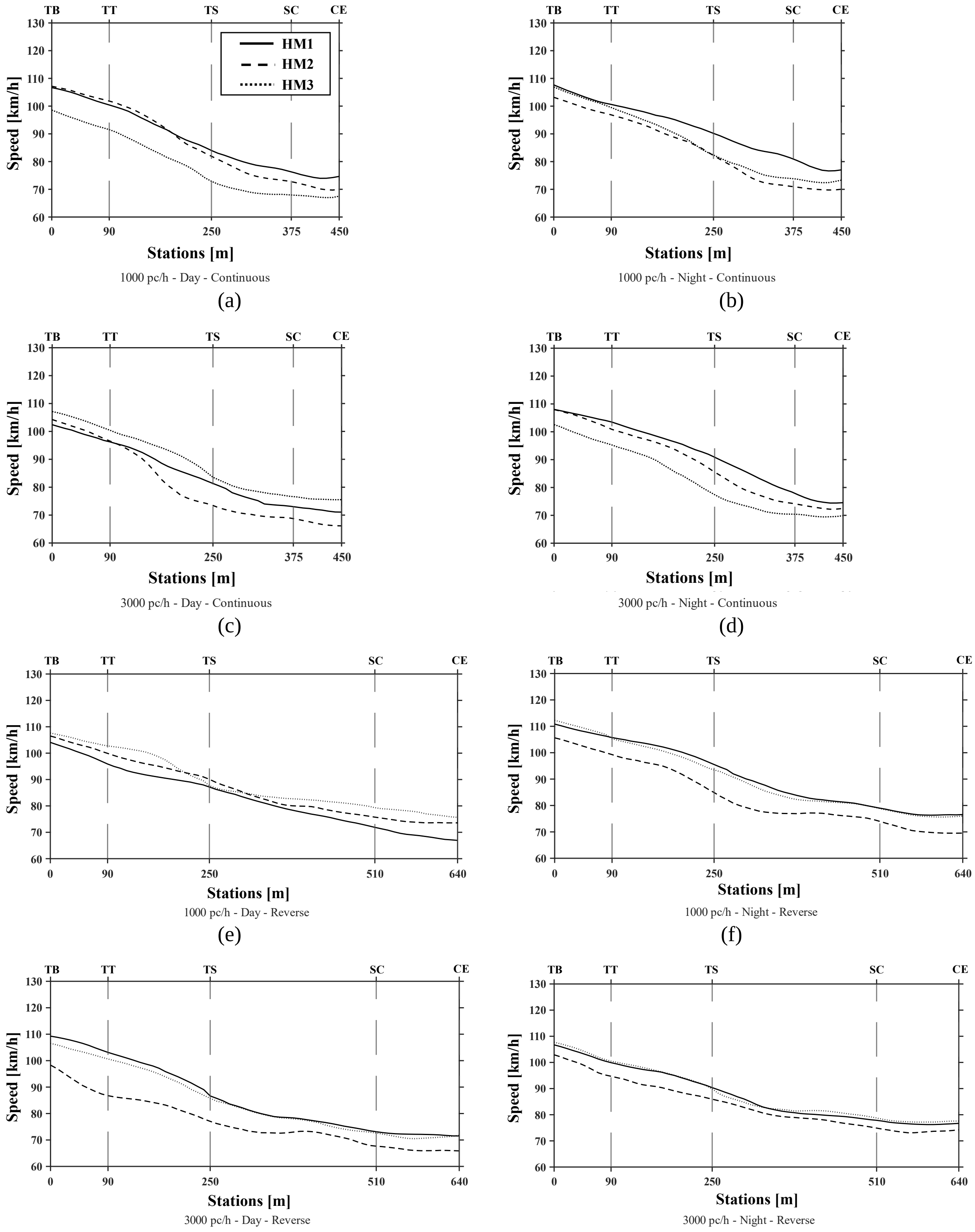


FIGURE 2. Longitudinal (speed) behavior along curved deceleration ramp terminals with a range of experimental factor combinations (TB = taper begin, TT = taper-to-terminal, TS = terminal-to-spiral, SC = spiral-to-curve, CE = curve end).

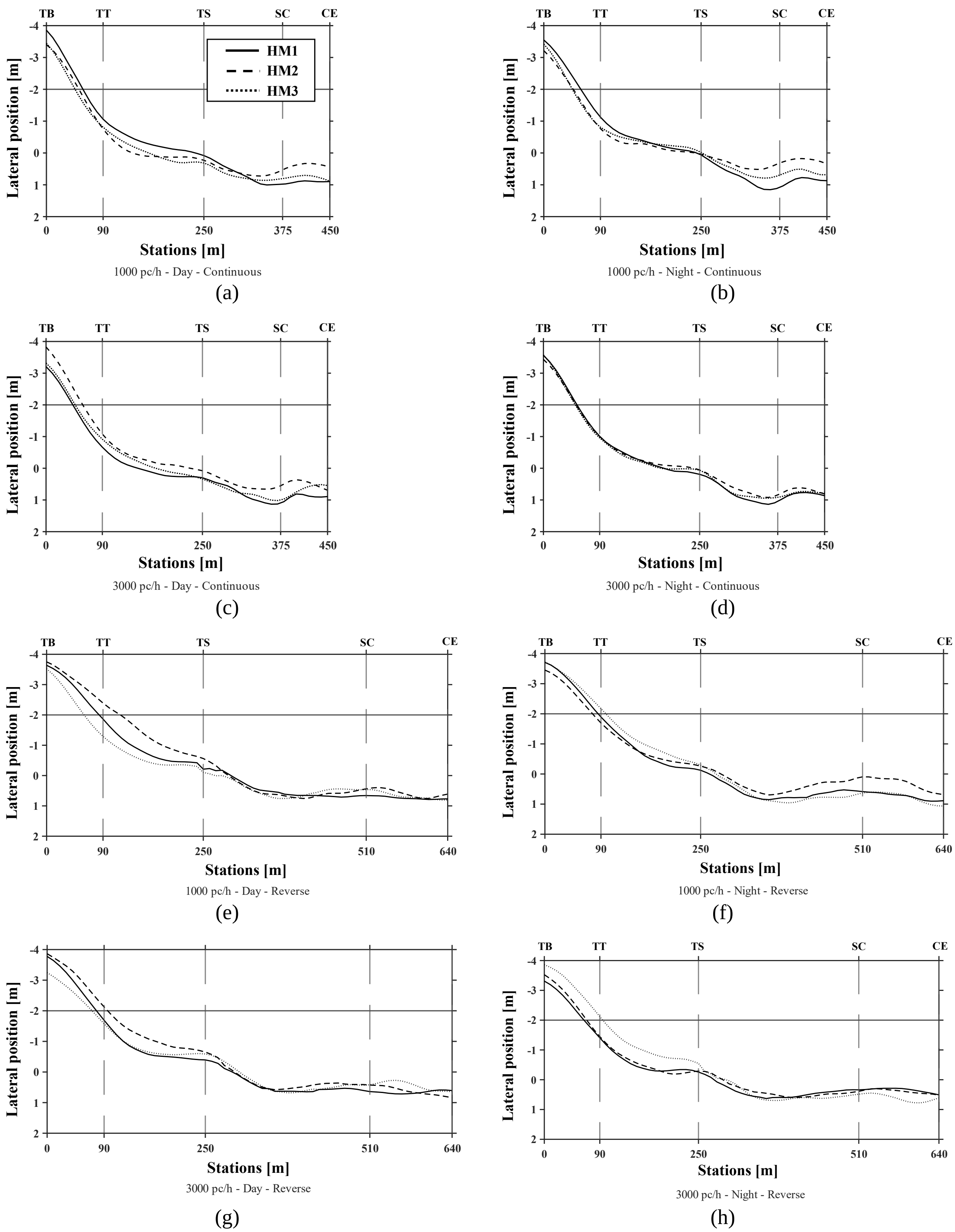


FIGURE 3. Transversal (lateral position) behavior along curved deceleration ramp terminals with variable experimental factor combinations (TB = taper begin, TT = taper-to-terminal, TS = terminal-to-spiral, SC = spiral-to-curve, CE = curve end).

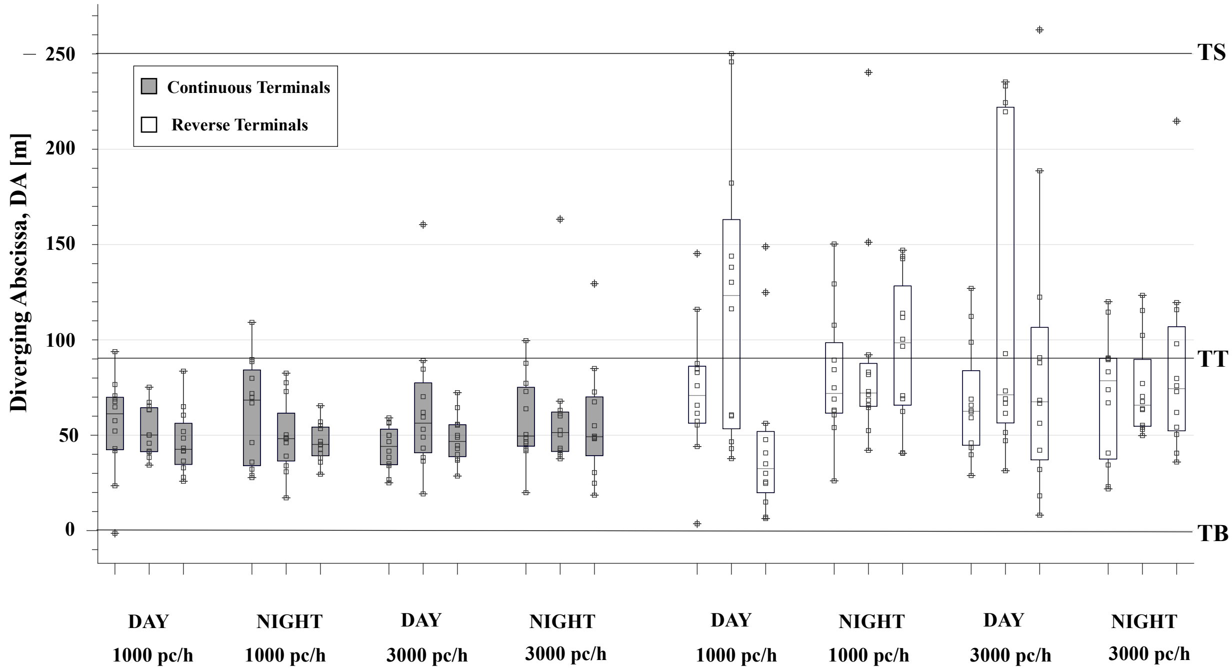


FIGURE 4. Boxplots of diverging abscissa for three HM designs in continuous and reverse ramp terminals.

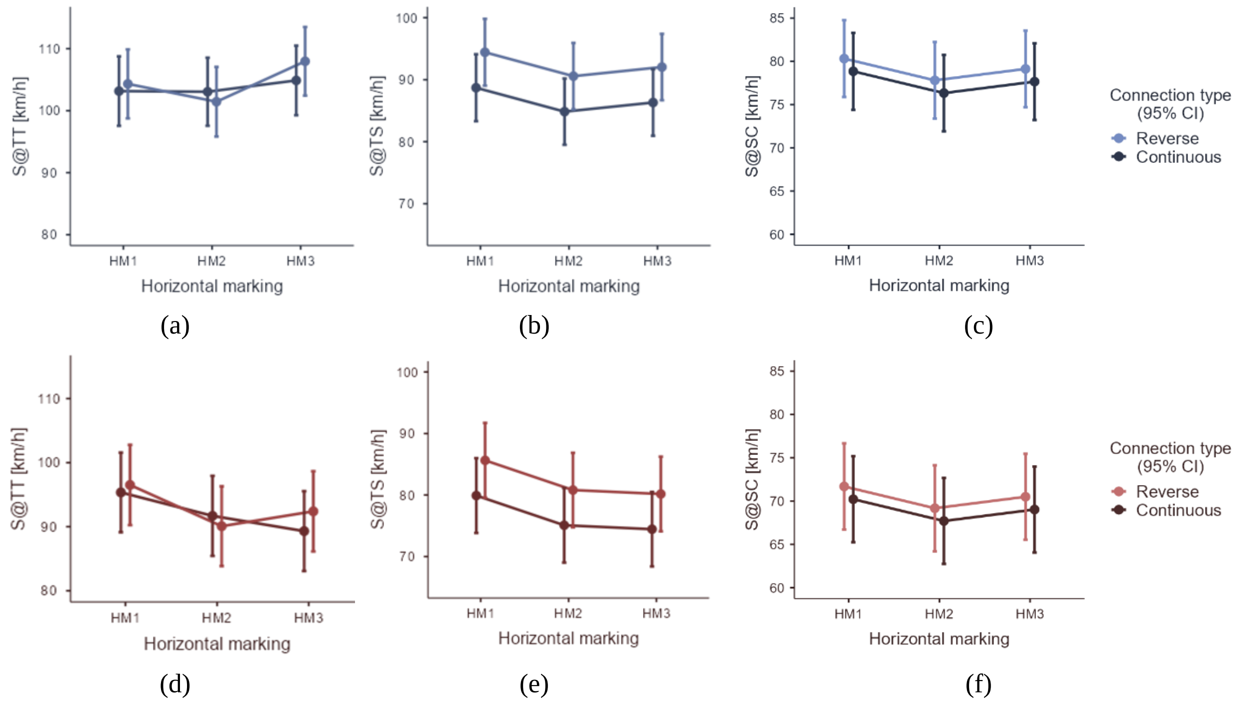
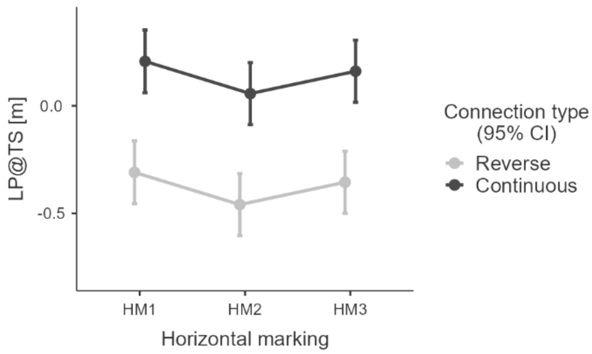
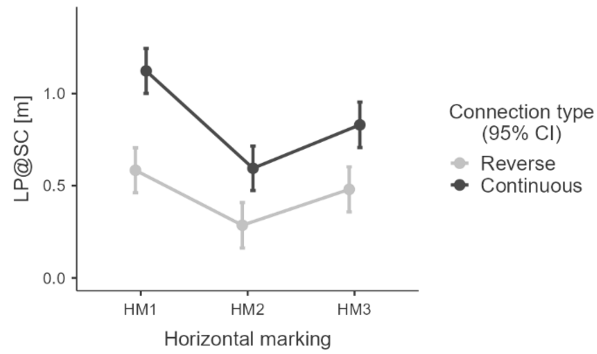


FIGURE 5. Speeds (*S*) for horizontal markings designs at TT (a, d), TS (b, e) and SC (c, f) sections. (a), (b) and (c) plots refer to male drivers, while (d), (e) and (f) refer to female drivers.

Figure 6 Click here to access/download;Figure;Figure 6.pdf



(a)



(b)

FIGURE 6. Plots of lateral position (*LP*), for the three horizontal markings designs at (a) TS and (b) SC sections.