

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

Original

Longitudinal and Transversal Driver Behaviour with Innovative Horizontal Markings Along Curved Motorway On Ramps and Terminals / Bassani, Marco; Portera, Alberto; Raimondo, Giorgia. - In: TRANSPORTATION LETTERS. - ISSN 1942-7867. - ELETTRONICO. - (2023). [10.1080/19427867.2022.2035121]

Availability:

This version is available at: 11583/2954845 since: 2022-02-08T12:08:29Z

Publisher:

Taylor and Francis

Published

DOI:10.1080/19427867.2022.2035121

Terms of use:

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

Publisher copyright

Taylor and Francis preprint/submitted version

This is an Author's Original Manuscript of an article published by Taylor and Francis in TRANSPORTATION LETTERS on 2023, available at <http://www.tandfonline.com/10.1080/19427867.2022.2035121>

(Article begins on next page)

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

3
4

5 **Marco Bassani** ¹ (*)

6 (*) = corresponding author

7 marco.bassani@polito.it

8 **ORCID: 0000-0003-2560-1497**

9
10

11 **Alberto Portera** ¹

12 alberto.portera@polito.it

13 **ORCID: 0000-0002-6685-4805**

14 <https://it.linkedin.com/in/alberto-portera-75a40367>

15
16

17 **Giorgia Raimondo** ¹

18 giorgia.raimondo@studenti.polito.it

19 <https://it.linkedin.com/in/giorgia-raimondo-484291197>

20

21 ¹ Department of Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino
22 24, corso Duca degli Abruzzi, Torino, 10129 - Italy.

23
24

25 **2021 World Transport Conference paper**

26 Paper number: GL0404-P-001

27

28 **ABSTRACT**

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

38
39 **KEYWORDS:** On-ramp terminal, clothoid, driver behaviour, driving simulation, horizontal markings.

40

41

PREPRINT VERSION

42 **1 INTRODUCTION**

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

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

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

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

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

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

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

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

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

98 The data were collected on curved on-ramp-terminals. The experiment was carried out at the fixed-base
99 driving simulator at the Road Safety and Driving Simulation Lab of the Politecnico di Torino. The behaviour
100 of forty-eight licensed participants was evaluated for the three different horizontal markings, two traffic flows
101 (1000 pc/h and 3000 pc/h), and two lighting conditions (day and night). In addition, simulations included
102 driving on two different curved on-ramp terminals, one continue ramp-terminal and one reverse ramp-terminal.
103

104 **2 METHOD**

105 **2.1 Setting**

106 The fixed-base driving simulator (AV Simulation, France) was relatively validated for speed (Catani, 2019,
107 Bassani et al., 2018) and lateral behaviour (Catani & Bassani, 2019). The vision system was made up of three
108 32-inch full HD covering approximately 130° of the driver field of view. SCANeRStudio™ (AV Simulation,
109 France) was used to design tracks, manage the vehicle parameters, generate the experimental scenarios, run
110 the simulations, collect and extract data.
111

112 **2.2 Design of road scenarios and horizontal markings**

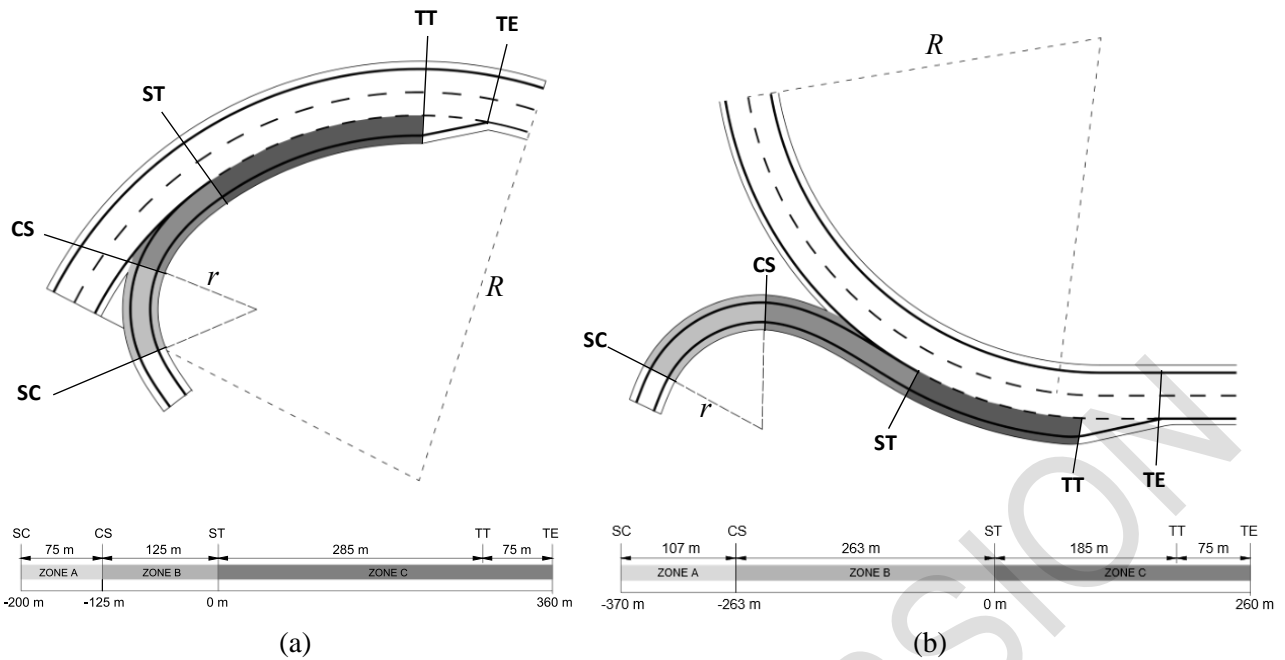
113 Twelve circuits including direct ramps to connect two-lane rural highways to motorway segments were
114 designed to facilitate the performance of merging manoeuvres. Each circuit consisted of two curved motorway
115 sections with an entry ramp located along each motorway. The first ramp had the same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

117 circuit had an opposite curvature to the motorway curve, so a reverse ramp-terminal design was adopted
118 (Figure 1b). Ramps were designed in accordance with the Italian policy for intersection and interchanges (MIT,
119 2006), with terminal lengths designed according to the Highway Capacity Manual (TRB, 2016) for a level of
120 service corresponding to B. The motorway cross-section presented two lanes per direction, with a lane width
121 of 3.75 m and a right shoulder width of 3 m. According to the Italian Policy (MIT, 2006), the ramp had one 4
122 m wide lane and two 1.5 m wide shoulders.

123 Ramp terminals were located along curved sections. The radius of the motorway (R) was set equal to
124 964 m, which is the minimum radius for the maximum design speed for Italian motorways (140 km/h). The
125 ramp radius was set to $r = 150$ m with a design speed of 60 km/h. In the case of the continue terminal
126 (Figure 1a), the connection between terminal and ramp was an egg-shaped 125 m long clothoid, and the ramp
127 terminal of 285 m long. In the reverse terminal (Figure 1b), the clothoid was a reverse S-shape design and was
128 263 m long, and the ramp terminal was 185 m long. The clothoid lengths are different because of their shape
129 despite having the same scale factor (set equal to 150 m). The terminal lengths also differ so as to make it
130 possible for drivers to reach the same design speed at the TT section (120 km/h) under the design acceleration
131 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.

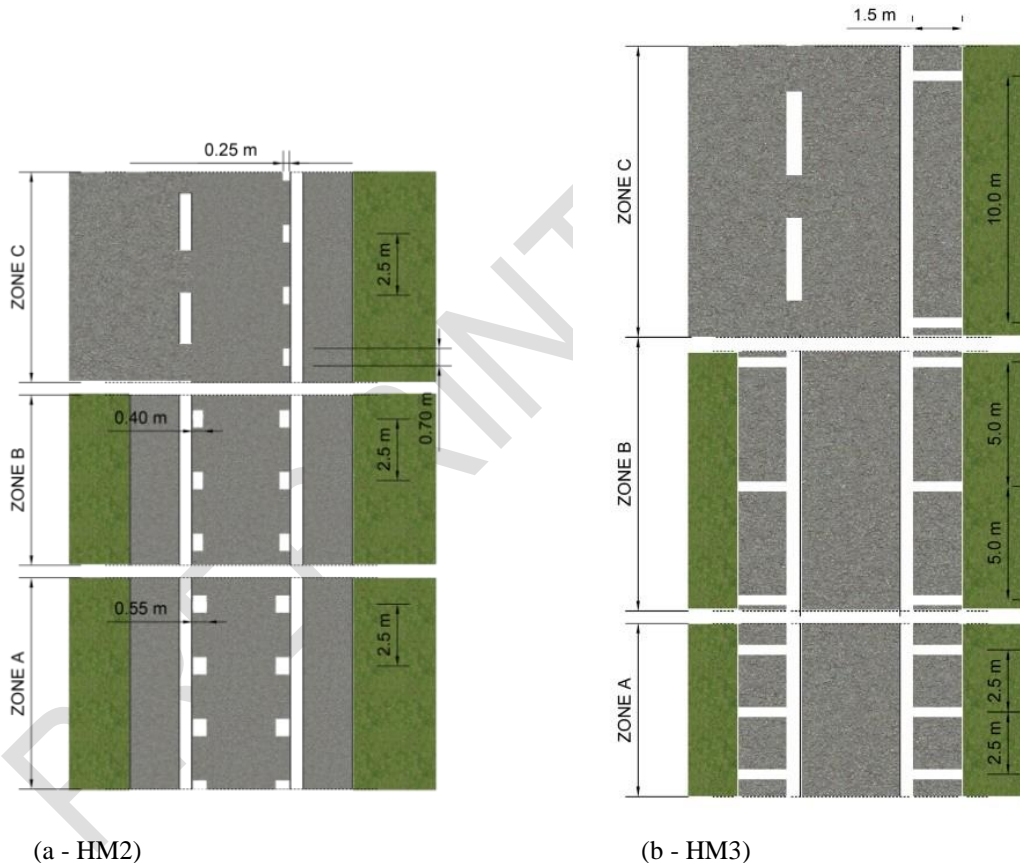
132 The three different horizontal markings were implemented along the entire length of the ramp-terminal
133 system (Figure 2). Each ramp was divided into three zones (Figure 1). Zone A is the circular portion of the
134 ramp which starts at the SC section (spiral-to-curve) and ends at the CS section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

142



143
144
145
146

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.



147
148
149
150
151
152

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.

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

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

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

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

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

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

189

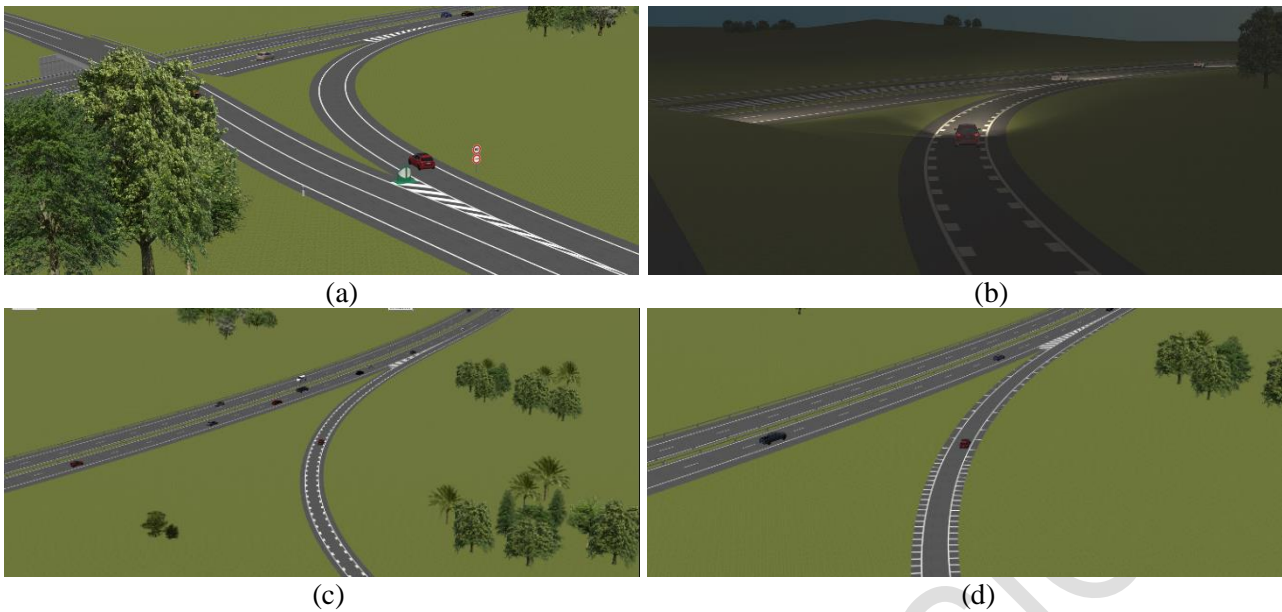


Figure 3. Examples of testing scenarios: (a) continue ramp-terminal daytime condition with HM1, (b) continue ramp-terminal night-time condition with HM2, (c) reverse ramp-terminal daytime condition with HM2, (d) reverse ramp-terminal daytime condition with HM3.

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

215 experiment; the post-drive questionnaire was related to the virtual environment and the subjective judgment
216 of the driving experience.

217 Cognitive tests were administered to check for any possible variation in cognitive performance before
218 and after driving. The test was carried out on the available tool on <http://cognitivefun.net/>. Attentional response
219 times to both visual (visual reaction test) and auditory stimuli (auditory reaction test) were recorded. Cognitive
220 test results showed that the experiment did not induce any significant change(s) in attentional responses. This
221 result was confirmed by the t-test carried out on, before and after data on the visual reaction time ($t_{94} = -0.463$,
222 $p = .64$), and the auditory stimuli ($t_{94} = 0.087$, $p = .93$). This result confirms that driver performance remained
223 constant during the experiment, and that drivers did not suffer from any excessive mental workload, which
224 might have influenced their performance levels.

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

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

240

241 **2.5 Data analysis and modelling**

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

244 Linear mixed-effect models (LMM) fit with a restricted maximum likelihood (REML) algorithm were
245 calibrated to determine which factors conditioned the driver's longitudinal and transversal behaviour along the
246 investigated road scenarios. LMM include both fixed and random effects and predict the degree to which the
247 experimental outcomes depend on the variables (i.e., horizontal marking type, traffic conditions, lighting
248 conditions, and gender) and covariates (i.e., age and driving experience of participants) as fixed effects, and
249 clustered variables (i.e., test driver ID) which were included as random effects. In LMM, random effects are
250 assumed to be normally distributed with a null mean. Model calibration and all statistical tests (e.g., post-hoc

251 analyses with Holm correction, and simple effect analysis) were carried out through *Jamovi* (ver. 1.8.1.0), with
252 the submodule GAMLj (ver. 2.4.7) (www.jamovi.org/).

253

254 **3 RESULTS**

255 **3.1 Continue ramp-terminal**

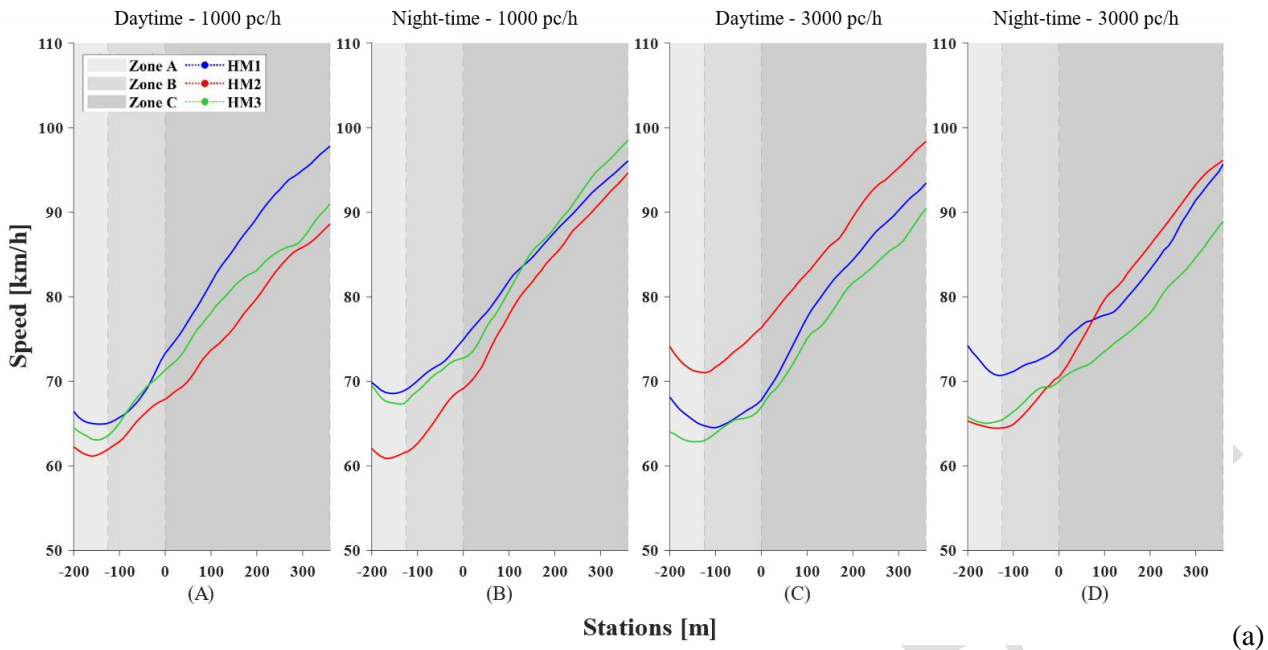
256 Longitudinal behaviour has been described through speed data. Figure 4a shows the average speeds recorded
257 along seven significant sections indicated in Figure 1a, with the three different horizontal markings, the two
258 lighting and the two-traffic flow conditions in the through motorway lanes.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

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

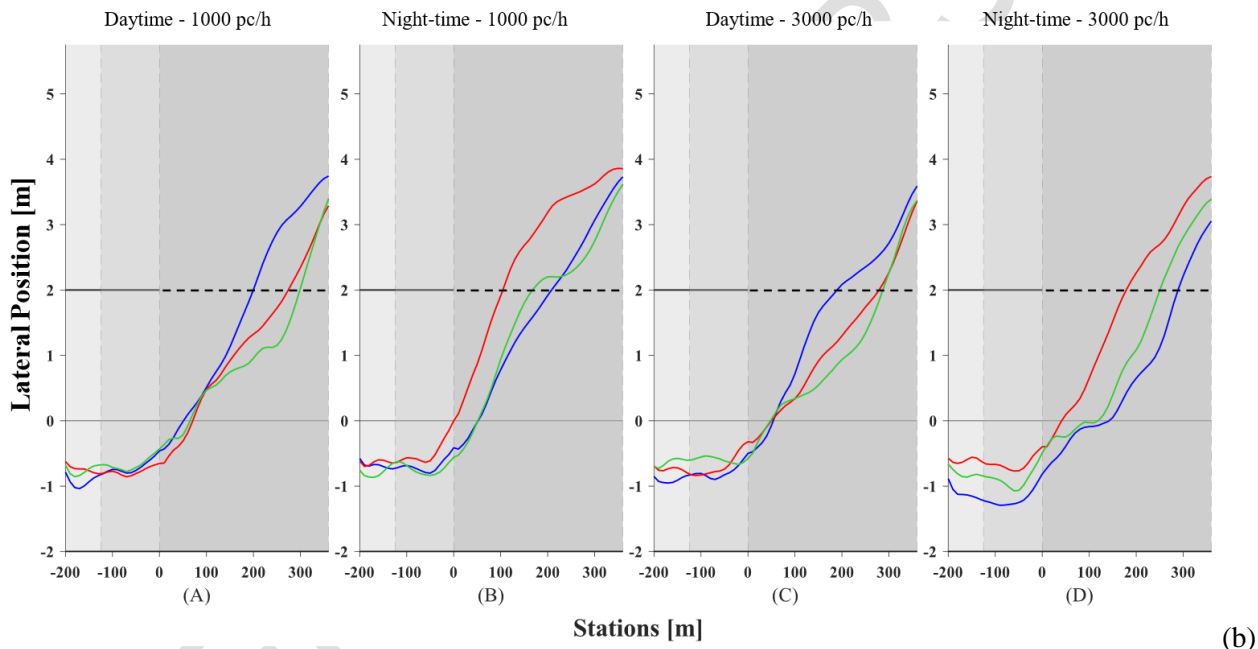
266 In the case of a 1000 pc/h traffic flow in Figures 4a(A) and Figure 4a(B), the lowest speeds were
267 recorded with HM2. Conversely, in the daily case with 3000 pc/h flow, the highest speeds were observed with
268 HM2. Drivers subjected to HM1 and HM3 generated similar speed values; in Figure 4a(D),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

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

276



277



278

279

280

281

282

283

284

285

286

287

288

289

290

291

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

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

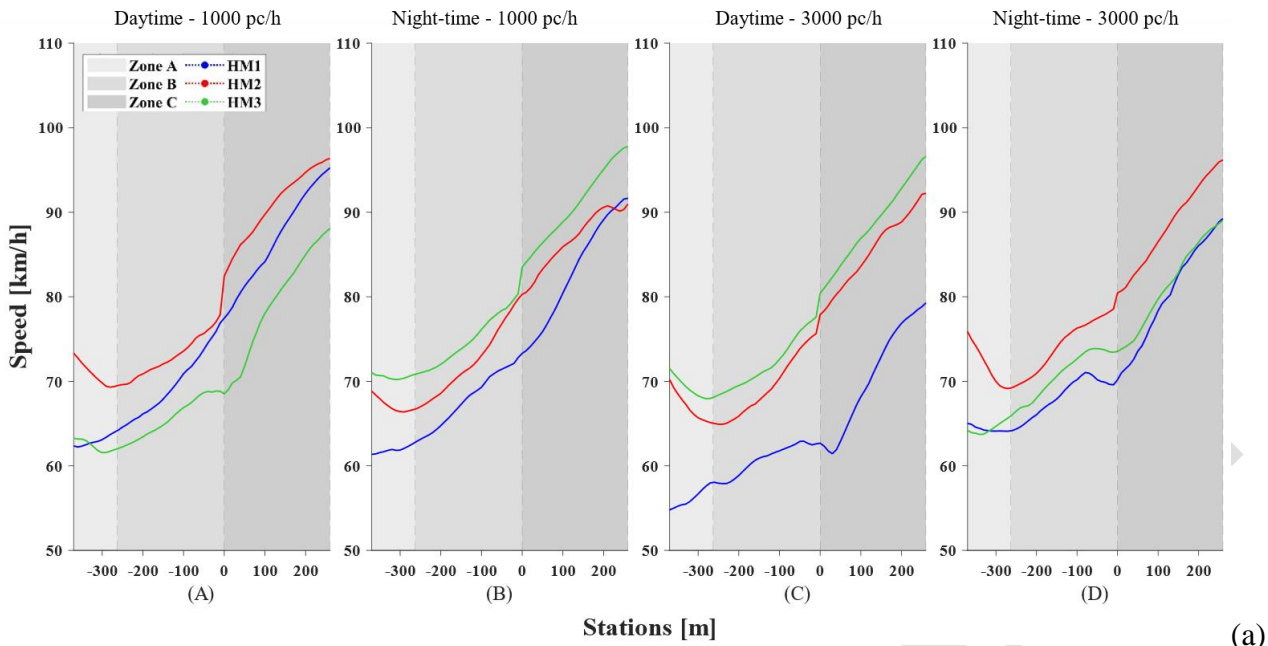
294

295 **3.2 Reverse ramp-terminal**

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

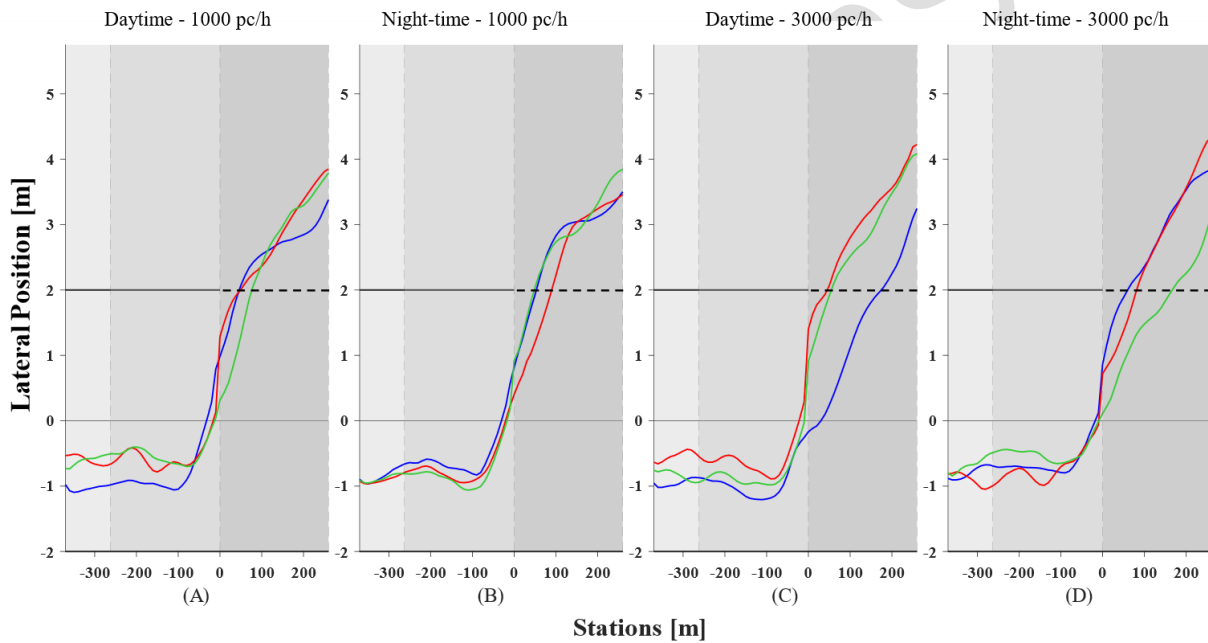
304

PREPRINT VERSION



305

(a)



306

(b)

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

309

310 4 ANALYSIS

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

317

318 **4.1 Continue ramp-terminal**

319 From a calibration of the LMM on speed data, the influence of the innovative HM on speeds proved negligible
320 (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
321 developed for speeds @ST and @TT, the fixed effects associated with participants accounted for more than
322 22% of the total variance in the model. Gender was considered as a factor and proved significant
323 ($F_{44,7} = 14.966$, $p = <.001$) with males being faster than females. However, covariates relating to the personal
324 characteristics of participants (driver experience and age) were all found to be irrelevant across all the models.
325 According to the experimental hypothesis, driver speeds in zones B and C featuring HM2 and HM3 were
326 expected to travel at a higher speed than those travelling with HM1, with drivers merging into the motorway
327 at speeds close to that of drivers in the motorway through lanes. However, the LMM outcomes fail to support
328 this hypothesis. This is explained by the fact that the peripheral vision of drivers merging into zone C cannot
329 process the information provided by the additional markings (Figure 2). Finally, no other experimental factors
330 had an impact on the speed decision.

331 Contrary to what was observed for speeds, LMM indicates that HM type significantly influenced the
332 lateral position of the vehicle. Figure 6 evidences that vehicles subject to the influence of innovative HM
333 remain closer to the ramp centreline than they do in the presence of ordinary HM. When TF = 3000 v/h and
334 during daytime, the difference in LP between HM3 and HM1 is significant ($t_{111} = 2.383$, $p = 0.019$), as it is
335 during night-time between HM2 and HM1 ($t_{103} = 3.014$, $p = .003$), and between HM3 and HM1 ($t_{116} = 2.227$,
336 $p = .028$). Figure 6b also indicates that during night-time, drivers reacted to the higher volume of traffic on the
337 motorway by keeping a larger lateral distance, i.e. maintaining the vehicle closer to the right lane edge. In
338 contrast, drivers approaching the terminal in conditions of lower traffic volumes did not adopt such wide lateral
339 distance values.

340 Nevertheless, the positive influence of HM2 on transversal behaviour is evident in both Figure 6c and
341 6d, with drivers maintaining better trajectory control during both daytime and night-time conditions.
342 Surprisingly, HM3 was found to be ineffective on SDLP in daytime conditions (Figure 6c). It is worth noting
343 that the calibrated LMM for SDLP suffers from heteroscedasticity of residuals as indicated by the normal
344 distribution violation as per the KS test ($p < .001$), due to the excessive SDLP values of four of the 48 drivers.
345 It is also worth noting that Schielzeth et al. (2020) observed that LMM are robust enough even when
346 assumption checks are violated.

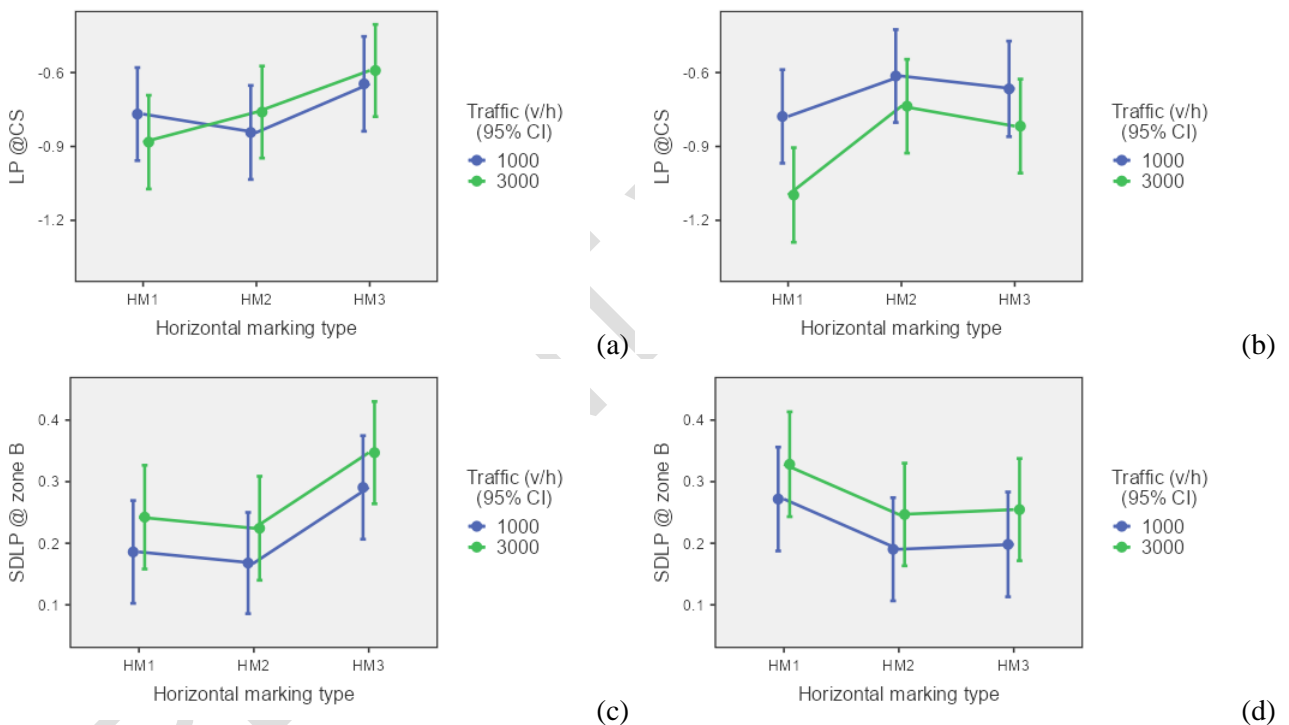
347 Traffic volume impacts on the lateral behaviour of drivers as evidenced in Table 2. This effect is
348 explained by the absence of any traffic barriers or sight obstructions restricting the view of oncoming
349 motorway traffic from the ramp. During night-time when TF = 3000 v/h, drivers drove closer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

353
354
355

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

Variables	Effect	Estimated model coefficients (p-value)			
		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

358



359

360

361 **Figure 6. (a, b) Lateral position @CS and (c, d) standard deviation of lateral position along zone B (the**
 362 **ramp-terminal connection) during day (a, c) and night-time (b, d) lighting conditions for the continue**
 363 **ramp-terminal**
 364

365 **4.2 Reverse ramp-terminal**

366 In the case of the reverse ramp-terminal, the interrelation between the innovative horizontal markings and
 367 longitudinal and transversal user behaviour is more complex. Interactions between HM type and lighting
 368 conditions were captured by the LMM (Table 3). Along the ST section during daytime conditions and low
 369 traffic volumes, HM2 ($t_{99.8} = 3.187$, $p = .002$) results in drivers travelling at higher speeds than with HM1,
 370 while speeds at the highest traffic volumes for both HM2 ($t_{101.7} = 2.413$, $p = .018$) and HM3 ($t_{96.6} = 2.577$,
 371 $p = .011$) were found to be significantly higher than speeds with baseline conditions (i.e., HM1). Similar trends
 372 were observed with the TT section. This outcome differs from that of the continue case, because the reverse

373 clothoid used for this ramp-terminal connection is longer than that used in the continue connection. A longer
 374 ramp-terminal connection ensures that drivers are exposed to the innovative marking for a longer time before
 375 merging into the motorway. It is worth noting that the higher the speed of merging vehicles along the terminal,
 376 the less disruptive the interaction between motorway through traffic and merging vehicles.

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

381 Slightly lower values for SDLP were recorded in the case of HM2 and night-time conditions (Figure 7).
 382 In night-time conditions, no significant differences were observed between the three horizontal markings. In
 383 daytime conditions and for low traffic levels, significant reductions in SDLP values under HM3 ($t_{112} = -2.976,$
 384 $p = .004$) and non-significant reductions under HM2 ($t_{116} = -1.613, p = .110$) were observed with respect to
 385 conventional HM.

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

388

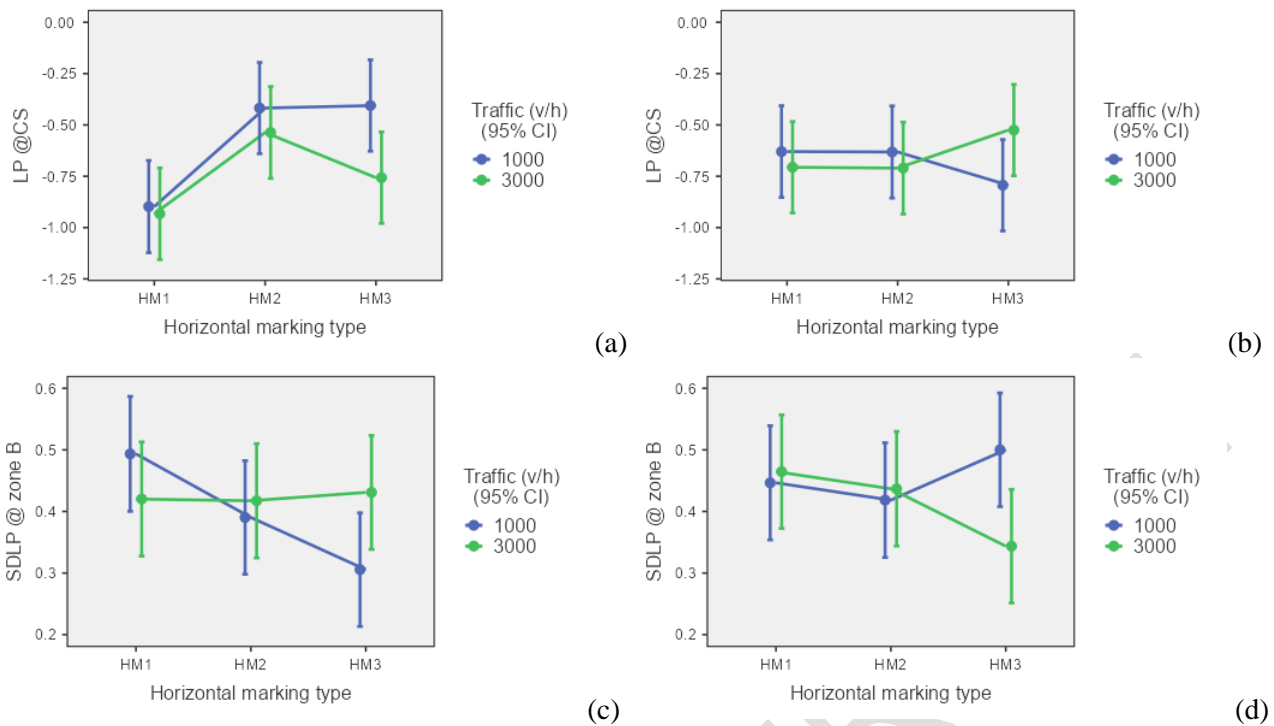
389 **Table 3. LMM outputs on significant factors affecting speeds, LP and SDLP along reverse terminals**
 390 **(HM = horizontal markings type, TF = traffic flow, LC = lighting conditions)**

Variables	Effect	Estimated model coefficients (p-value)			
		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

391

392

393



394

395

396

397

398

399

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

400

5 DISCUSSION AND CONCLUSIONS

401

402

403

404

405

406

407

408

409

410

411

412

413

414

415

416

417

418

419

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.

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

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

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

442

443 REFERENCES

- 444 Ahammed, M. A., Hassan, Y., and T.A. Sayed. 2008. "Modeling Driver Behavior and Safety on Freeway Merging
445 Areas". *Journal of Transportation Engineering* 134(9): 370-377. doi: [https://doi.org/10.1061/\(ASCE\)0733-
446 947X\(2008\)134:9\(370\)](https://doi.org/10.1061/(ASCE)0733-947X(2008)134:9(370)).
- 447 Ariën, C., Brijs, K., Vanroelen, G., Ceulemans, W., Jongen, E.M., Daniels, S., Brijs, T., and G. Wets. 2017. "The
448 effect of pavement markings on driving behaviour in curves: a simulator study". *Ergonomics* 60(5): 701-713.
449 doi: <http://dx.doi.org/10.1080/00140139.2016.1200749>.
- 450 Awan, H.H., Pirdavani, A., Houben, A., Westhof, S., Adnan, M., and T. Brijs. 2019. "Impact of Perceptual
451 Countermeasures on Driving Behavior at Curves Using Driving Simulator". *Traffic Injury Prevention*
452 20(1): 93–99. doi: <https://doi.org/10.1080/15389588.2018.1532568>.
- 453 Catani, L., and M. Bassani. 2019. "Anticipatory Distance, Curvature, and Curvature Change Rate in Compound
454 Curve Negotiation: a Comparison Between Real and Simulated Driving". *Proceedings of the 98th
455 Transportation Research Board Annual Meeting*, Washington DC, US.
- 456 Babić, D., Fiolčić, M., Babić, D., and T. Gates. 2020. "Road Markings and Their Impact on Driver Behaviour and
457 Road Safety: A Systematic Review of Current Findings". *Journal of Advanced Transportation*, 2020: 7843743.
458 doi: <https://doi.org/10.1155/2020/7843743>.

- 459 Babić, D., and T. Brijs. 2021. “Low-Cost Road Marking Measures for Increasing Safety in Horizontal Curves: A
460 Driving Simulator Study”. *Accident Analysis and Prevention* 153: 106013. doi
461 <https://doi.org/10.1016/j.aap.2021.106013>.
- 462 Bassan, S. 2016. “Sight Distance Restriction on Highways’ Horizontal Curves: Insights and Sensitivity Analysis”.
463 *European Transport Research Review* 8(3): 21. doi: <https://doi.org/10.1007/s12544-016-0208-6>.
- 464 Bassani, M., Catani, L., Ignazzi, A. A., and M. Piras. 2018. “Validation of a Fixed Base Driving Simulator to Assess
465 Behavioural Effects of Road Geometrics”. *Proceedings of the DSC 2018 EUROPE VR Driving Simulation*
466 *Conference & Exhibition* (pp. 101–108), Antibes, France.
- 467 Ben-Bassat, T., and D. Shinar. 2011. “Effect of Shoulder Width, Guardrail and Roadway Geometry on Driver
468 Perception and Behavior”. *Accident Analysis and Prevention* 43(6): 2142-2152.
469 doi: <https://doi.org/10.1016/j.aap.2011.06.004>.
- 470 Calvi, A., and M.R. De Blasiis. 2011. “Driver Behavior on Acceleration Lanes: Driving Simulator Study”.
471 *Transportation Research Record* 2248(1): 96-103. doi: <https://doi.org/10.3141/2248-13>.
- 472 Charlton, S. G. 2007. “The Role of Attention in Horizontal Curves: a Comparison of Advance Warning, Delineation,
473 and Road Marking Treatments”. *Accident Analysis and Prevention* 39(5): 873-885.
474 doi: <https://doi.org/10.1016/j.aap.2006.12.007>.
- 475 Charlton, S. G., Mackie, H. W., Baas, P. H., Hay, K., Menezes, M., and C. Dixon. 2010. “Using Endemic Road
476 Features to Create Self-explaining Roads and Reduce Vehicle Speeds”. *Accident Analysis and Prevention*
477 42(6): 1989-1998. doi: <https://doi.org/10.1016/j.aap.2010.06.006>.
- 478 Charlton, S. G., Starkey, N. J., and N. Malhotra. 2018. “Using Road Markings as a Continuous Cue for Speed
479 Choice”. *Accident Analysis and Prevention* 117: 288-297. doi: <https://doi.org/10.1016/j.aap.2018.04.029>.
- 480 MIT, Ministero delle Infrastrutture e dei Trasporti. 2006. *Norme Funzionali e Geometriche per la Costruzione delle*
481 *Intersezioni Stradali* (in Italian). Decreto Ministeriale 19 Aprile 2006, Roma, Italy.
- 482 MIT, Ministero delle Infrastrutture e dei trasporti. 2001. *Norme Funzionali e Geometriche per la Costruzione delle*
483 *Strade* (in Italian). Decreto Ministeriale 5 novembre 2001, n. 6792, Roma, Italy.
- 484 Denton, G. G. 1980. “The Influence of Visual Pattern on Perceived Speed”. *Perception* 9(4): 393-402.
485 doi: <https://doi.org/10.1068/p090393>.
- 486 Ding, H., Zhao, X., Rong, J., and J. Ma. 2013. “Experimental Research on the Effectiveness of Speed Reduction
487 Markings Based on Driving Simulation: a Case Study”. *Accident Analysis and Prevention* 60: 211-218.
488 <https://doi.org/10.1016/j.aap.2013.08.007>.
- 489 Godley, S.T., Fildes, B.N., Triggs, T.J., and L.J. Brown. 1999. *Perceptual Countermeasures: Experimental*
490 *Research*. Monash University Accident Research Centre, Report Number CR 182, Clay, Victoria, Australia.
- 491 Godley, S.T., Triggs, T.J., and B.N. Fildes. 2004. Perceptual Lane Width, Wide Perceptual Road Centre Markings
492 and Driving Speeds. *Ergonomics* 47(3): 237–256. doi: <https://doi.org/10.1080/00140130310001629711>.
- 493 Hunter, M. P., Guin, A., Boonsiripant, S., and M. Rodgers. 2011. *Evaluation of the Effectiveness of Converging*
494 *Chevron Pavement Markings*. Governor’s Office of Highway Safety, No. FHWAGA-10-0713, Georgia, US.
- 495 Hunter, M. P., Rodgers, M. O., and P. Pratyaksa. 2014. *Safety Performance Evaluation of Converging Chevron*
496 *Pavement Markings*. Georgia Dept. of Transportation. Office of Materials & Research, FHWA-GA-14-1202,
497 Georgia, US.

- 498 Hunter, M., Boonsiripant, S., Guin, A., Rodgers, M. O., and D. Jared. 2010. "Evaluation of Effectiveness of
499 Converging Chevron Pavement Markings in Reducing Speed on Freeway Ramps". *Transportation Research*
500 *Record* 2149(1): 50-58. doi: <https://doi.org/10.3141/2149-06>.
- 501 Hussain, Q., Alhajyaseen, W.K., Reinolmann, N., Brijs, K., Pirdavani, A., Wets, G., and T. Brijs. 2021. "Optical
502 pavement treatments and their impact on speed and lateral position at transition zones: A driving simulator
503 study". *Accident Analysis and Prevention* 150: 105916. doi: <https://doi.org/10.1016/j.aap.2020.105916>.
- 504 Kondyli, A., and L. Elefteriadou. 2012. "Driver Behavior at Freeway-Ramp Merging Areas Based on Instrumented
505 Vehicle Observations". *Transportation Letters* 4(3): 129-142. doi: [https://doi.org/10.3328/TL.2012.04.03.129-](https://doi.org/10.3328/TL.2012.04.03.129-141)
506 [141](https://doi.org/10.3328/TL.2012.04.03.129-141).
- 507 Meyer, E. 2001. "A New Look at Optical Speed Bars". *ITE Journal (Institute of Transportation Engineers)*
508 71(11): 44.
- 509 Montella, A., Aria, M., D'Ambrosio, A., Galante, F., Mauriello, F., and M. Perneti. 2011. "Simulator Evaluation
510 of Drivers' Speed, Deceleration and Lateral Position at Rural Intersections in Relation to Different Perceptual
511 Cues". *Accident Analysis and Prevention* 43(6): 2072-2084. doi: <https://doi.org/10.1016/j.aap.2011.05.030>.
- 512 Portera, A., and M. Bassani. 2020. "Factors Influencing Driver Behaviour Along Curved Merging Interchange
513 Terminals". *Transportation Research Part F: Traffic Psychology and Behaviour* 75: 187-202.
514 doi: <https://doi.org/10.1016/j.trf.2020.10.006>.
- 515 Portera, A., and M. Bassani, M. 2021. "Experimental Investigation into Driver Behavior along Curved and Parallel
516 Diverging Terminals of Exit Interchange Ramps". *Transportation Research Record*, 2675: 254-267. doi:
517 <https://doi-org/10.1177/0361198121997420>.
- 518 Pratyaksa, P. 2013. *Safety Evaluation of Converging Chevron Pavement Markings*. Doctoral dissertation, Georgia
519 Institute of Technology, US.
- 520 Reinolmann, N., Alhajyaseen, W., Brijs, T., Pirdavani, A., Hussain, Q., and K. Brijs. 2019. "Investigating the
521 Impact of Dynamic Merge Control Strategies on Driving Behavior on Rural and Urban Expressways – A
522 Driving Simulator Study". *Transportation Research Part F: Traffic Psychology and Behaviour* 65: 469 484.
523 doi: <https://doi.org/10.1016/j.trf.2019.08.010>.
- 524 Schielzeth, H., Dingemanse, N. J., Nakagawa, S., Westneat, D. F., Allogue, H., Teplitsky, C., Réale, D.,
525 Dochtermann, N.A., Garamszegi, L.Z., and Y.G. Araya-Ajoy. 2020. "Robustness of Linear Mixed - Effects
526 Models to Violations of Distributional Assumptions". *Methods in Ecology and Evolution* 11(9): 1141-1152.
527 doi: <https://doi.org/10.1111/2041-210X.13434>.
- 528 TRB, Transportation Research Board. 2010. *Highway Capacity Manual*. National Academy of Sciences, US.
- 529 Verster, J. C., and T. Roth. 2011. "Standard Operation Procedures for Conducting the on-the-Road Driving Test,
530 and Measurement of the Standard Deviation of Lateral Position (SDLP)". *International Journal of General*
531 *Medicine* 4: 359. doi: <https://doi.org/10.2147/IJGM.S19639>.
- 532 Voigt, A., and S.P. Kuchangi. 2009. *Evaluation of Chevron Markings on Freeway-to-Freeway Connector Ramps*
533 *in Texas*. Texas Transportation Institute No. 09-1941, Austin, US.