

Factors influencing driver behaviour along curved merging interchange terminals

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1 **FACTORS INFLUENCING DRIVER BEHAVIOUR ALONG CURVED MERGING**
2 **INTERCHANGE TERMINALS**

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4

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13 **ABSTRACT**

14 **Problem statement.** To promote safe and comfortable driving operations, design manuals and policies call for
15 merging terminal ramps to be built along straight roadway sections. However, this prescription may need to
16 be overlooked when there is no alternative to terminals being designed along curves. This study aims to assess
17 the impact of design factors on driver behaviour along curved acceleration terminals with continue or reverse
18 curvature prior to joining the motorway. **Methodology.** A driving simulation experiment was conducted to
19 observe longitudinal and transversal driver behaviour when certain factors (i.e., radius, ramp length, motorway
20 curve direction, and traffic conditions along the motorway segment) were manipulated. The forty-eight drivers
21 involved were separated into groups based on age and gender. **Results.** The motorway radius has a significant
22 impact on longitudinal performance, while traffic volume impacts on the merging point where vehicles enter
23 the adjoining motorway lane. Compared to linear terminals, the merging abscissa need to be longer on curved
24 ones so as to compensate for the blind spot and enable drivers to identify and accept gaps between vehicles in
25 the traffic flow. The ramp-terminal connection type influences the speed at the beginning of the terminal, the
26 position of the merging point and transversal driver behaviour. **Conclusions.** Although some limitations in the
27 study were necessary to limit their impact on the experimental design, the results here may prove useful when
28 considering the adoption of appropriate engineering countermeasures at the design stage of entry terminals
29 along curved motorway segments.

30

31

32 **Keywords:** entry terminal, merging, curved terminal, blind spot, driver behaviour, driving simulation.

33 1. INTRODUCTION

34 Entrance terminals connect interchange ramps to the main through lanes of motorways. These road facilities
35 are critical because vehicles coming from the ramp have to merge into the motorway traffic; hence, vehicles
36 coming from two different directions have to operate together. Along terminals, the driver performs a mentally
37 demanding manoeuvre (De Waard *et al.*, 2009; De Waard *et al.*, 2010) because he/she has to coordinate
38 longitudinal driving decisions (i.e., speed, acceleration) with transversal ones (i.e., lane position in the
39 ramp-terminal system, change lane point to pass from terminal to the through lane) while also remaining aware
40 of other factors (i.e., surrounding vehicles, length available for the merging manoeuvre). Literature clearly
41 evidences that the terminal geometry (i.e., type, shape, width, and length) has a significant impact on the
42 operational and safety performance of such facilities (Ahammed *et al.*, 2008, Gu *et al.*, 2019; Reinolsmann *et*
43 *al.*, 2019).

44 Technical design manuals and policies indicate that on-ramp (entrance) terminals should be located
45 along tangent sections wherever possible to maximise the sight distance and optimise traffic operations
46 (CDOT, 2018; NJDOT, 2020; CALTRANS, 2020; INDOT, 2013). Similarly, the Italian geometric design
47 policy for intersections and interchanges suggests that they be located along straight road sections (MIT, 2006).
48 Based on experience, AASHTO standards indicate that parallel terminals are more effective in terms of traffic
49 operations and have lower crash frequencies than tapered ones (AASHTO, 2018).

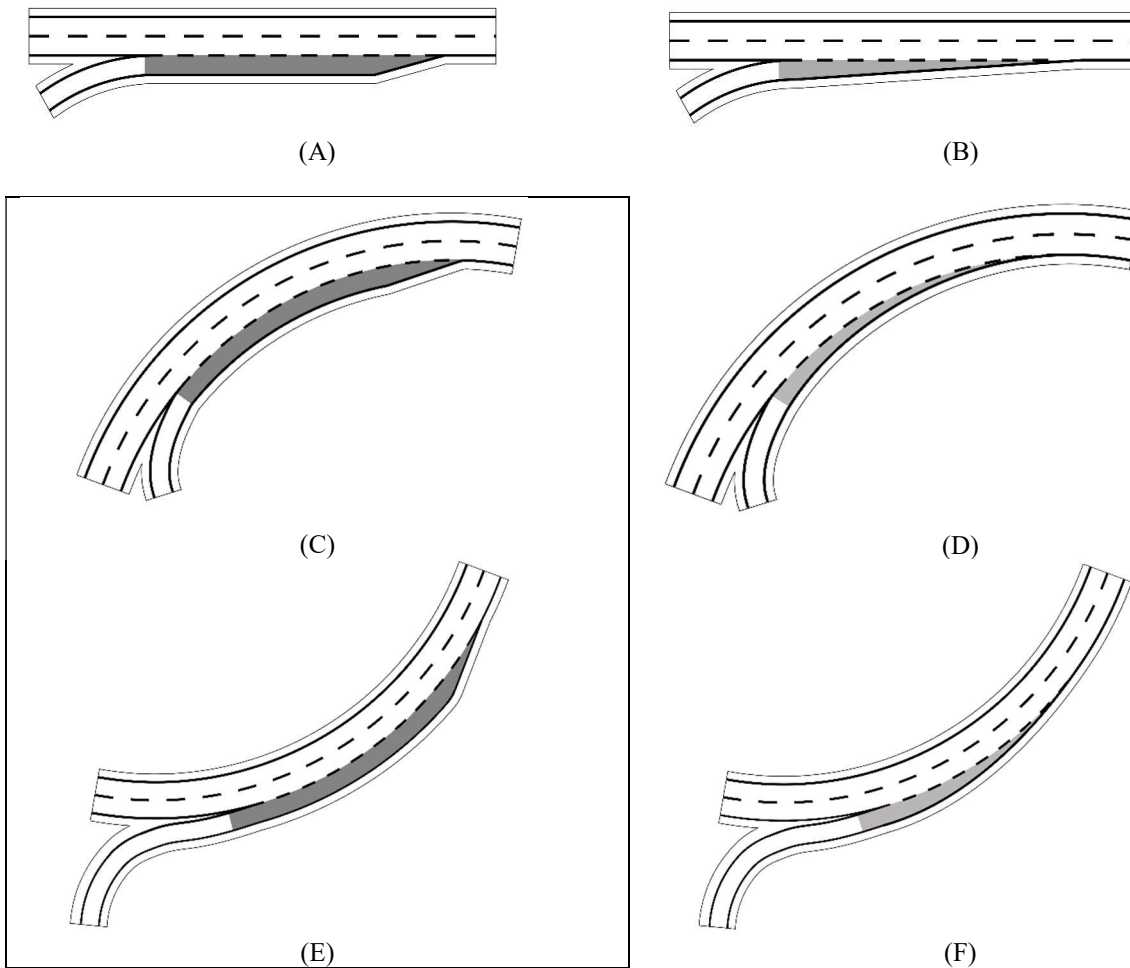
50 Literature confirms that parallel (Figure 1A) rather than tapered (Figure 1B) linear terminals better
51 support the driver task (Awan *et al.*, 2020). In fact, the latter lead to increased aggressiveness among drivers
52 who have no other choice than to forcefully insert themselves into the gaps between vehicles travelling on the
53 motorway lane (Kondyli and Elefteriadou, 2011). Field observations indicate that drivers remain longer on
54 tapered terminals and travel at speeds closer to those of vehicles on the motorway than they do on parallel
55 terminals (Kondyli and Elefteriadou, 2012). Traffic on both the motorway and on the ramp affect the merging
56 behaviour of drivers (TRB, 2016), while the length of the accelerating lane does not affect longitudinal and
57 transversal behaviours (Calvi and De Blasiis, 2011). When the volume of traffic on the motorway through
58 lanes increases, the length of the merging manoeuvre on the terminal, the variations in acceleration, and the
59 frequency of rejected gaps increase as well. Colonna and Delcarmine (1997) observed that parallel terminals
60 also work better along curved motorway sections (Figure 1C and Figure 1E) than on tapered ones (Figure 1D
61 and Figure 1F). However, on-site surveys in one specific case revealed that drivers tended to use the entire
62 length of the facility when evaluating the possibility of entering by using the left rear-view mirror. As a result,
63 the visibility issue evidently leads to a greater use of the acceleration lane. Unfortunately, this observational
64 evidence does not feature in the Highway Capacity Manual (HCM), rendering the manual suitable only for
65 resolving design issues related to linear terminals (TRB, 2016).

66 Consequently, too little attention has been devoted to the evaluation of driver behaviour along curved
67 on-ramp parallel terminals (Figure 1C and Figure 1E), and available tools can support the design of linear
68 terminals only (Figure 1A and Figure 1B). Since difficulties in collecting field data are evident, data on driver
69 merging behaviour in a variety of facility settings can be more conveniently collected from driving simulations

70 (Sarvi *et al.*, 2004) as was the case in this study. The effects of fundamental geometric factors on the
71 behavioural response of drivers while merging into a motorway through lane from a parallel curved on-ramp
72 terminal were evaluated. With respect to linear terminals, drivers along curved terminals need to exercise
73 caution because of the reduced visibility and possibility of detecting arriving vehicles. This makes the driving
74 task along curved terminals more demanding than along linear ones.

75 Different road scenarios were investigated at a fixed-base driving simulator. Factors accounted for in
76 the experiments include the terminal length, the traffic flow along the motorway, the motorway radius, and
77 most importantly the motorway curve direction. In particular, two different ramp-terminal connections were
78 investigated: the reverse type (i.e., S-shaped or inflected, Figure 1E), which links an on-ramp to a leftward
79 motorway curve, and the continue type (i.e., egg-shaped, Figure 1C) which links the on-ramp to a rightward
80 one.

81



82 **Figure 1. Synoptic table of possible entry terminal design: (A) parallel linear, (B) tapered linear, (C) parallel**
83 **continue curved, (D) tapered continue curved, (E) parallel reverse curved, (F) tapered reverse curved. The two**
84 **terminal types bordered in the figure are the subject of this study.**

85

86 **2. METHOD**

87 The scenarios were designed to enable test drivers perform merging manoeuvres into motorway sections
88 preserving the randomness with which the geometric characteristics of these elements were presented. The
89 drivers faced combinations of independent experimental factors in twelve different circuits formed by two
90 motorways and two two-lane highway segments (key plan in Figure 2). The drivers were asked to depart from
91 a lay-by on a two-lane rural highway (Figure 2A), and then enter a motorway segment (Figure 2B, Figure 2C).
92 Afterwards, drivers were invited to exit the motorway, use another two-lane rural highway segment and then
93 join a new motorway segment (Figure 2D, Figure 2E). Finally, they were invited to exit again and park the
94 vehicle in the same lay-by where they had initiated the driving task (Figure 2F). In this way, the motorway
95 segments were connected to the two-lane highway segments by means of direct ramps. It must be highlighted
96 that no traffic barriers were included in the study to exclude any behavioural effects due to sight limitations
97 and perceived risk levels (Bassani *et al.*, 2019).

98 All road facilities (motorways, two-lane highways, interchange ramps) were designed according to the
99 current Italian Policies on road geometric design (MIT, 2001; MIT, 2006). Within this framework, a merging
100 ramp is made up of three main components: (i) the acceleration segment, where drivers accelerate to reach an
101 appropriate merging speed, (ii) the merging segment where drivers merge into the motorway though lane, and
102 (iii) the taper of a fixed length (75 m) which ends the terminal.

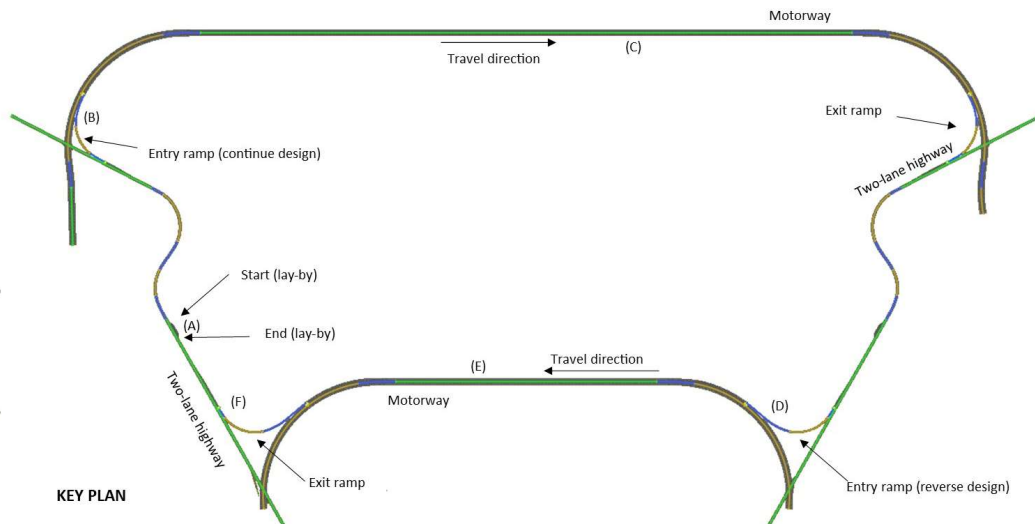
103 The acceleration segment ^[1] starts from the beginning of the transition curve that links the ramp to the
104 terminal, while the merging segment was designed according to the Highway Capacity Manual (TRB, 2016).
105 According to the Italian regulations (MIT, 2006), the merging segment is designed to allow comfortable and
106 safe merging manoeuvres; these manoeuvres, therefore, should not end in the final taper. This last element is
107 simply a connection between the terminal and the motorway lane; it is short enough to invite drivers to merge
108 rapidly onto the motorway lane.

109

^[1] The acceleration segment length (L_a) was computed according to the following formula:

$$L_a = \frac{v_t^2 - v_r^2}{2a}$$

where v_t is the speed to be reached on the terminal (at least 80% of the design speed of the motorway section), v_r is the design speed of the ramp, a is the acceleration (assumed equal to 1 m/s²).



(A)



(B)



(C)



(D)



(E)



(F)

110 **Figure 2. Key plan of the circuits (top) and screenshot from the driver point of view: (A) departure from the**
 111 **lay-by, (B) entry from a continue terminal, (C) first motorway segment, (D) entry from a reverse terminal, (E)**
 112 **second motorway segment and (F) arrive at the lay-by (letters in the key plan indicate locations where the**
 113 **screenshots were taken).**
 114

115 2.1 Equipment

116 The experiment was carried out at the Road Safety and Driving Simulation (RSDS) Laboratory of Politecnico
 117 di Torino. The laboratory is equipped with a driving simulator (AV Simulation), the characteristics of which
 118 are listed in Table 1. In previous studies, this simulator was validated in relative terms for longitudinal (Catani,
 119 2009; Bassani *et al.*, 2018) and transversal driver behaviour (Catani and Bassani, 2019).

120

121 **Table 1. Specifications of the fixed-base driving simulator.**

Computers and monitors	
CPU:	Quad-core
Video card:	NVIDIA GeForce® GTX 780 Ti
Memory:	8 Gb of random-access memory
Monitor:	Three 32-inch full HD (cover approximately 130° of driver field of view)
Hardware	
Cockpit:	Car seat, steering wheel, manual gearbox, pedals, and dashboard
Interactions between vehicle and road:	Steering wheel returns active force feedback to the driver, simulating wheels' rolling, pavement roughness, and shocks. Vibration pads return vehicle vibrations to the seat and pedals
Software	
SCANeR™ Studio:	Design tracks, manage the vehicle parameters, generate the experimental scenarios, run the simulations, collect and extract data

122
 123 The vision system consisted of one frontal and two lateral 32-inch full HD monitors. One central and
 124 two lateral back mirrors provide support to drivers during the merging manoeuvre. The three screens provided
 125 a 130° view in front. The simulator worked with SCANeR Studio® software to create driving scenarios,
 126 manage the test (i.e., to simulate traffic), and collect operational data.

127
 128 **2.2 Independent factors and experimental design**

129 In this study, the values adopted for the independent parameters in the experiment were those used in Calvi
 130 and De Blasiis (2011), who investigated merging behaviour in linear terminals. In their work, road elements
 131 were also designed according to the Italian standards. In view of this, the results obtained here on curved
 132 terminals can be compared with those for linear terminals.

133 The experimental parameters in this study are: (i) the terminal length (L_t , three values), (ii) the highway
 134 radius (R , two values), (iii) the traffic flow along the motorway (V , two values), and (iv) the connection type
 135 between the ramp and the terminal (CT, two values).

136 The three terminal lengths (L_t) were defined starting from the central (reference) value of 360 m
 137 estimated according to the HCM (TRB, 2016) and the Italian Policy on intersections and interchanges design
 138 (MIT, 2001; MIT, 2006). This reference L_t value is the minimum length that guarantees a level of service B
 139 assuming a volume of traffic on the motorway of 1000 pc/h/ln, and on the on-ramps of 200 pc/h. The shortest
 140 L_t value was defined by decreasing the reference by 50 m, while the longest L_t was defined by increasing the
 141 reference by 75 m.

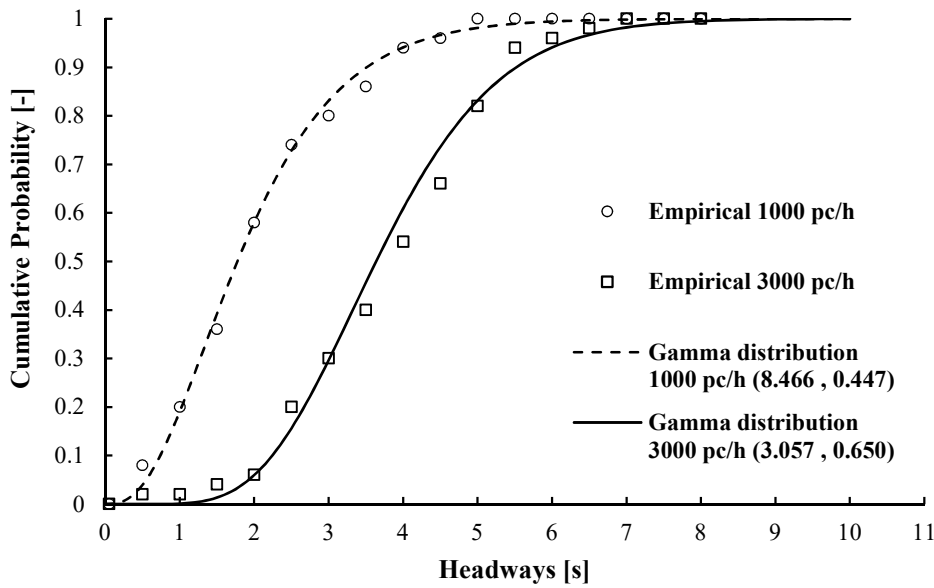
142 Referring to the Italian Policy (MIT, 2001), two alignment motorway radii (964 and 437 m) were
 143 chosen by assuming the design speeds of 140 km/h (i.e., the maximum design speed for motorways in Italy)
 144 and 100 km/h respectively. In particular, the value of 964 m represents the minimum radius that can be
 145 travelled at the maximum design speed (MIT, 2001).

146 A traffic flow of autonomous passenger cars (pc) travelling at 120 km/h was generated along the two
 147 through lanes on the motorway with volumes (V) of 1000 and 3000 pc/h, corresponding to the levels of service
 148 A and C respectively (TRB, 2016). No traffic was simulated along the ramps. The software can assume a value
 149 for the traffic volume and generates a flow of autonomous vehicles with variable headways. Figure 3 shows

150 the results of the headway fitting with a Gamma distribution function. The Kolmogorov-Smirnov (KS) test
 151 was used to demonstrate that the two data samples were from a Gamma distributed population ($V = 1000$ pc/h;
 152 $D_{(17)} = .044$, $p = .968$; $V = 3000$ pc/h: $D_{(17)} = .040$, $p = .973$).

153 Finally, two different connection types (CT) to link the ramp to the terminal were considered: (i) a
 154 continue (egg-shaped) spiral to link a rightward ramp to a rightward motorway curve (Figure 4A), and (ii) a
 155 reverse (inflected, or S-shaped) spiral to connect a rightward curve to a leftward motorway curve (Figure 4B).
 156 The spiral type used in this study was the clothoid, also called the *Cornu* spiral (Lorenz, 1971; Kobryń, 2017).
 157 The clothoid satisfies the parametric equation $rL = A^2$, where r is the radius, L is the length of the clothoid, and
 158 A the scale factor [2].

159



160

161 **Figure 3. Cumulative distributions of headways for $V = 1000$ pc/h (LOS = A) and $V = 3000$ pc/h (LOS = C)**
 162 **generated by SCANeR® in the two through lanes of the motorway. Continue curves represent the Gamma**
 163 **cumulative distribution function based on α (shape) and β (scale) parameters.**

164

[2] The relationship between the geometric variables in the design was calculated according to the Lorenz (1971) equations for continue spirals:

$$A^2 = 2R' \cdot \sqrt{\frac{6DR' \cdot \left(\frac{1-k}{k}\right)}{3(k-1)^2 - \left(\frac{1-k}{k}\right) \cdot (1-k^3)}}$$

and reverse (S-shaped) spirals:

$$A^2 = 2R' \cdot \sqrt{\frac{3D \cdot \left[D + 2R' \cdot \left(\frac{k+1}{k}\right)\right]}{3 \cdot (1+k)^2 + \left(\frac{k+1}{k}\right) \cdot (1+k^2)}}$$

where $k = \frac{R'}{r}$, r is the ramp radius, R' is the radius of the right motorway lane, D is the distance between the two circular curves. The R' value was calculated from the motorway radius R (Figure 4) as follows:

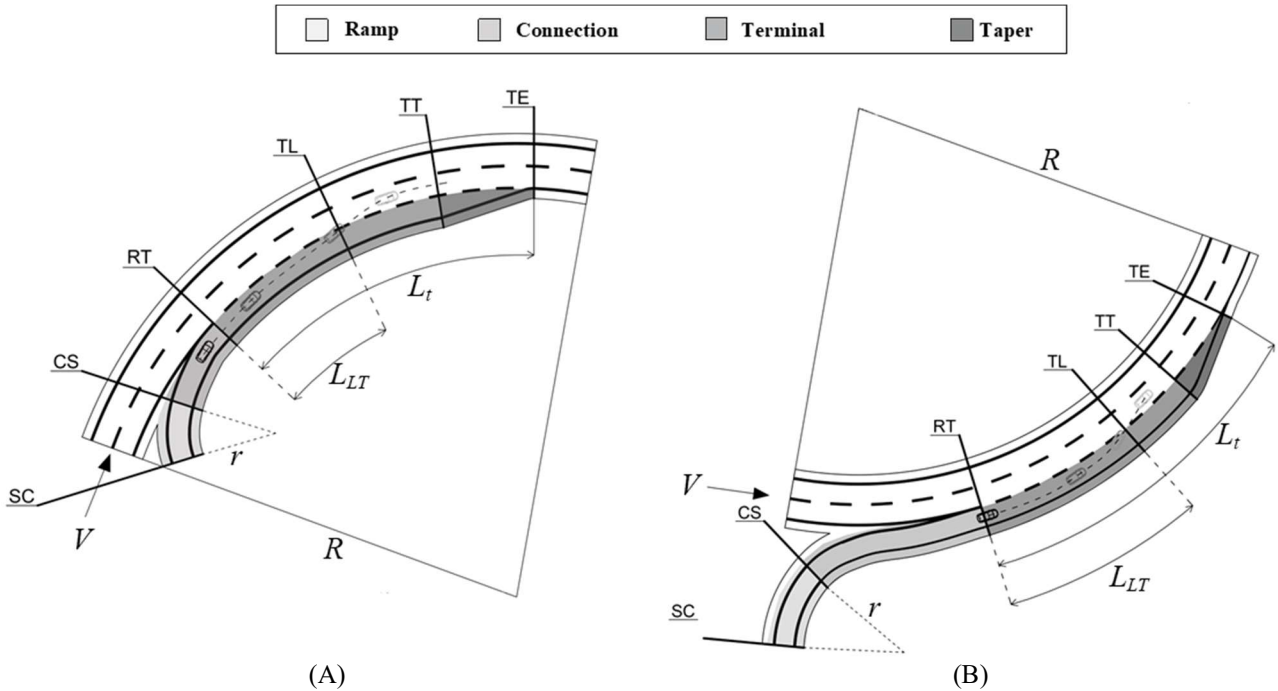
- continue spiral, $R' = R - 2 \cdot l_w - \frac{m}{2}$,
- reverse spiral, $R' = R + 2 \cdot l_w + \frac{m}{2}$;

where l_w is the lane width (3.75 m), m is the median width (4 m).

165 In all the scenarios, r was set equal to 150 m, while A was 150 m for both continue and reverse
 166 clothoids. In real driving conditions and with the same A factor, drivers travelling at the same speed would be
 167 subjected to the same linear variation in lateral acceleration, and to the same constant lateral jerk. In both real
 168 and simulated driving with the same A factor, drivers follow curves which appear with the same variation in
 169 curvature ($1/r$) and require the same rate of change of the steering angle.

170 Table 2 summarizes the factors and numerical values assumed in the experiment. Various
 171 combinations of these factors led to the twelve circuits listed in Table 3.

172



173

174

175 **Figure 4. Ramp-terminal connection (between sections CS and RT) with continue (egg-shaped) curvature (A),**
 176 **and reverse (S-shaped, inflected) curvature (B). Experimental factors include: motorway radius (R), length of**
 177 **terminal (L_t), and traffic volume (V). Ramp radius (r) was assumed equal to 150 m (Notes: SC = spiral-to-curve,**
 178 **CS = curve-to-spiral, RT = ramp-to-terminal, TL = terminal-to-lane, TT = terminal-to-taper, TE = terminal**
 179 **end).**

180

181 **Table 2. Factors and corresponding levels included in the experimental design.**

Factors	Levels		
	-1	0	+1
Motorway radius, R [m]	437	964	-
Terminal length, L_t [m]	310	360	435
Traffic Flow, V [pc/h]	1000	3000	-
Connection type, CT [-]	continue	-	reverse

182

183 **Table 3. Circuits and corresponding factor levels (-1, 0 and +1 levels are listed in Table 2)**

Factors	Connection type, CT	Circuits											
		1	2	3	4	5	6	7	8	9	10	11	12
Motorway radius, R	-	0	0	0	0	0	0	-1	-1	-1	-1	-1	-1
Terminal length, L_t	-1	-1	0	+1	0	+1	-1	+1	-1	0	+1	0	-1
	+1	+1	-1	0	-1	0	+1	0	+1	-1	-1	+1	0
Traffic flow, V	-1	-1	-1	-1	0	0	0	-1	-1	-1	0	0	0
	+1	0	0	0	-1	-1	-1	0	0	0	-1	-1	-1

184

185 **2.3 Participants**

186 A sample of forty-eight licensed volunteers were involved in the experiment. This sample was stratified to
 187 reflect the Italian driving population in terms of gender and age distributions. Drivers did not receive any
 188 benefit or payment from their involvement in the investigation and signed an informed consent in accordance
 189 with the European General Data Protection Regulation (European Parliament, 2016) form prior to the
 190 experimental session. This procedure is in line with the Code of Ethics of the World Medical Association
 191 (Williams, 2008). A synthesis of the sample features is given in Table 4.

192 Candidates were invited to participate in November 2019, while the tests were carried out in December
 193 2019 and January 2020. The invitation included information on how the test would be conducted and the time
 194 required for completion. Three circuits from the list in Table 3 were randomly assigned to each test driver,
 195 hence a total of twelve test drivers were randomly associated with each circuit.

197 **Table 4. Descriptive statistics on participants (Notes: M = mean, Min = minimum value, Max = maximum value,**
 198 **SD = standard deviation).**

Participant characteristics		M	Min	Max	SD
Age [y]	Male	42.2	19	61	13.5
	Female	41.6	20	57	12.4
	Total	41.4	19	61	12.9
Driving Experience [y]	Male	22.8	1	43	13.3
	Female	22.1	1	37	11.6
	Total	22.5	1	43	12.8
Distance travelled [km/y]	Male	16 096	500	40 000	11 652
	Female	9 100	300	24 000	7 643
	Total	12 615	300	40 000	10 787
Crash experience (#)	Male	1.1	0	4	1.3
	Female	1.4	0	10	2.3
	Total	1.2	0	10	1.8

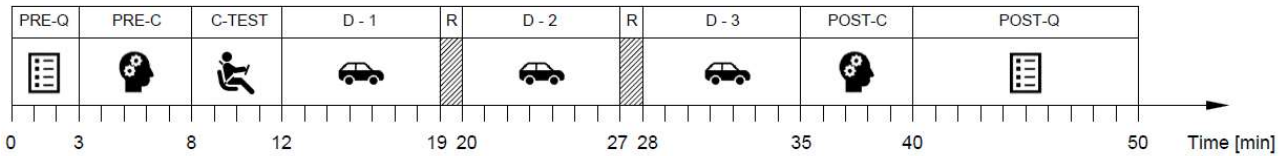
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200 **2.4 Experiment protocol**

201 Each participant completed the five-step protocol depicted in Figure 5 consisting of (i) a pre-drive
 202 questionnaire, (ii) pre-drive cognitive tests (visual and auditory), (iii) the driving simulation, (iv) post-driving
 203 cognitive tests, and finally (v) a post-drive questionnaire.

204 The pre-drive questionnaire was designed to evaluate the health and physical condition of participants.
 205 In the pre- and post-cognitive tests, the reaction times of participants to visual and auditory stimuli were
 206 measured using an online tool (available free at: www.cognitivefun.net) to detect any possible changes in their
 207 cognitive performances due to impairments resulting from the test. The driving experience consisted of an
 208 initial test on a circuit to gain familiarity with the simulator (C-TEST phase, Figure 5), followed by the driving
 209 task on the three assigned circuits (D-1, D-2, and D-3 in Figure 5) where data was collected. With the post-
 210 drive questionnaire, information relating to the experience of participants was collected with outputs on
 211 simulation sickness.

212



213 **Figure 5. Experimental protocol dispensed to participants, consisting of the following phases: pre-drive**
 214 **questionnaire (PRE-Q), pre-cognitive tests (PRE-C), test circuit (C-TEST), driving on the circuits (D-1, D-2,**
 215 **D-3), rest time between two driving tasks (R), post-cognitive test (POST-C) post-drive questionnaire (POST-Q).**
 216
 217

218 2.5 Observed variables

219 Behavioural data were determined from the spatial-temporal coordinates of the vehicle mass centre in the
 220 (x,y,t) format at 100 Hz. From spatio-temporal coordinates the following variables were extracted:

- 221 (i) the longitudinal speed (S) at RT (S_{RT}), TL (S_{TL}), and TE (S_{TE}) sections;
- 222 (ii) the abscissa of the TL section (L_{TL}), i.e. the path travelled along the terminal from the RT section;
- 223 (iii) the standard deviation of lateral position ($SDLP$), which is the standard deviation of the distances
 224 between the mass centre and the lane centreline, measured from CS to RT termini (Figure 3); and
- 225 (iv) the speed of rotation of the steering wheel.

226 The speed variable reveals how drivers were able to reach the speed values necessary to merge into
 227 the gap offered by two vehicles travelling at a speed close to 120 km/h in the through lane. The closer drivers
 228 are to this value, the simpler it is to merge into the motorway traffic. Conversely, drivers travelling at speeds
 229 which are significantly higher or lower than that of vehicles in the through lanes will need to stay longer on
 230 the terminal, and will create more turbulence when merging into the motorway lane (TRB, 2016).

231 The merging abscissa L_{TL} indicates the section where drivers change lane to merge into the motorway
 232 right through lane (Figure 3). $SDLP$ expresses the amount of oscillation (weaving) of the vehicle and measures
 233 the ability of the driver to control the vehicle trajectory under the influence of geometric and traffic related
 234 factors. In this study, this parameter was measured between the CS and RT termini, i.e. in the ramp-terminal
 235 connection. Data from the RT section were not taken into account so as to preclude any effects due to the effect
 236 of the lane change manoeuvre. High $SDLP$ values indicate difficulties in keeping to the lane alignment and
 237 high levels of vehicle oscillation. Conversely, low values indicate reduced oscillations and therefore greater
 238 vehicle control when following the driving path. $SDLP$ cannot be intended in absolute terms, but can be used
 239 in a relative way to compare different trajectories and lateral control performance.

240 Finally, the speed of rotation of steering wheel (in $^{\circ}/s$) measurement evaluated the driver performance
 241 while negotiating the entire trajectory from the ramp to the motorway lane. This typical driver input was used
 242 to understand the actions of drivers as they sought to maintain control over the vehicle in the lane under the
 243 influence of experimental factors.

245 3. RESULTS AND DISCUSSION

246 3.1 Questionnaires and cognitive tests

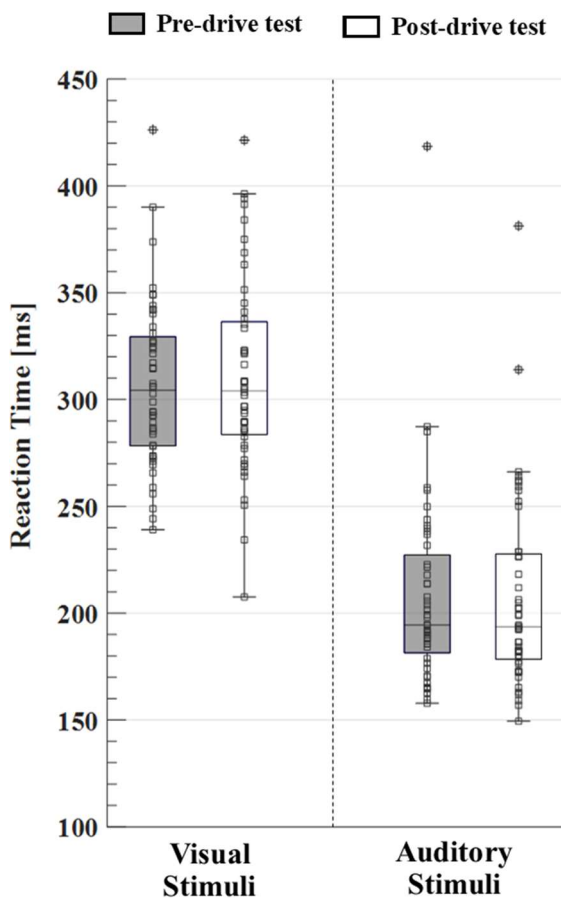
247 The questionnaire results revealed that during the simulation some drivers (25% of the participants)
 248 experienced disorders like visual fatigue, fatigue, and blurred vision. However, these discomforts were of a

249 mild intensity and therefore were considered acceptable for the purpose of the experiment. Only one driver
250 experienced a level of simulator sickness which prevented him from completing the driving task. Hence, he
251 was replaced with another male driver of the same age.

252 The decision to consider all the data collected valid, was corroborated by the cognitive responses
253 before and after the driving test. Figure 6 shows the box-plots of the perception and reaction time value
254 distributions for auditory and visual stimuli. The time reactions from visual stimuli are evidently longer than
255 those from auditory ones because of the difference in time needed to process and react to the signal received
256 (Kemp, 1973), which is longer in the case of visual stimuli. These results are consistent with previous
257 observations from Thompson *et al.* (1992) and Pain and Hibbs (2007).

258 The KS test for normality confirmed that cognitive test reaction times were normally distributed
259 (pre-drive visual reaction: $D_{(48)} = .08$, $p = .847$; pre-drive auditory reaction: $D_{(48)} = .14$, $p = .228$; post-drive
260 visual reaction: $D_{(48)} = .12$, $p = .435$; post-drive auditory reaction: $D_{(48)} = .17$, $p = .102$). Figure 5 shows that
261 test results before and after the driving task both for visual ($F_{(47,47)} = .728$, $p = .140$; $t_{(94)} = -0.463$, $p = .644$) and
262 auditory ($F_{(47,47)} = 1.018$, $p = .475$; $t_{(94)} = .087$, $p = .930$) reaction times were not significantly different from a
263 statistical point of view. As a result, the experimental protocol adopted did not affect the auditory and visual
264 performances of participants.

265



266
267
268

Figure 6. Visual and auditory reaction time distribution in the pre- and post-drive phases.

269 **3.2 Driving task**

270 Table 5 summarizes the mean and standard deviation of speed values in the significant sections of the terminal
 271 (S_{RT} , S_{TL} and S_{TE}), merging abscissa (L_{TL}), and the $SDLP$ between CS and RT sections, i.e. along the
 272 ramp-terminal connection (Figure 4). The data in Tables 5 and Table 6 are differentiated by connection type
 273 (continue and reverse). All data distributions passed the KS test for normality.

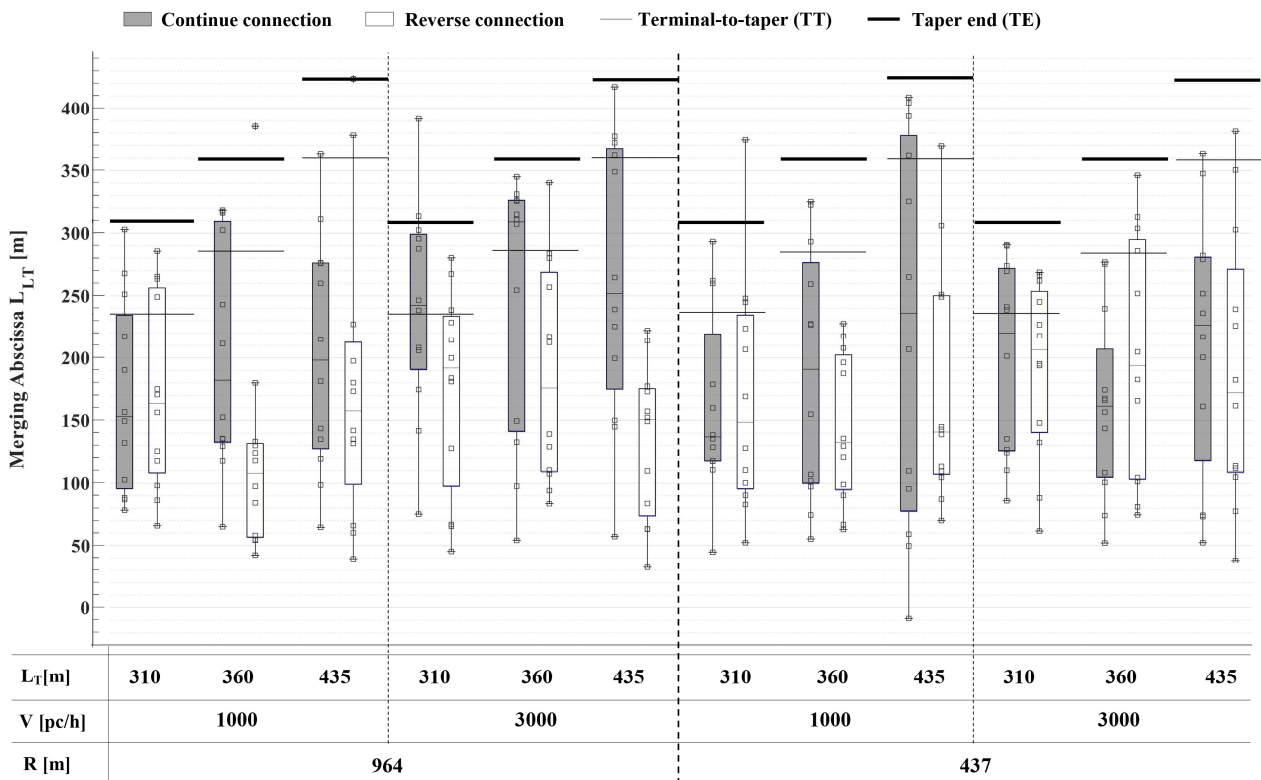
274 As expected, speeds increase along the trajectory when drivers pass from RT to TE along the terminal
 275 and the through motorway lane. At the RT section, the overall average S_{RT} along the reverse connection
 276 ($M_R = 75.3$ km/h) was higher than the corresponding value along the continue one ($M_C = 70.2$ km/h), while
 277 the mean values of S_{TL} ($M_R = 81.1$ km/h, $M_C = 83.4$ km/h) and S_{TE} ($M_R = 93.7$ km/h, $M_C = 93.0$ km/h) in the
 278 two connection types were closer. Furthermore, for the same affecting factors the average value of L_{TL} was
 279 significantly longer for the continue connection ($M_C = 207.9$ m) compared to the reverse one ($M_R = 170.1$ m).

280 **Table 5. Descriptive statistics of dependent variables (Notes: M = mean value, SD = standard deviation).**
 281

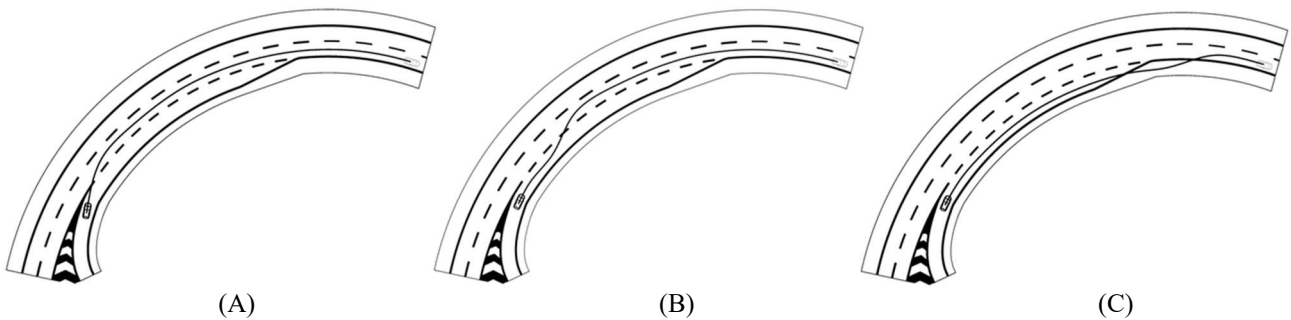
Connection type, CT	R [m]	V [veh/h]	L [m]	S_{RT} [km/h]		S_{TL} [km/h]		S_{TE} [km/h]		L_{TL} [m]		$SDLP$ [m]	
				M	SD	M	SD	M	SD	M	SD	max	M
Continue	964	1000	310	66.9	11.3	79.7	13.4	89.0	14.2	168.7	76.9	302.9	0.23
			360	72.1	13.3	85.5	14.0	96.0	10.3	203.6	106.0	318.3	0.26
			435	67.8	16.5	84.0	16.0	97.4	13.9	203.7	113.3	363.3	0.22
		3000	310	79.6	13.7	90.1	16.9	94.4	17.7	240.1	85.7	391.3	0.24
			360	77.4	14.7	88.2	15.6	95.7	15.4	245.8	106.0	345.0	0.26
			435	72.1	13.5	87.8	16.8	98.6	13.3	263.3	113.3	417.3	0.38
	437	1000	310	72.1	9.9	85.9	10.9	93.8	11.3	162.2	73.8	292.3	0.34
			360	70.3	12.0	82.1	13.3	91.2	13.1	187.1	100.0	325.1	0.25
			435	71.2	16.2	83.4	15.1	93.8	15.6	222.7	156.1	408.9	0.27
		3000	310	69.4	13.5	81.3	16.8	88.6	13.3	199.0	77.6	290.8	0.20
			360	67.9	14.0	79.5	12.2	91.1	10.5	187.1	73.3	276.9	0.26
			435	55.7	11.8	73.7	12.0	86.4	8.9	211.6	104.1	363.4	0.35
Reverse	964	1000	310	81.5	21.1	86.7	19.4	95.0	17.7	171.6	77.1	285.7	0.50
			360	84.3	13.4	88.8	14.6	105.1	13.8	121.8	92.6	385.3	0.64
			435	80.2	12.3	87.2	15.3	99.7	19.1	179.5	118.4	423.7	0.43
		3000	310	74.0	18.4	79.8	18.8	88.1	18.1	175.0	80.6	280.4	0.49
			360	74.6	14.8	83.8	13.9	98.1	14.6	187.9	88.0	340.4	0.39
			435	70.8	15.3	78.0	16.2	97.3	14.0	133.1	61.8	222.1	0.44
	437	1000	310	64.3	12.7	70.0	14.5	79.8	11.5	169.3	93.3	374.5	0.49
			360	75.6	13.6	78.9	14.3	91.4	12.9	145.2	59.8	227.7	0.43
			435	74.7	14.6	79.3	12.5	95.7	13.8	173.9	96.0	369.5	0.39
		3000	310	71.6	15.3	78.9	16.2	86.7	14.0	192.2	70.3	268.8	0.49
			360	73.6	18.2	78.9	16.3	88.0	17.6	201.3	97.8	346.2	0.53
			435	78.0	9.4	82.5	11.3	99.3	11.2	190.8	110.6	381.3	0.43

282

283 Figure 7 shows the box-plots for the merging abscissa (L_{TL}) distribution in the experiments as a
 284 function of the independent factors. In the case of continue connections to the smallest motorway radius, one
 285 driver merged into the motorway before the RT section, i.e. from the ramp-terminal connection to the lane.
 286 This merging manoeuvre is evidenced in Figure 8 and classified as type A. Drivers who do not use the terminal
 287 appropriately may create hazards for other drivers travelling in the motorway lane, which may even result in
 288 unavoidable collisions. The type A manoeuvre was also observed in the field by Colonna and Delcarmine
 289 (1997) along a curved merging terminal connected to a 500 m radius motorway curve. They observed one in
 290 twenty passenger cars, and one in five heavy vehicles abruptly joining the through lane employing a type A
 291 manoeuvre.
 292



293 Figure 7. Box-plots for L_{TL} (merging abscissa) values across different terminal lengths (L_T), traffic flow (V), and
 294 motorway radius (R) values, for both continue (grey box-plots) and reverse (white-boxplots) ramp-terminal
 295 connections.
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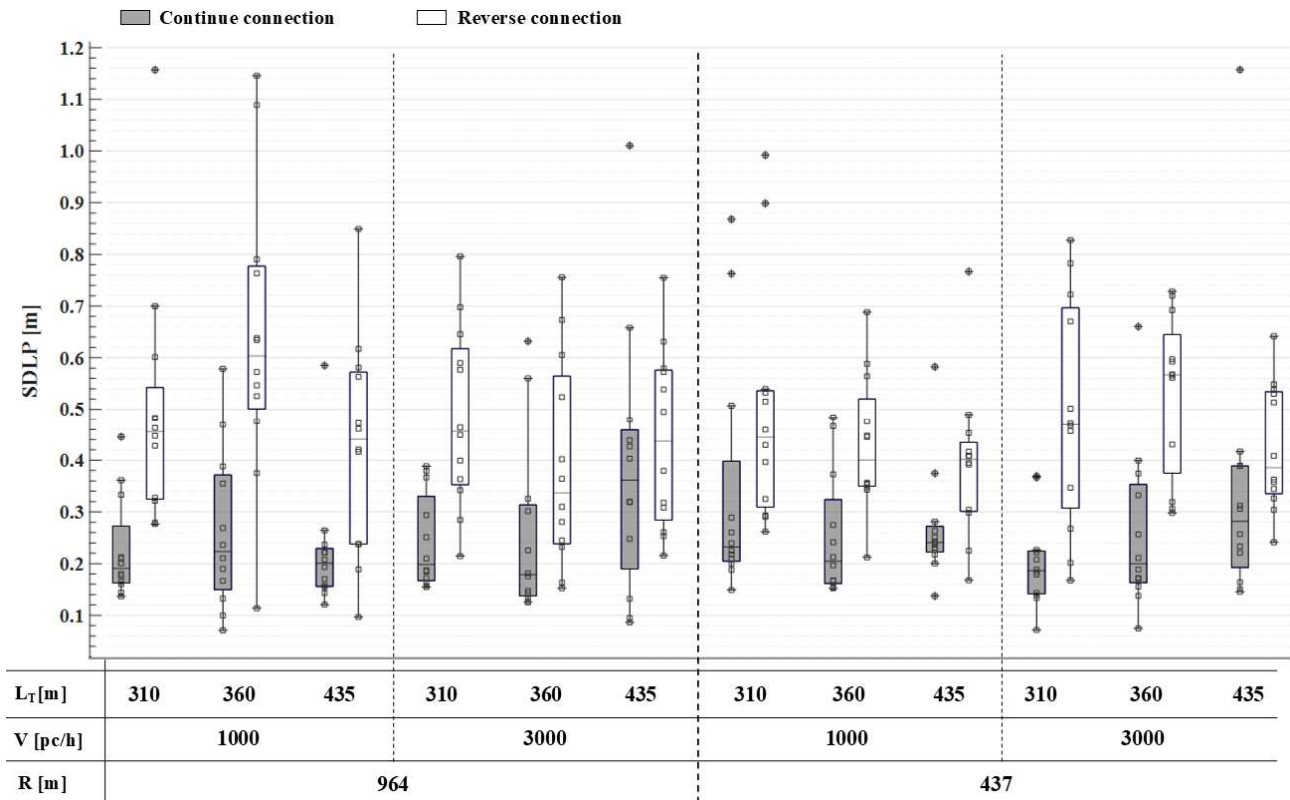


298 (A) (B) (C)
 299 Figure 8. Classification of merging manoeuvres: (A) anticipated merging, (B) correct merging, and (C) late
 300 merging.
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303 Figure 7 also reveals that four drivers were not able to merge with the correct type B manoeuvre
 304 (Figure 8), so they performed a late merging type C one using the motorway shoulder at the end of the taper
 305 to merge into the motorway lane. Colonna and Delcarmine (1997) also observed similar situations in the field.
 306 In real driving conditions, the type C manoeuvre is hazardous because merging vehicles may encounter
 307 vehicles parked along the emergency lane with the possible presence of traffic barriers, slopes or vegetation
 308 limiting sight distance values. As expected, in this study manoeuvre type C occurred more frequently along
 309 short terminals in both ramp-terminal connection types.

310 Figure 9 shows the distribution of *SDLP* data. The values observed for the reverse connection are
 311 always higher than for the continue one. Since the effects of the other experimental factors are not clearly
 312 evident from the graph, they need to be investigated by subjecting the results (which are reported in Table 6)
 313 to an ANOVA. In the ANOVA, the experimental factors were categorical.

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Figure 9. *SDLP* in continue and reverse ramp-terminal connections for different terminal length (L_T), traffic flow (V), and motorway radius (R) values.

Table 6. AVOVA, significant main and interaction effects (Note: RMSE = root mean squared error).

Factors	S_{RT}		S_{TL}		S_{TE}		L_T		$SDLP$	
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
	RMSE = 14.53		RMSE = 14.80		RMSE = 14.12		RMSE = 93.90		RMSE = 0.185	
R	7.61	.006	9.66	.002	11.81	<.001	0.34	.559	0.02	.886
V	0.64	.424	0.19	.665	0.59	.442	4.84	.029	0.00	.982
L_T	1.16	.315	0.32	.728	5.78	.004	0.74	.477	0.15	.864
CT	8.73	.003	1.81	.180	0.17	.681	4.18	.042	82.9	<.001
$R \times V \times CT$	14.41	<.001	10.12	.002	4.57	.033	3.44	.065	5.31	.022

320 **3.3 Longitudinal behaviour**

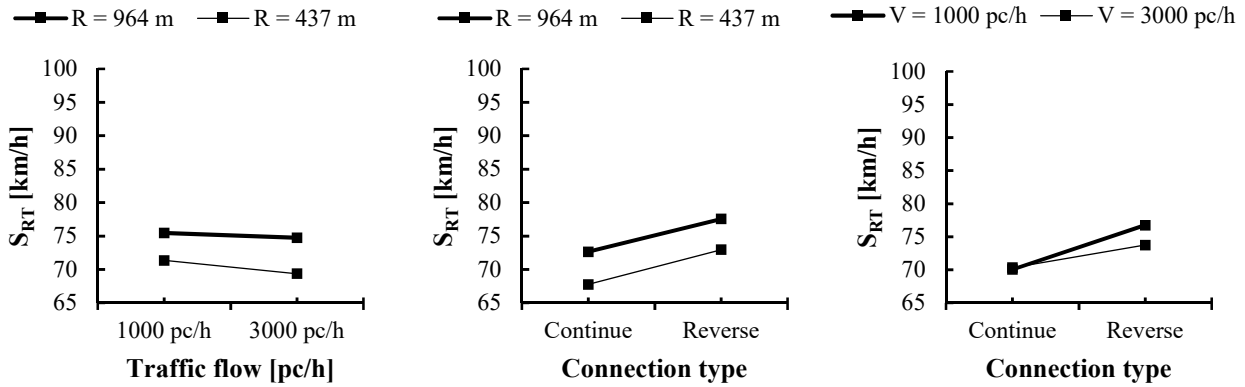
321 In this study, longitudinal behaviour was monitored through the speeds recorded at RT, TL and TE sections.
322 ANOVA reveals that R has a significant impact on speeds from the beginning to the end of the terminal
323 (Figure 10). As expected, and consistent with the design assumptions in manuals and policies (AASHTO,
324 2018; MIT, 2001), when the radius increases, the average speed at the investigated section also increases
325 (Liapis *et al.*, 2001).

326 Traffic flow (V) does not significantly affect speeds, while terminal length has a significant impact
327 ($p = .004$) on the speed observed at the taper end (TE section) only. The connection type affects the speed at
328 the RT section (S_{RT}) only ($p = .003$): this is because reverse connections were longer than continue ones, thus
329 allowing drivers to reach higher speeds. In addition, the reverse connection includes the inflection point where
330 the curvature is null, enabling drivers to increase their speed even further. On the rest of the terminal, speeds
331 were significantly affected by R (the motorway radius). As indicated in Figure 10, although they were
332 considerable at the beginning, the differences between speed values observed on the TL (S_{TL}) and TE (S_{TE})
333 sections of the curved terminal became less marked and the effects of the connection type became
334 progressively weaker before becoming negligible ($p = .180$ and $.681$ respectively).

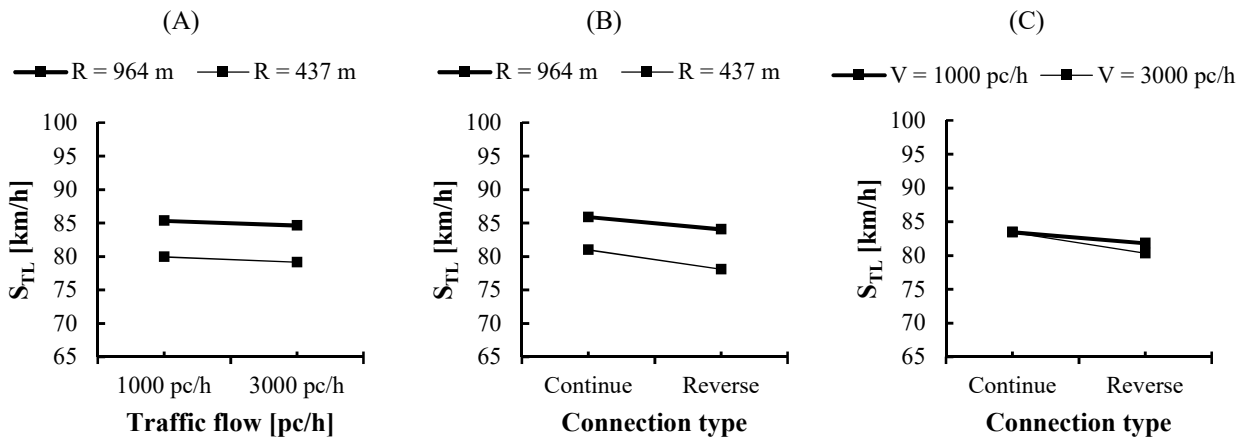
335 ANOVA evidences the significant three-way complex interaction illustrated in Figure 10 between
336 traffic flow and terminal radius and their effect on speed across the two ramp-terminal CTs. This may be
337 attributed to the fact that drivers could see the motorway ahead and were aware of the traffic present before
338 merging in (it should be noted that no traffic barriers were used along the ramp and on the right side of the
339 motorway). Furthermore, a lower motorway radius combined with a high traffic flow induces drivers to
340 proceed along the terminal with greater caution, thus creating significant differences in speeds compared to
341 the large radius and reduced traffic-flow scenario.

342 These results differ slightly from those obtained by Calvi and De Blasiis (2011) on linear terminals,
343 who observed that speeds at the merging point were not influenced by the length of the acceleration lane.
344 However, they were significantly influenced by the traffic volume (again, they adopted the same values here
345 equal to 1000 and 3000 pc/h). Conversely, results from this study indicate that for the same volumes, traffic
346 volume is not a significant factor. Differences between the two studies are attributed to the different headway
347 distributions mentioned previously: in this experiment, a variable and more realistic gap was adopted in line
348 with what happens in the field (Figure 3). With variable gaps, most drivers would have experienced little
349 difficulty merging into the through lane. This explanation is supported by field observation on linear terminals
350 by Ahammed *et al.* (2008), who noticed that hourly traffic flow in off-peak periods had no impact on merging
351 speed.

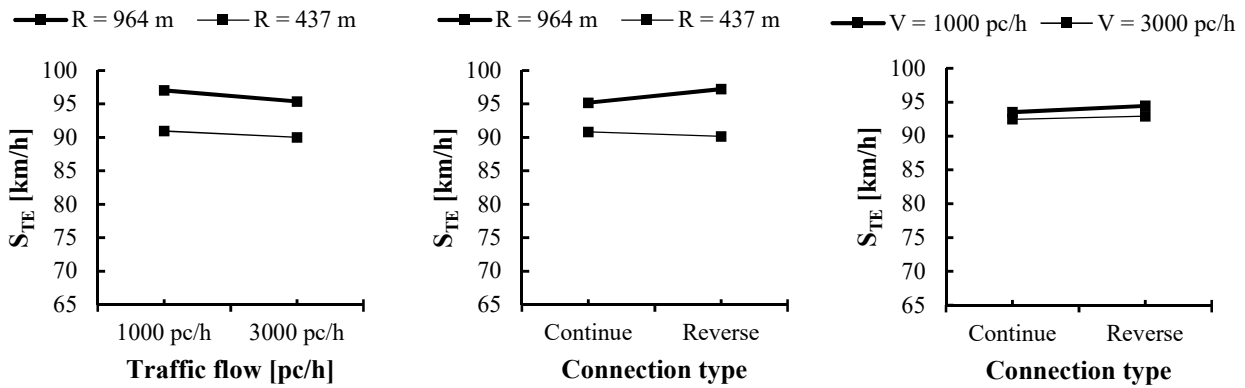
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359 **Figure 10. Speed outputs as a function of radius (R), traffic flow (V), and connection type (CT).**

360

361 **3.4 Transversal behaviour**

362 With this study, transversal driver behaviour was explored as per the merging abscissa (L_{TL}) and the standard
 363 deviation of lateral position ($SDLP$) measured in the ramp-terminal connection only. The ANOVA reveals that
 364 the motorway radius R does not affect the L_{TL} . More specifically, it has a limited impact on continue
 365 ramp-terminal connections ($p = .068$), while having no impact on reverse connections ($p = .245$). Traffic
 366 conditions influenced the merging abscissa ($p = .029$): as expected, more vehicles on the motorway increase
 367 the difficulty of merging into the lateral through lane. The same influence was documented in straight
 368 acceleration terminals in Calvi and De Blasiis (2011).

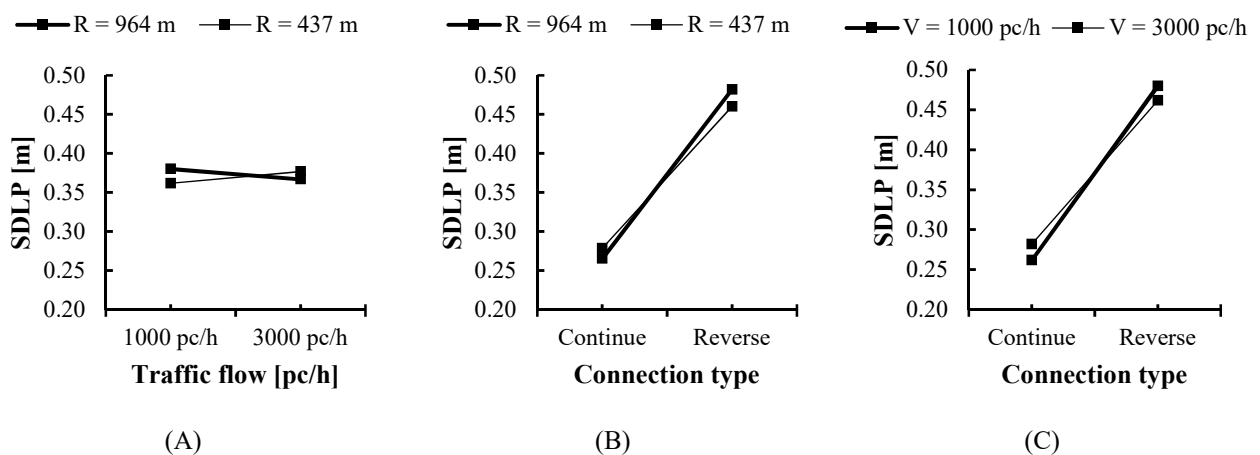
369 The ANOVA reveals that L_T does not influence the merging abscissa (L_{TL}). As indicated in Figure 7,
 370 the L_T variation does not correspond to a specific pattern in L_{TL} results. Figure 7 also indicates that a significant
 371 number of manoeuvres were completed in the taper (i.e., data points between the thin black line indicating the
 372 TT section, and the thick black line indicating the TE section), with some completed beyond the taper. This
 373 result clearly reflects the apprehension experienced by some drivers when attempting to move into the gap
 374 between vehicles due to limited visibility of the lane they were merging into. This was also the case for the
 375 reverse CT, notwithstanding the fact that drivers had a longer connection on which to increase their speed
 376 before merging. However, on the reverse CT all the merging manoeuvres were completed before the TE
 377 section.

378 These results evidenced that the reference length evaluated according to the HCM (TRB, 2016) and
 379 adapted to the prescriptions of the Italian policy for intersections (MIT, 2006) should consider the difficulties
 380 drivers face when accepting gaps under conditions of impaired visibility. Drivers were induced to use longer
 381 merging abscissa along the terminal with a continue ramp-terminal connection. These results are in evident
 382 contrast to the case of straight terminals investigated in Calvi and De Blasiis (2011). As a result, a curved
 383 terminal requires an increased terminal length to compensate for the blind spot which could impede full vision
 384 of the vehicles arriving on the motorway lane being merged into.

385 The ramp-terminal CT has a limited albeit significant influence on the merging abscissa ($p = .042$).
 386 This may be due to the indirect effect of CT on speeds, which in turn may have an influence on the ability of
 387 drivers to negotiate their entrance onto the motorway lane.

388 The ANOVA carried out on $SDLP$ data (Table 6) indicates that the differences in Figure 9 and
 389 Figure 11 are significantly influenced by the CT with the reverse CT resulting in larger vehicle trajectory
 390 weavings than the continue one. In the case of the reverse CT, vehicles were close to the right side of the lane
 391 in the initial part of the connection, then they moved laterally closer to the left lane edge approaching the
 392 terminal.

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Figure 11. $SDLP$ outputs as a function of radius (R), traffic flow (V), and connection type (CT).

398 A further reason is evident in the diagrams in Figure 12, which exhibit the average steering wheel
399 angle (in °) obtained from the conversion of the steering wheel angle speed in °/s for the two different terminal
400 types (please note that three different lengths are plotted due to the three L_T values assumed in the experimental
401 design). Diagrams reveal that in the case of the reverse CT, some weavings due to sudden steering angle
402 changes occurred around the inflection point in the trajectory (where the steering angle is null), and after the
403 inflection point before passing into the terminal, with a pattern common to all the reverse connections
404 investigated (Figures 12B, 12D, 12F, 12H).

405 This output evidences the difficulty drivers have in managing the vehicle direction upon entering the
406 terminal and, when affected by the blind spot, they had to start scanning the traffic arriving on the adjoining
407 lane prior to negotiating the lane change. Furthermore, along reverse connections drivers reached higher speeds
408 which, in turn, may induce more corrections to vehicle direction due to the misleading perception of curvature,
409 an effect that was clearly evidenced by Milleville-Pennel *et al.* (2007). All this evidence explains the
410 significantly larger *SDLP* values for reverse connections presented in Figure 8, and accounts for the three-way
411 interaction of factors like R , V and CT evidenced by the ANOVA (Table 6).

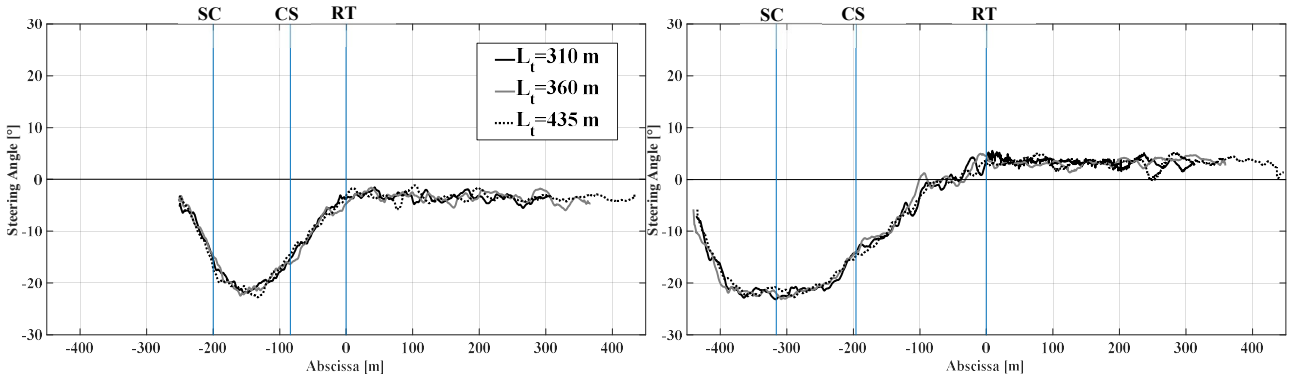
412 The curves in Figure 10 indicate that drivers anticipated their rotation of the steering wheel before
413 exiting the circular curve (i.e., before the CS sections). This behaviour is consistent with previous observations
414 documented in literature in real driving conditions (Godthelp, 1986; Bonneson, 2000), as well as in simulated
415 driving where drivers tend to anticipate more than in the field (Catani and Bassani, 2019). Anticipation is a
416 typical driving phenomenon arising from the perceived egocentric distances which are more likely to be
417 underestimated in the virtual environment than in the real world (Willemsen and Gooch, 2002).

418 Along curve-terminal connections (i.e., between CS and RT sections), drivers change the steering
419 angle at a constant rate to pass from the ramp curve (r) to the terminal one (R), as clearly shown in Figure 12.
420 Positive angles indicate a counter-clockwise rotation of the steering wheel with respect to the straight position.
421 Continue CTs induced higher speed of rotation of steering wheel than reverse ones. For example, in the case
422 of a motorway radius of 964 m, the average (and standard deviation) of the steering angle speed was equal to
423 4.07 (1.86) °/s (Figure 12A) and to 4.83 (1.80) °/s (Figure 12C) for 1000 and 3000 pc/h respectively on the
424 continue CT. For the reverse CT, the average steering speed was lower and equal to 3.47 (1.04) °/s (Figure
425 12B) and to 2.23 (1.08) °/s (Figure 12D) respectively for the two traffic volumes.

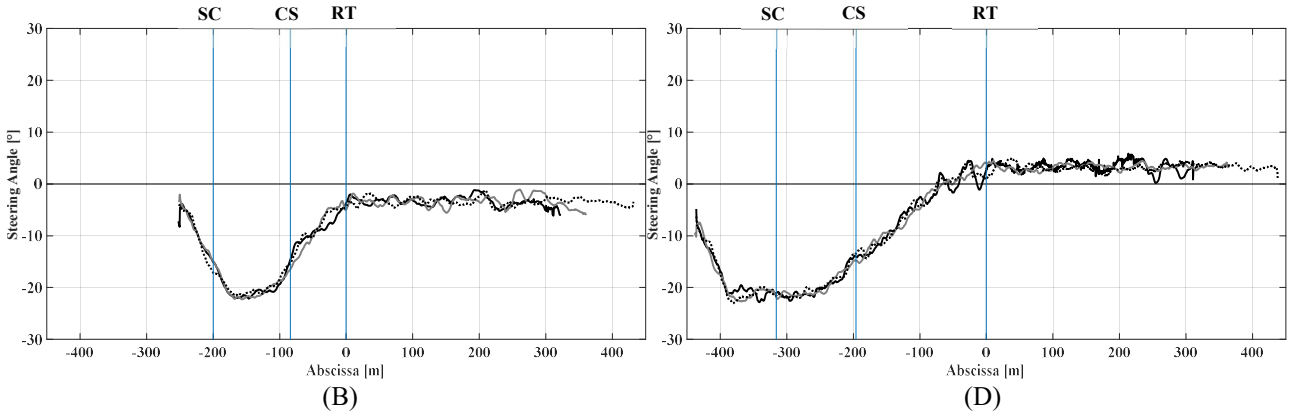
426 For $R = 964$ m, after the RT section the steering angle was maintained constant at an average of $+3.25^\circ$
427 along the leftward curve, and -3.37° along the rightward one. Individual profiles revealed positive peaks for
428 the steering angle in this area, corresponding to the action of the driver on the steering wheel while moving
429 into the adjoining motorway lane. The results in Figure 12 indicate that drivers react with different steering
430 angle speeds to the same curvature rate on the basis of the connection type. This may be due to the misleading
431 perception of the same curvature change in the two investigated cases.

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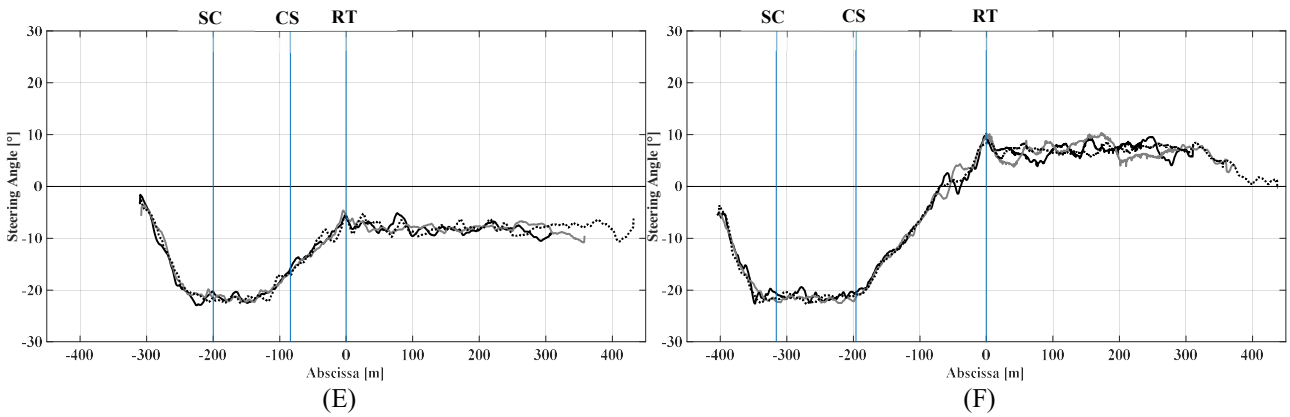
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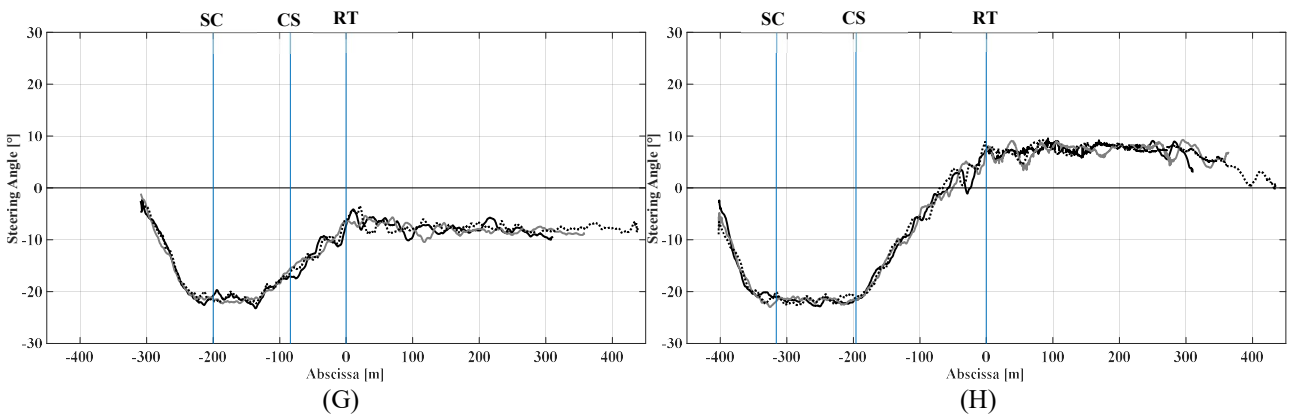
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444 **Figure 12. Steering angle values in continue (A, C, E, and G) and reverse (B, D, F, and H) ramp-terminal**
445 **connections. Cases A, B, E and F refer to $V = 1000$ pc/h, cases C, D, G and H to 3000 pc/h. Cases A, B, C and D**
446 **refer to $R = 964$ m, cases E, F, G and H to $R = 437$ m. The acquisition frequency of the data was 100 Hz (Notes:**
447 **SC = spiral-to-curve, CS = curve-to-spiral, RT = ramp-to-terminal, TT = terminal-to-taper, TE = taper end).**
448

449 The radius has a lower but still significant effect on the *SDLP*. According to the design assumptions,
450 a smaller radius generates a shorter ramp-terminal connection. Smaller radii required lower steering angle
451 speeds, equal to 3.44 (1.80) °/s and 2.13 (0.60) °/s for continue and reverse CTs respectively. After the RT
452 section, the constant angle for $R = 437$ m led to $+7.17^\circ$ along leftward curves, -7.73° along the rightward
453 curves.

454 ANOVA evidences that the radius interacts in a complex way with traffic flow and connection type
455 also in the case of *SDLP* (Table 6). The higher the radius, the smaller the *SDLP* for high traffic-flow levels
456 (3000 veh/h), while the opposite occurs with reduced levels of traffic-flow (1000 veh/h) (Figure 11A). The
457 effects of connection type are shown in Figure 11B in combination with radius, and in Figure 11C in
458 combination with traffic volume. In both cases, the connection type alters the effects produced by the variation
459 in radius and in traffic volume on *SDLP*.

460

461 4. CONCLUSIONS

462 Linear on-ramp terminals offer safer and superior operational performance levels than curved ones since
463 drivers have a greater vision of the motorway lane that they are going to merge onto. On linear terminals, the
464 driver benefits from the greater sight distance values available ahead and behind, which helps them to make
465 the correct decision vis-à-vis the time and place at which to merge into the gap between two vehicles on the
466 motorway section. Conversely, along curved terminals drivers are heavily influenced by the blind spot when
467 evaluating the gaps presented by arriving vehicles. This is why design manuals and policies suggest that
468 terminals should be located along straights. However, curved terminals are sometimes designed when no other
469 options are available.

470 In this study, right-hand and left-hand motorway curves were considered in conjunction with direct
471 ramps. As a result, two different ramp-terminal connections were evaluated: (i) the continue (i.e., egg-shaped)
472 and (ii) the reverse (i.e., S-shaped or inflected) connection. The longitudinal and transversal behaviour of a
473 sample of drivers representative of the general Italian population was analysed. Other factors like (i) the
474 motorway curve radius, (ii) the terminal length, and (iii) the traffic flow in the motorway through lanes were
475 also modified in this experiment.

476 The results indicate that drivers are significantly affected by the motorway radius, so care has to be
477 taken in the design of curved terminals with respect to linear ones. Since drivers are visually challenged by the
478 curvature, terminals having a length equal to the minimum value suggested by the HCM (TRB, 2016) are
479 inadequate. Terminal lengths need to be greater than the reference values to facilitate safer merging operations.

480 Continue connections between ramp and terminal tend to witness more cases of anticipated merging
481 (type A manoeuvre, Figure 8) into the through lane, which can create excessive hazards for following vehicles
482 on the motorway lane. In these circumstances, drivers in the motorway lane are obliged to react with a sudden
483 reduction in speed and/or a change of lane to avoid a collision. This phenomenon, which has been evidenced
484 here but also in literature, needs to be mitigated against via the adoption of appropriate countermeasures

485 (i.e., adopting the largest possible motorway radii values, alerting oncoming drivers in the motorway through
486 lane).

487 Results clearly indicate that the speeds on the terminal are mainly determined by the radius. While the
488 connection type has an effect at the beginning, its influence wanes at successive significant sections (i.e., TL,
489 TE). Although the terminal length was found to have a significant effect on speed at the taper-end section only,
490 those terminals which exceed the minimum length indicated in current standards (for linear terminals), serve
491 to provide drivers with the confidence required to change lane and merge onto the motorway. In this
492 experiment, a significant number of drivers changed the lane in the taper or after it. The traffic flow has a
493 significant influence on the merging abscissa so, similarly to linear terminal, longer terminal may guarantee
494 safer operations.

495 It is worth highlighting that the results presented here depend on the geometric characteristics of the
496 road facilities assumed for this study. New outcomes should be expected with the inclusion in new experiments
497 of factors that may influence driver visibility and perceived risk (e.g., traffic barriers, traffic on the ramp). The
498 use of ADAS technologies to counter the effects of blind spots (i.e., the blind spot monitor) should be
499 investigated in driving scenarios similar to those created and analysed here.

500

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505

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510

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