Factors influencing driver behaviour along curved merging interchange terminals

FACTORS INFLUENCING DRIVER BEHAVIOUR ALONG CURVED MERGING INTERCHANGE TERMINALS

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ABSTRACT

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

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

1. INTRODUCTION

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

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

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

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

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

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

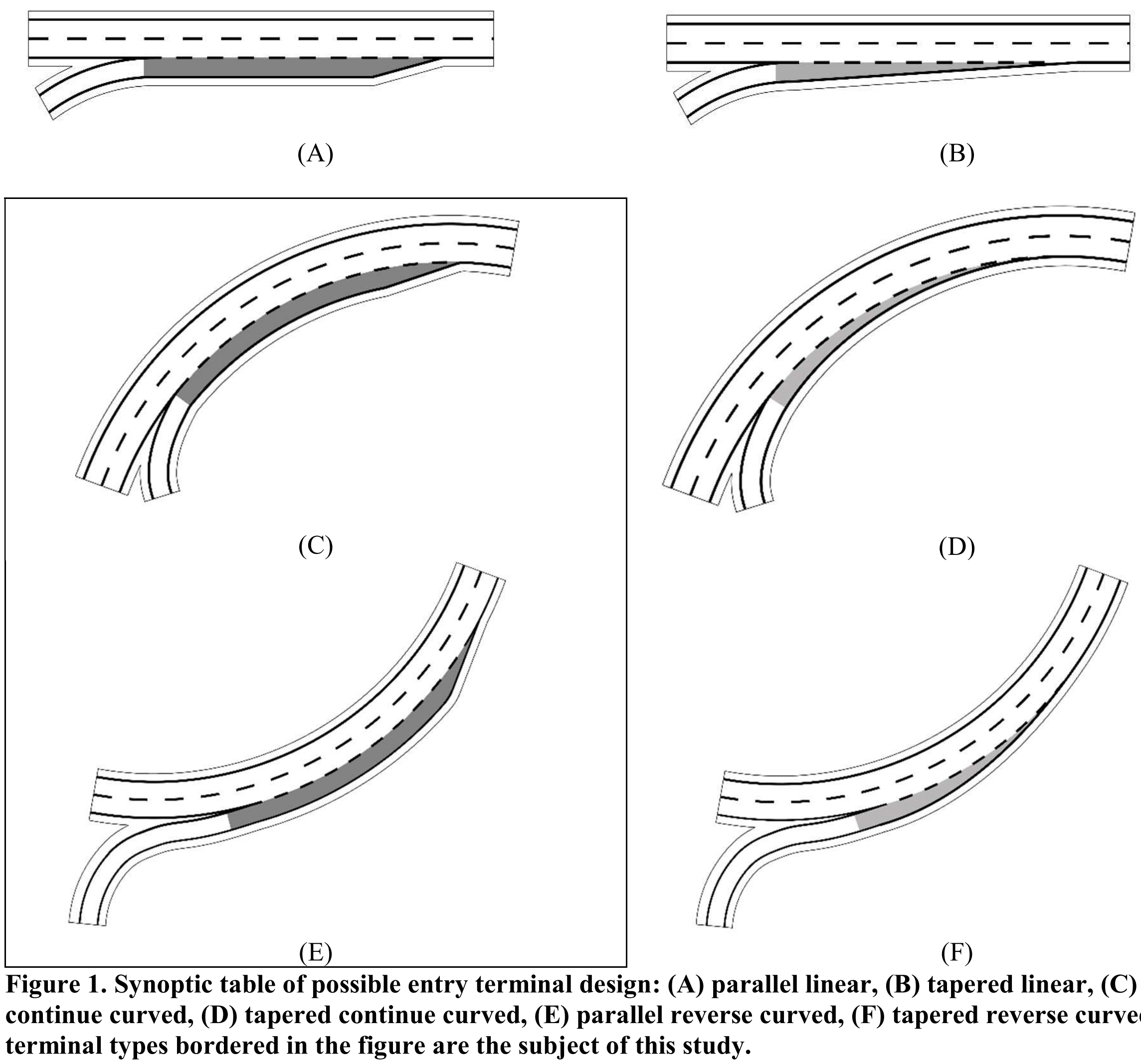

Figure 1. Synoptic table of possible entry terminal design: (A) parallel linear, (B) tapered linear, (C) parallel continue curved, (D) tapered continue curved, (E) parallel reverse curved, (F) tapered reverse curved. The two terminal types bordered in the figure are the subject of this study.

2. METHOD

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

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

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

[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/s^2).

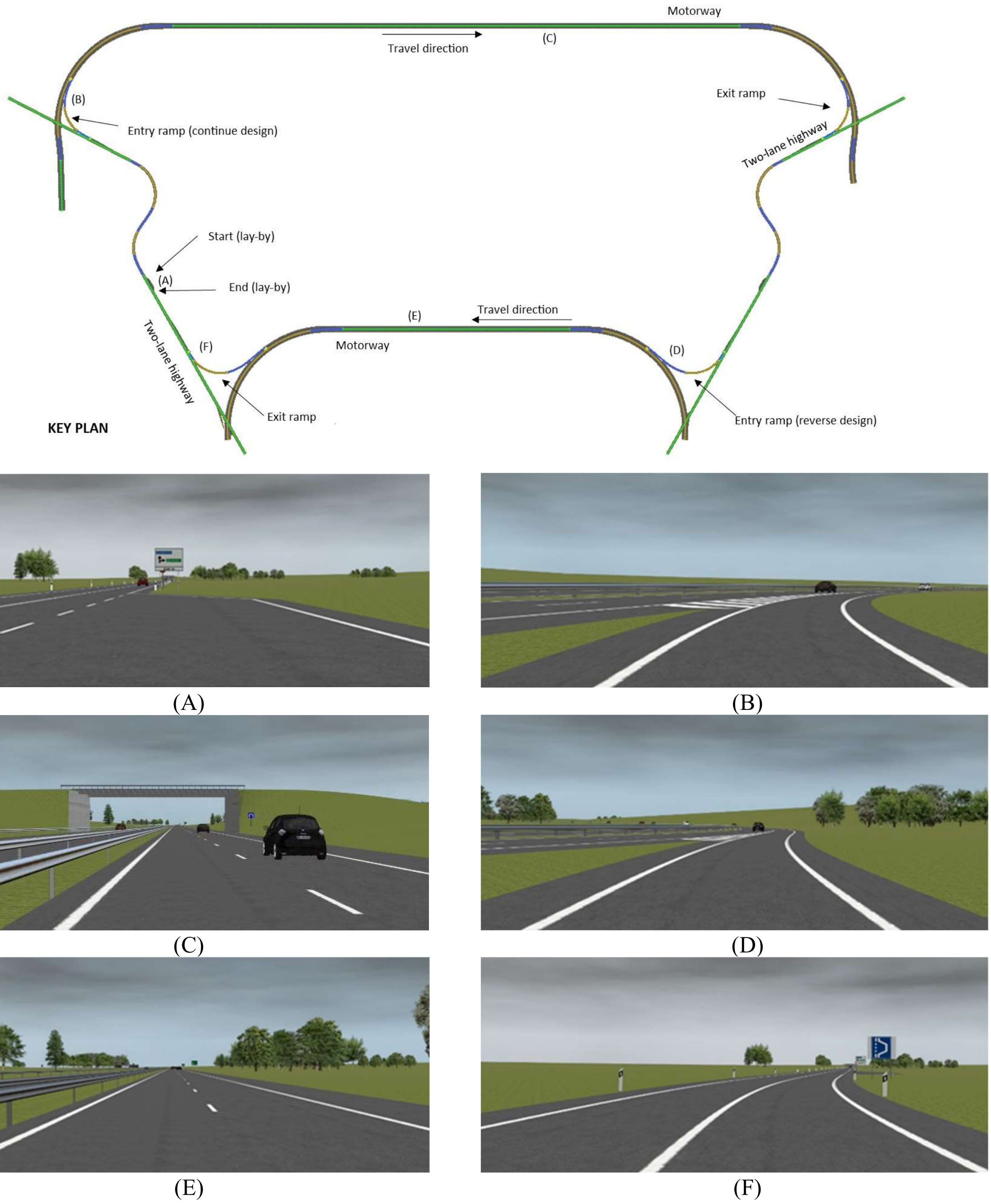

Figure 2. Key plan of the circuits (top) and screenshot from the driver point of view: (A) departure from the lay-by, (B) entry from a continue terminal, (C) first motorway segment, (D) entry from a reverse terminal, (E) second motorway segment and (F) arrive at the lay-by (letters in the key plan indicate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

2.1 Equipment

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

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 130º 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

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

2.2 Independent factors and experimental design

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

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

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

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

A traffic flow of autonomous passenger cars (pc) travelling at 120 km/h was generated along the two through lanes on the motorway with volumes (V) of 1000 and 3000 pc/h, corresponding to the levels of service A and C respectively (TRB, 2016). No traffic was simulated along the ramps. The software can assume a value for the traffic volume and generates a flow of autonomous vehicles with variable headways. Figure 3 shows the results of the headway fitting with a Gamma distribution function. The Kolmogorov-Smirnov (KS) test was used to demonstrate that the two data samples were from a Gamma distributed population (V = 1000 pc/h; $D_{(17)}$ = .044, p = .968; V = 3000 pc/h: $D_{(17)}$ = .040, p = .973).

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

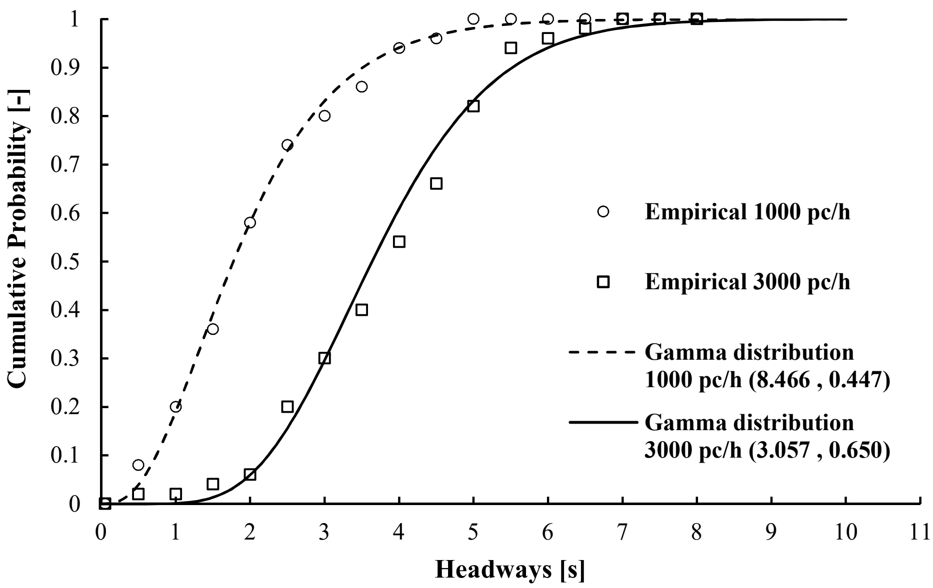

Figure 3. Cumulative distributions of headways for V = 1000 pc/h (LOS = A) and V = 3000 pc/h (LOS = C) generated by SCANeR® in the two through lanes of the motorway. Continue curves represent the Gamma cumulative distribution function based on α (shape) and β (scale) parameters.

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[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:

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

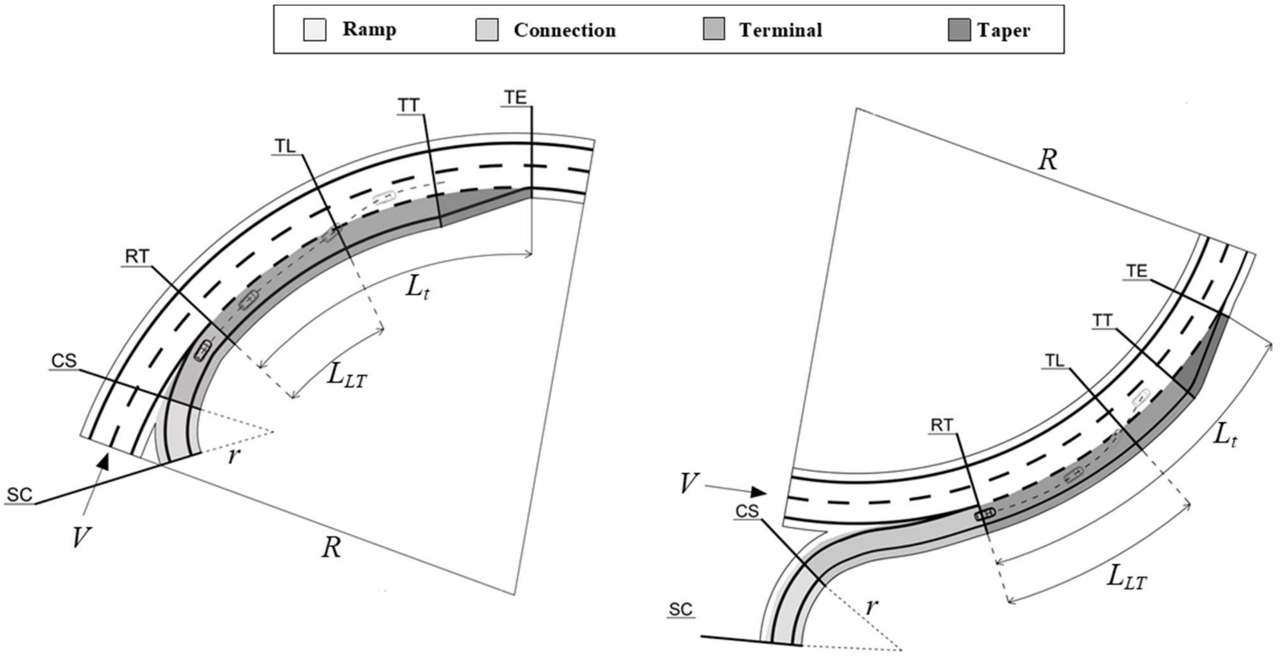
where $k = \frac{R'}{r}$, r is the ramp radius, R' is the radius of the right motorway lane, D is the distance between the two circular curves. The R' value was calculated from the motorway radius R (Figure 4) as follows:

- 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).

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

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



(A) (B)

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

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

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

2.3 Participants

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

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

Table 4. Descriptive statistics on participants (Notes: M = mean, Min = minimum value, Max = maximum value, 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

2.4 Experiment protocol

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

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

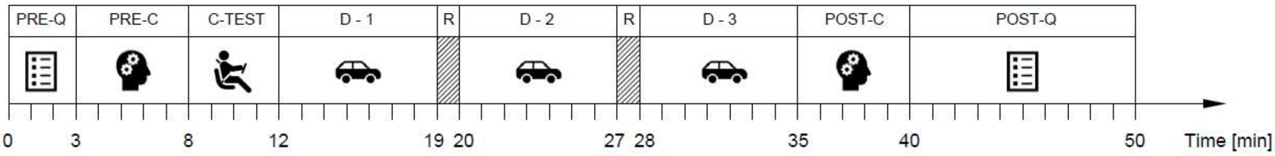


Figure 5. Experimental protocol dispensed to participants, consisting of the following phases: pre-drive questionnaire (PRE-Q), pre-cognitive tests (PRE-C), test circuit (C-TEST), driving on the circuits (D-1, D-2, D-3), rest time between two driving tasks (R), post-cognitive test (POST-C) post-drive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

2.5 Observed variables

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

(i) the longitudinal speed (*S*) at RT (S_{RT}), TL (S_{TL}), and TE (S_{TE}) sections;

(ii) the abscissa of the TL section (L_{TL}), i.e. the path travelled along the terminal from the RT section;

(iii) the standard deviation of lateral position (*SDLP*), which is the standard deviation of the distances between the mass centre and the lane centreline, measured from CS to RT termini (Figure 3); and

(iv) the speed of rotation of the steering wheel.

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

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

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

3. RESULTS AND DISCUSSION

3.1 Questionnaires and cognitive tests

The questionnaire results revealed that during the simulation some drivers (25% of the participants) experienced disorders like visual fatigue, fatigue, and blurred vision. However, these discomforts were of a mild intensity and therefore were considered acceptable for the purpose of the experiment. Only one driver experienced a level of simulator sickness which prevented him from completing the driving task. Hence, he was replaced with another male driver of the same age.

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

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

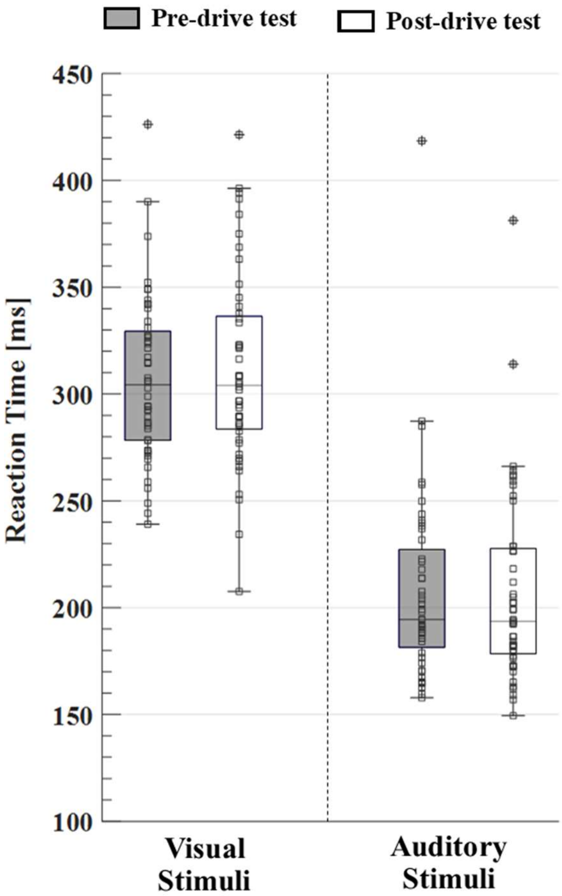


Figure 6. Visual and auditory reaction time distribution in the pre- and post-drive phases.

3.2 Driving task

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

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

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

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

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

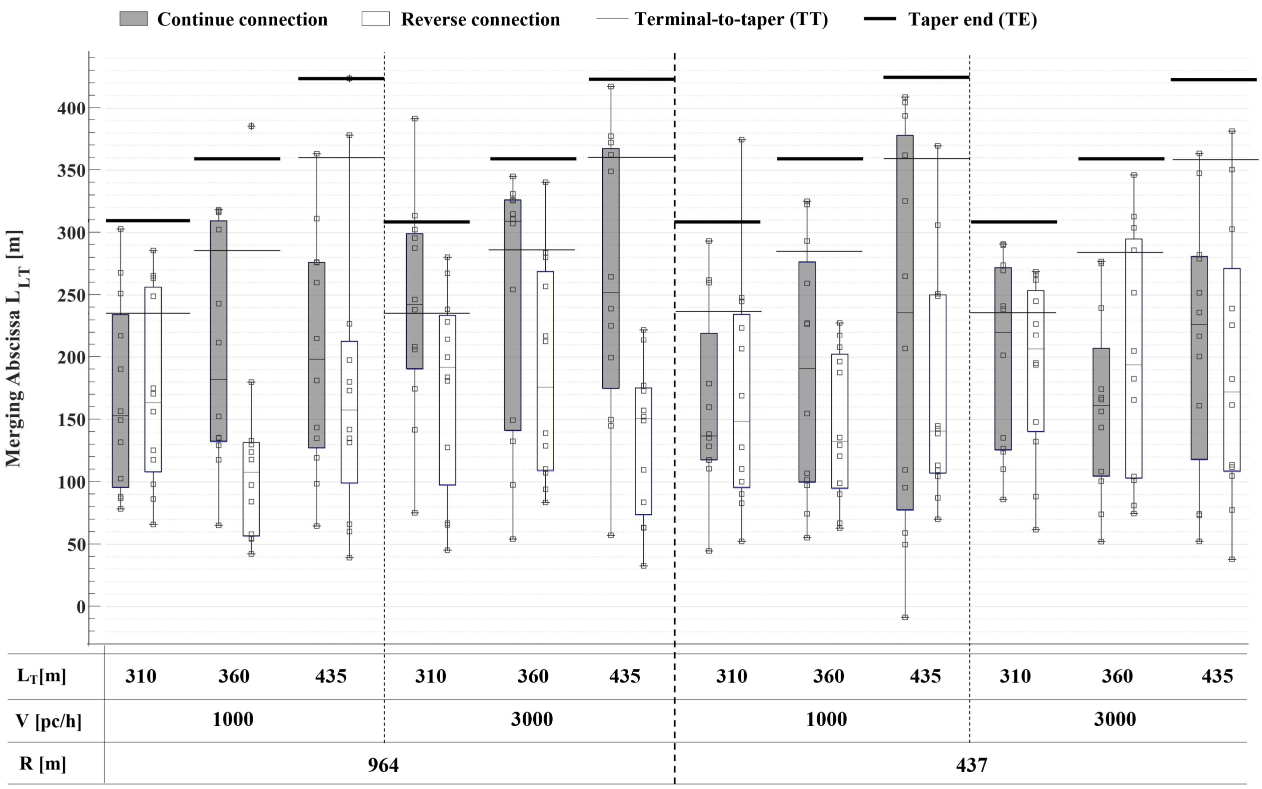
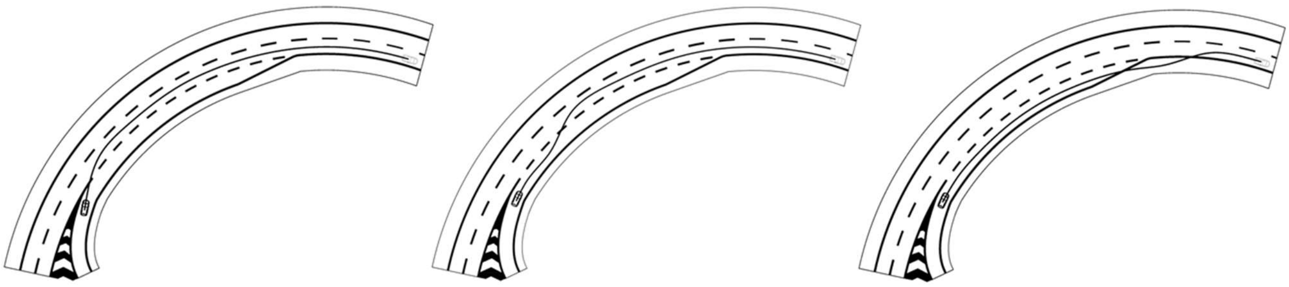


Figure 7. Box-plots for L_{TL} (merging abscissa) values across different terminal lengths (L_T), traffic flow (V), and motorway radius (R) values, for both continue (grey box-plots) and reverse (white-boxplots) ramp-terminal connections.



(A) (B) (C)

Figure 8. Classification of merging manoeuvres: (A) anticipated merging, (B) correct merging, and (C) late merging.

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

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

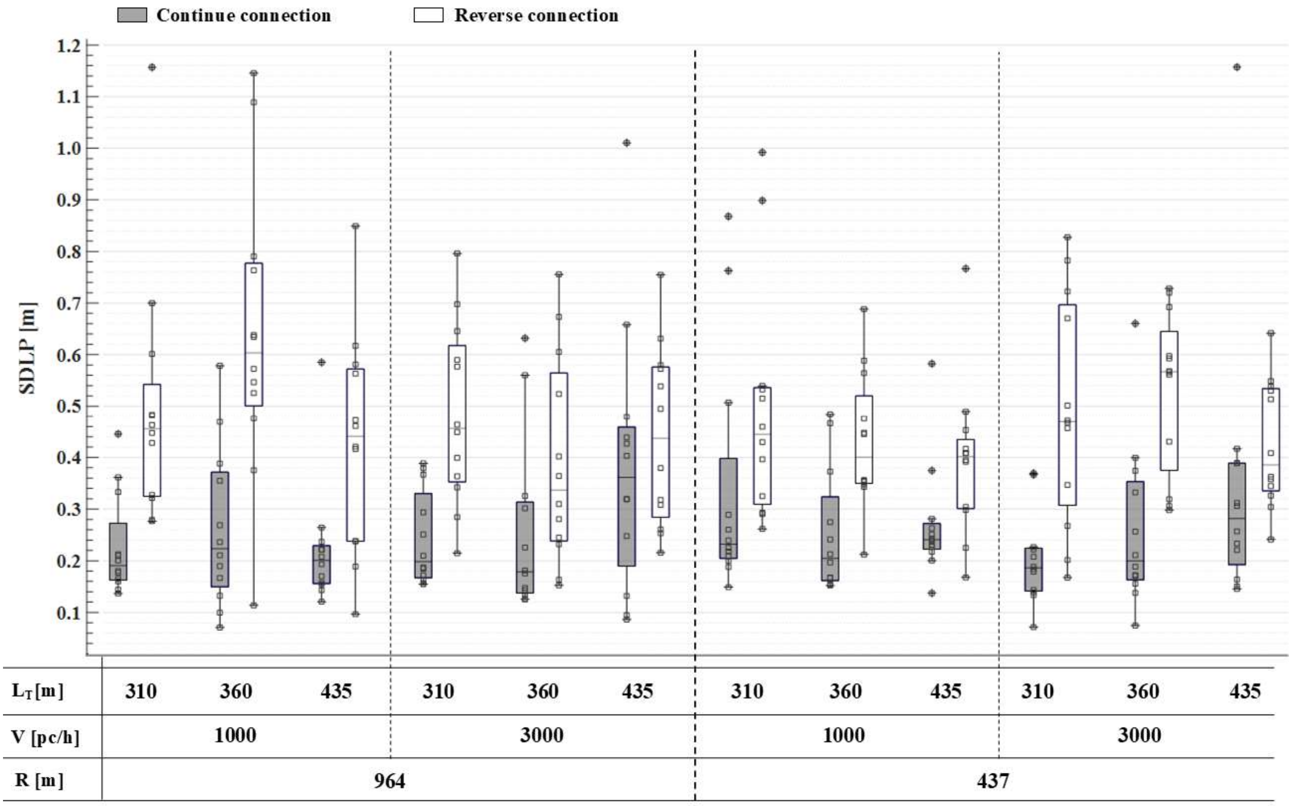


Figure 9. *SDLP* in continue and reverse ramp-terminal connections for different terminal length (L_T), traffic flow (*V*), and motorway radius (*R*) values.

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

Factors	S_{RT}		S_{TL}		S_{TE}		L_{TL}		*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 × *V* × CT	14.41	<.001	10.12	.002	4.57	.033	3.44	.065	5.31	.022

3.3 Longitudinal behaviour

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

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

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

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

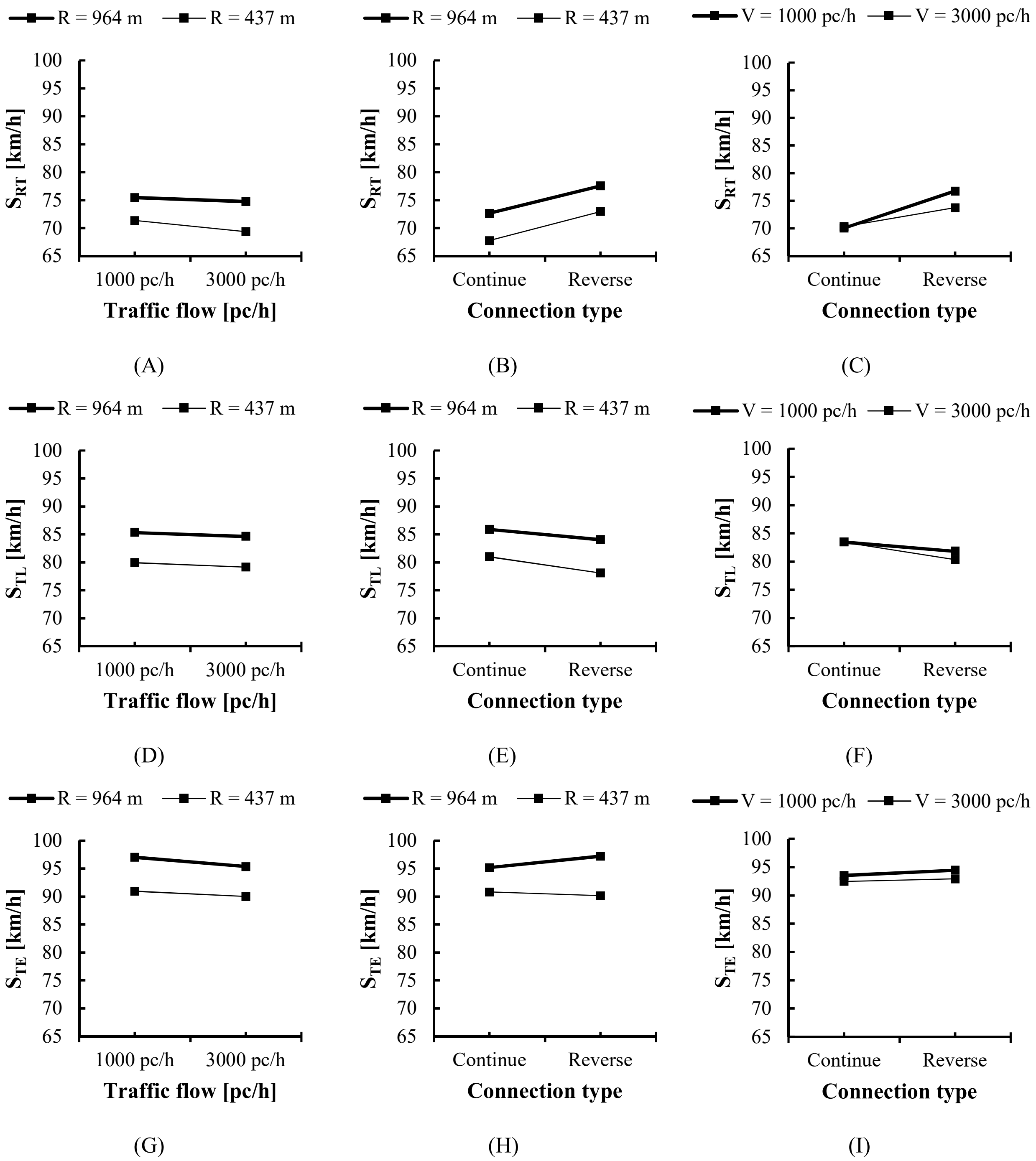


Figure 10. Speed outputs as a function of radius (*R*), traffic flow (*V*), and connection type (CT).

3.4 Transversal behaviour

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

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

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

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

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

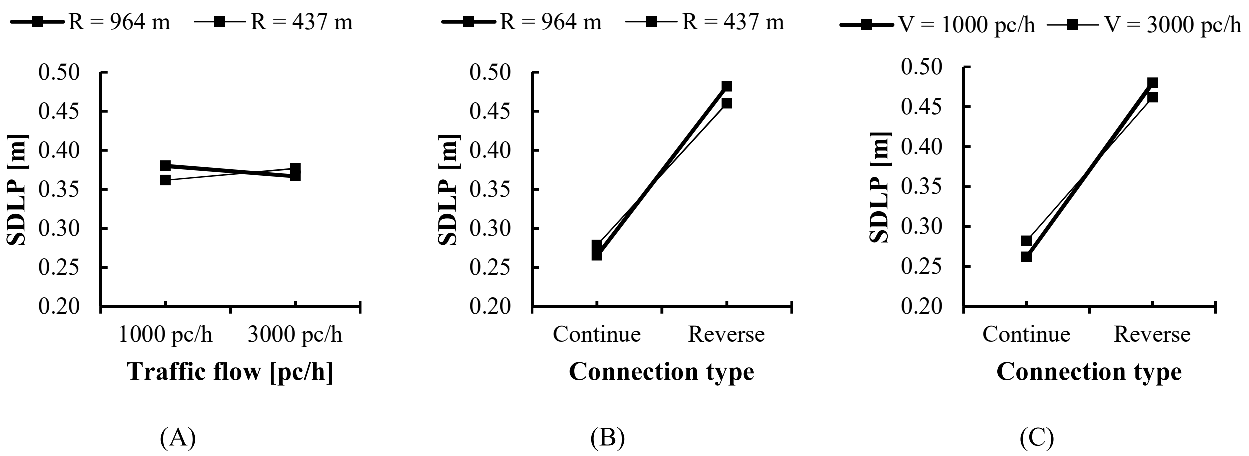


Figure 11. SDLP outputs as a function of radius (*R*), traffic flow (*V*), and connection type (CT).

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

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

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

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

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

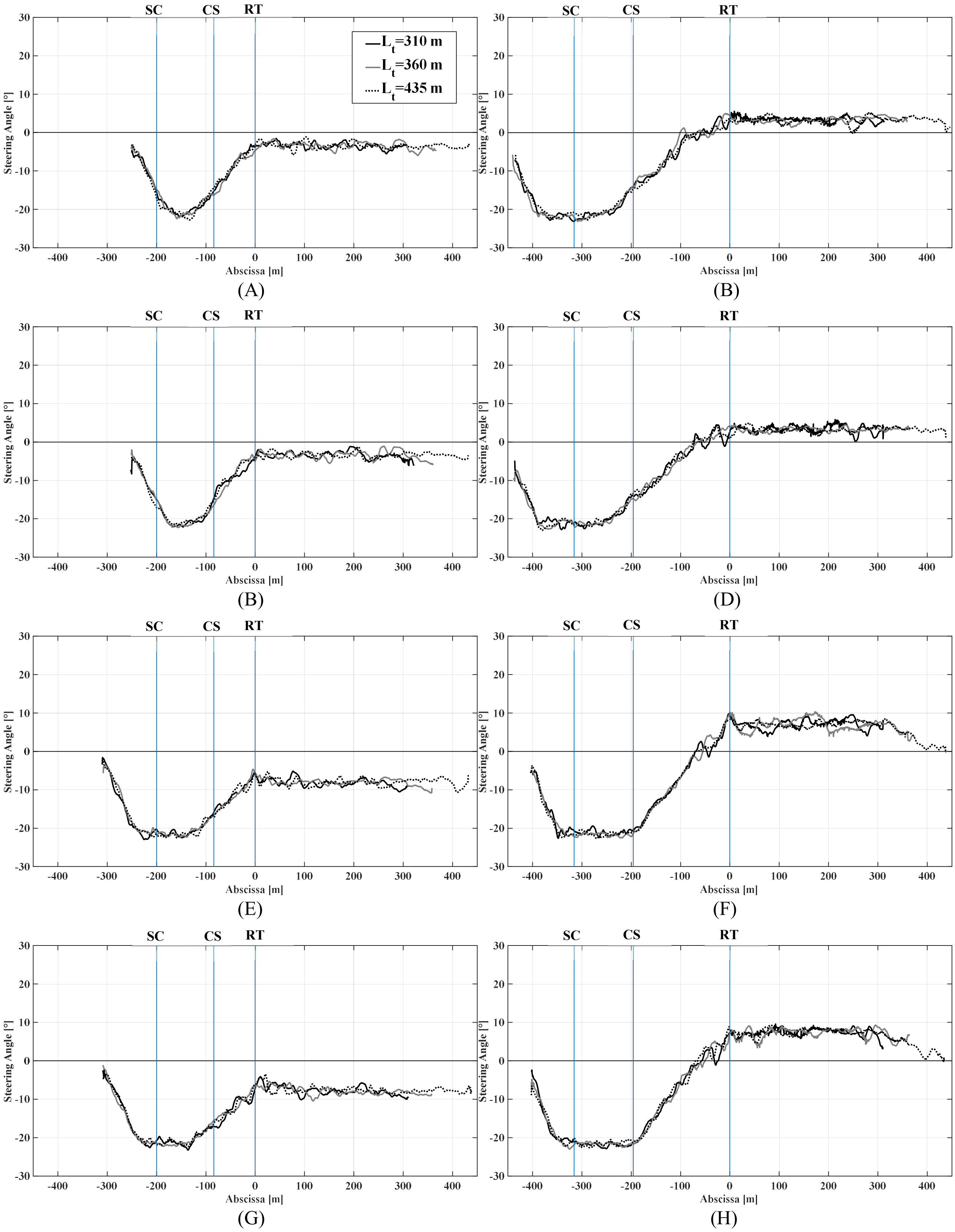


Figure 12. Steering angle values in continue (A, C, E, and G) and reverse (B, D, F, and H) ramp-terminal connections. Cases A, B, E and F refer to V = 1000 pc/h, cases C, D, G and H to 3000 pc/h. Cases A, B, C and D refer to R = 964 m, cases E, F, G and H to R = 437 m. The acquisition frequency of the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

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

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

4. CONCLUSIONS

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

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

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

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

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

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

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