

Experimental Investigation into Driver Behavior along Curved and Parallel Diverging Terminals of Exit Interchange Ramps

*Original*

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(Article begins on next page)

1 **An Experimental Investigation into Driver Behavior along Curved and Parallel Diverging**  
2 **Terminals of Exit Interchange Ramps**

3

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1 **ABSTRACT**

2 Current design manuals provide guidance on how to design exit ramps to facilitate driving operations and  
3 minimize the incidence of crashes. They also suggest that interchanges should be built along straight  
4 roadway sections. These criteria may prove ineffective in situations where there is no alternative to  
5 terminals being located along curved motorway segments.

6 The paper investigates driving behavior along parallel deceleration curved terminals, with  
7 attention paid to the difference in impact between terminals having a curvature which is the same sign as  
8 the motorway segment (i.e. continue design), and those having an opposite curvature (i.e. reverse design).  
9 A driving simulation study was set up to collect longitudinal and transversal driver behavioral data in  
10 response to experimental factor variations. Forty-eight drivers were stratified on the basis of age and  
11 gender, and asked to drive along three randomly assigned circuits with off-ramps obtained by combining  
12 experimental factors like motorway radius (2 values), terminal length (3), curve direction (2) and traffic  
13 conditions (2).

14 The freeway radius was found to be significant for drivers' preferred speed when approaching the  
15 terminal. Terminal length and traffic volume do not have any significant impact on both longitudinal and  
16 transversal driver outputs. However, the effect of curve direction was found to be significant, notably  
17 reverse terminals which do not compel drivers to select appropriate speeds and lane change positions.  
18 This terminal type can give rise to critical driving situations that should be considered at the design stage  
19 to adopt appropriate safety countermeasures.

20

21 **Keywords:** Off-ramps, terminal, parallel design, driver behavior, driving simulation.

1 **INTRODUCTION**

2 An interchange is a system of curved roadways connecting carriageways with one or more grade  
3 separations. This system is made up of ramps linked to carriageways through acceleration and  
4 deceleration terminals. Road designers establish the geometric characteristics of the ramps and terminals  
5 required to facilitate safe and efficient traffic operations. In particular, off-ramp terminals are designed to  
6 reduce conflicts between diverging vehicles and those proceeding straight ahead and to facilitate  
7 deceleration prior to negotiating the ramp curve. The only two exit terminals are the parallel type, in  
8 which a lane parallel to the main carriageway leads to the off-ramp, and the tapered one, in which an  
9 inclined lane is detached from the carriageway to form an off-ramp (1,2).

10 Manuals and geometric policies provide design criteria to help designers establish the  
11 characteristics of the requisite geometric elements for a terminal and the subsequent ramp (1,2). They also  
12 indicate that deceleration terminals should be located along straight segments to facilitate vehicle  
13 operations (2). However, terminals are also designed along curved motorway sections and since the  
14 technical literature omits the case of curved terminals, designers do not have the tools needed to evaluate  
15 the issues affecting driver behavior along these facilities.

16 In the case of parallel design, Italian policy (2) assumes that vehicles exiting the motorway  
17 continue along the through lane to the terminal at the motorway design speed, and that in the middle of  
18 the taper the driver starts decelerating at a constant value ( $3 \text{ m/s}^2$ ) to reach the design speed of the  
19 off-ramp curve. However, field and laboratory observations demonstrate that drivers assume a variety of  
20 behaviors and make decisions that are often at variance with these standard assumptions (3,4). This  
21 occurs when drivers do not adopt a constant deceleration rate; i.e. off-ramp terminals are designed which  
22 fail to incorporate the full range of driver behavior and the factors which impact on same.

23 Studies on linear deceleration terminals have been carried out in the past (3-5). Lower traffic flow  
24 results in higher average and maximum deceleration rates, higher exiting speeds, and earlier braking in  
25 the main lane. Conversely, the lane change point and the speed at the end of the deceleration lane do not  
26 seem to be influenced by traffic flow (3). Lyu *et al.* (4) confirmed that drivers behave differently from  
27 road geometric standard assumptions. In their study, vehicle speed decreased by up to 80 km/h when  
28 drivers were leaving the main lane, a deceleration which could cause safety issues due to the speed  
29 differential with other vehicles proceeding along the main lane. Furthermore, the speeds in the exit ramp  
30 were significantly higher than the posted speed limit. This evidence confirms that many drivers are  
31 reluctant to decelerate correctly. Other studies have evidenced that the terminal geometry (i.e., type,  
32 width, and length) impacts on the operational and safety performance of such facilities (6-9). Calvi *et al.*  
33 (6) demonstrated that the choice of designing a tapered or parallel lane significantly affects the speeds of  
34 diverging drivers, resulting in problematic forms of interaction with those drivers proceeding straight on  
35 the motorway.

36 Colonna and Del Carmine (10) conducted an observational study on a leftward curved  
37 deceleration terminal combined with a rightward off-ramp. They observed that more than 90% of exiting  
38 users employed the last 15-20 m of the parallel lane due to the extended available sight distance along the  
39 leftward motorway section. Drivers tended to point the exit by "rectifying" the diverging trajectory; based  
40 on this observation, they suggested the adoption of tapered deceleration lanes which would oblige drivers  
41 to make better use of the exit lane. The "S" maneuver, with double steering, seemed very unlikely for a  
42 vehicle not conditioned by the traffic on the main road. However, their study covered only one type of  
43 curved exit ramp in a specific study section.

44 To cover the gap in knowledge on this topic, this study investigates the behavior of drivers along  
45 curved exit terminals incorporating various combinations of geometric and operational factors not  
46 included in previous studies (10). A driving simulation study was carried out in light of the results  
47 obtained in a previous work by Bella *et al.* (5), who compared field observations of drivers moving along  
48 linear terminals with the behavior of other drivers using a driving simulator which recreated a road  
49 environment and traffic conditions identical (or almost) to that of the real terminals. They found that  
50 when compared to the field data, the average trajectory in the driving simulation was similar but speeds  
51 were higher. This result is explained by the fact that the perception of risk is higher in real driving

1 conditions with respect to simulated ones. However, the study did demonstrate the potential of driving  
 2 simulations in the study of driver behavior along ramp terminals.

3 The factors considered in this experiment include the terminal length, the traffic flow along the  
 4 motorway, the motorway radius, and the motorway curve direction. In particular, two ramp-to-terminal  
 5 connections were investigated: the reverse type (i.e., S-shaped, or inflected), which links an off-ramp to a  
 6 terminal along a leftward motorway curve, and the continue type (i.e., egg-shaped) which links the  
 7 off-ramp to a terminal along a rightward motorway curve. The differences between curved and straight  
 8 terminals have been analyzed by comparing the results documented here with those from literature. A  
 9 series of driving simulations were also carried out.

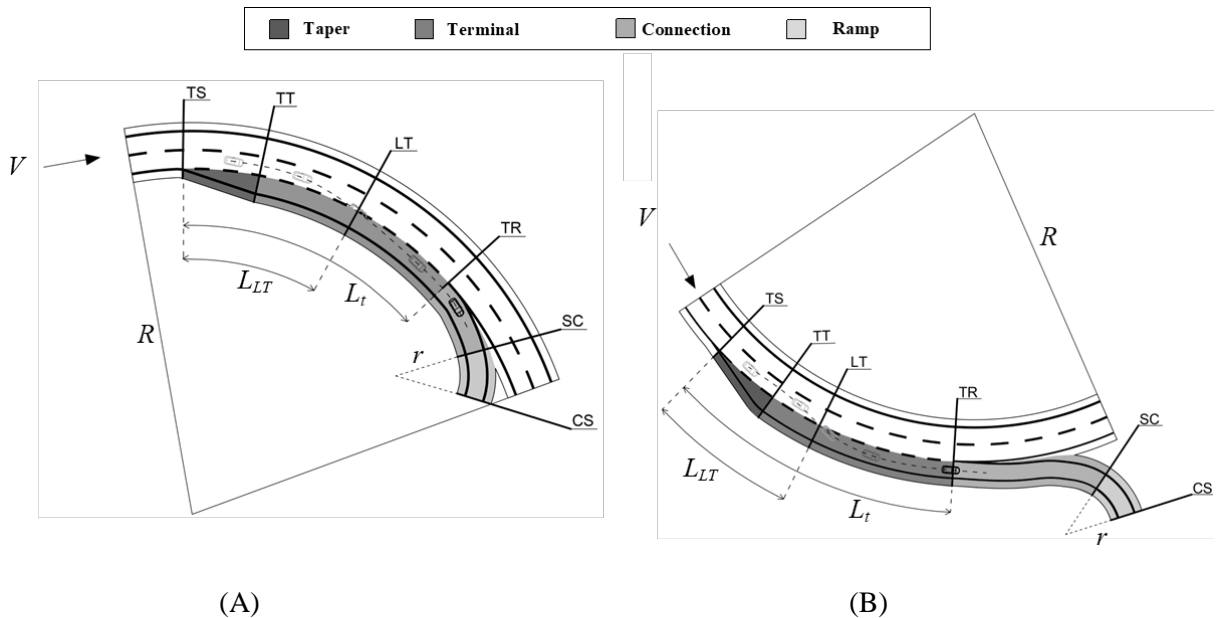
## 11 METHODS

### 12 Equipment

13 The fixed-base driving simulator (AV Simulation, France) used has a vision system composed of three  
 14 monitors (32-inch full HD) which cover a  $130^\circ$  field of view, a fully-equipped cockpit with seat, steering  
 15 wheel, manual gearbox, pedals and dashboard, a force feedback on the steering wheel and vibration pads  
 16 to return wheel rolling, pavement roughness and shocks. The simulator was relatively validated for  
 17 longitudinal (11) and transversal driver behavior (12), as well as for passing maneuvers (13) on two-lane  
 18 rural highways. SCANeR Studio® simulation software (<https://www.avsimulation.com/scanerstudio/>)  
 19 was used to model the driving scenarios and record the dependent variables such as temporal-spatial data  
 20 for trajectories, which were then used to derive speed and lateral positions.

### 22 Experimental design, driving scenarios, and independent factors

23 Twelve circuits were designed to allow drivers to perform diverging maneuvers into the motorway  
 24 sections. Each circuit was made up of two motorway sections and two two-lane highway segments  
 25 designed according to Italian road geometric design standards (14). It included two curved off-ramp  
 26 terminals with parallel design: the continue (Figure 1A) and the reverse one (Figure 1B).



31 **Figure 1** Geometric factors considered in the design of continue (A) and reverse (B) terminals  
 32 include motorway radius ( $R$ ), terminal length ( $L_t$ ), and traffic volume ( $V$ ). Ramp radius was  
 33 assumed constant in the experiment ( $r = 150$  m). Significant termini: terminal start (TS),  
 34 taper-to-terminal (TT), lane-to-terminal (LT), terminal-to-ramp (TR), spiral to curve (SC), curve to  
 35 spiral (CS).

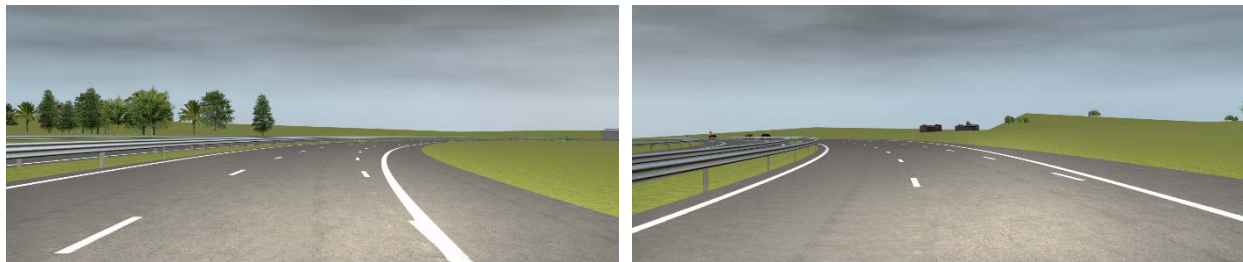
1 The motorway cross-section presented two lanes per direction, with a lane width of 3.75 m and a  
 2 right shoulder width of 3.00 m. The lane width and the shoulder width of the two-lane highway were  
 3 3.75 m and 1.50 m respectively. The off-ramps were designed in accordance with Italian Policy (2), the  
 4 main details of which are summarized in **Appendix A**. The ramps consisted of (i) a taper of a fixed length  
 5 equal to 90 m (TS-TT segment in **Figure 1**), and (ii) a deceleration segment of variable length (TT-TR  
 6 segment in **Figure 1**) with the TR section placed at the diverging theoretical gore between the motorway  
 7 lane and the off-ramp. The ramp had one 4.0 m wide lane and two 1.0 m wide paved shoulders. **Figure 2**  
 8 shows some frames from the simulated environment for the continue (**Figure 2A, 2C, 2E**) and the reverse  
 9 terminals (**Figure 2B, 2D, 2F**). It is worth noting that no traffic barriers were used on either the motorway  
 10 roadside or the ramps to preclude any effects caused by this potential experimental factor. Furthermore,  
 11 two vertical signs placed 1000 and 250 m before the TS section were used to inform drivers of the exit  
 12 ramp.

13 In the experimental design (i) the motorway radius ( $R$ ), (ii) the traffic volume ( $V$ ), (iii) the  
 14 terminal length ( $L_t$ ), and (iv) the connection type ( $CT$ ) between terminal and ramp were included. Each  
 15 variable was modified at two levels (indicated as “-1” and “+1” in **Table 1**), except for the terminal length  
 16 which presented three levels (indicated as “-1”, “0”, and “+1” in **Table 1**).

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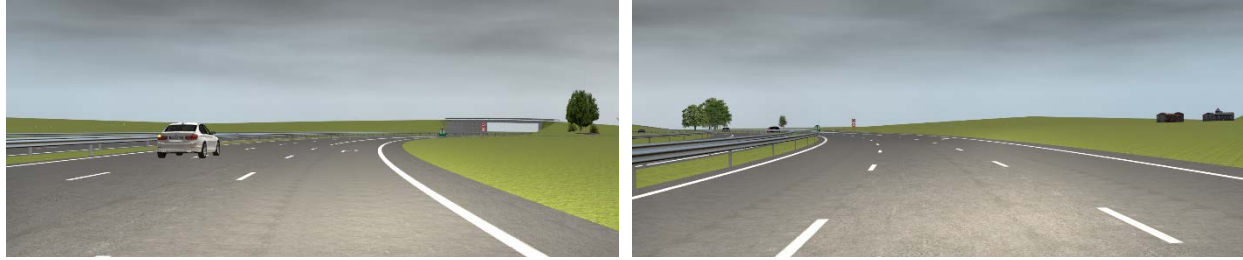


(A)

(B)

20

21



(C)

(D)

22

23



(E)

(F)

24 **Figure 2** Frames from the simulated environment depicting the driver point of view approaching the  
 25 off-ramp in the case of continue (A, C, E) and reverse (B, D, F) terminals.

26

1  $R$  was assumed equal to 964 and 437 m for a design speed ( $v_1$ ) of 140 and 100 km/h respectively  
 2 (14). Two traffic condition scenarios for the autonomous vehicles were generated along the motorway.  
 3 Traffic volumes of 1000 and 3000 pc/h, representing LOS A and LOS C respectively were used (15), with  
 4 simulated vehicles traveling at a speed in the 120-130 km/h range with variable headways following a  
 5 Gamma probability distribution function, with  $\alpha$  (shape) and  $\beta$  (scale) parameters equal to 8.466 and  
 6 0.477 respectively for 1000 pc/h, and 3.057 and 0.650 respectively for 3000 pc/h. In accordance with  
 7 reference studies on linear terminals (3,5,6), no traffic was generated along the exit ramps.

8 As previously indicated a continue terminal is obtained when the motorways and the terminal  
 9 curves are of the same (right) direction (**Figure 1A**). A reverse terminal is necessary when the motorway  
 10 curve has the opposite direction (i.e., leftward) respect to the ramp (**Figure 1B**). **Appendix B** provides the  
 11 design details of the two ramp-terminal connections.

12 The deceleration distance ( $L_d$ ) was computed by starting from the middle of the taper (middle  
 13 point between TS and TT) and the TR section (**Figure 1**). The other two  $L_d$  values were obtained by  
 14 increasing the value estimated in **Equation A1** by 75 m and decreasing it by 50 m.

15 **Table 1** provides the levels of the independent variables (experimental factors), while **Table 2**  
 16 shows how these levels were combined in the twelve circuits specifically designed for the experiment.  
 17

18 **TABLE 1 Factors and levels included in the experimental design.**

Experimental factors	Levels of factors		
	-1	0	+1
Motorway radius, $R$ [m]	437	-	964
Traffic flow, $V$ [pc/h]	1000	-	3000
Terminal Length, $L_t$ [m]	200	250	325
Connection type, $CT$ [-]	Continue	-	Reverse

19  
 20 **TABLE 2 Circuits and levels of investigated factors.**

Circuit	Continue terminal			Reverse terminal		
	Motorway radius, $R$ [m]	Traffic flow, $V$ [pc/h]	Terminal Length, $L_t$ [m]	Motorway radius, $R$ [m]	Traffic flow, $V$ [pc/h]	Terminal Length, $L_t$ [m]
<b>1</b>	+1	-1	0	+1	+1	-1
<b>2</b>	+1	-1	+1	+1	+1	0
<b>3</b>	+1	-1	-1	+1	+1	+1
<b>4</b>	+1	+1	+1	+1	-1	0
<b>5</b>	+1	+1	-1	+1	-1	+1
<b>6</b>	+1	+1	0	+1	-1	-1
<b>7</b>	-1	-1	-1	-1	+1	+1
<b>8</b>	-1	-1	0	-1	+1	-1
<b>9</b>	-1	-1	+1	-1	+1	0
<b>10</b>	-1	+1	0	-1	-1	0
<b>11</b>	-1	+1	-1	-1	-1	-1
<b>12</b>	-1	+1	+1	-1	-1	+1

## 1 Participants

2 Forty-eight participants took part in the experiment, the conduct of which was in compliance with the  
 3 Code of Ethics of the World Medical Association (18). They participated voluntarily, so they received no  
 4 benefit or payment for their involvement. All participants signed an informed consent form before the  
 5 experimental session. The sample of participants, whose characteristics are summarized in **Table 3**,  
 6 included a cross-section of drivers between the ages of 19 and 61 to best represent the licensed driver  
 7 population in Italy. In particular, 10% of the drivers were between 19 and 24, 42% between 25 and 44,  
 8 and 48% between 44 and 61.

9  
 10 **TABLE 3 Descriptive statistics about participants (Notes: Ave. = average value, Min = minimum**  
 11 **value, Max = maximum value, SD = standard deviation, M = males, F = females).**

	Age, y			Driving Experience, y			Distance Travelled, km/y			Crash Experience, No.		
	M	F	M&F	M	F	M&F	M	F	M&F	M	F	M&F
Ave.	42.2	41.6	41.4	22.8	22.1	22.5	16,096	9,100	12,615	1.1	1.4	1.2
Min	19	20	19	1	1	1	500	300	300	0	0	0
Max	61	57	61	43	37	43	40,000	24,000	40,000	4	10	10
SD	13.5	12.4	12.9	13.3	11.6	12.8	11,652	7,643	10,787	1.3	2.3	1.8

## 12 Experimental protocol

13 A pre-drive questionnaire relating to their health status, and the consumption of any food and/or  
 14 substances prior to the driving task was dispensed to each test driver. Drivers were administered pre- and  
 15 post-drive cognitive tests to record their perception and reaction times (PRT) to visual and auditory  
 16 stimuli. The results obtained were used to determine if the cognitive performance of participants changed  
 17 during the test. Prior to the simulation, participants were introduced to the simulator and familiarized  
 18 themselves with the use of the steering wheel, pedals, and gearbox, and drove a trial circuit to test the  
 19 apparatus and get familiar with the hardware and the virtual environment (19). Then, each participant  
 20 drove three out of twelve randomly assigned circuits (**Table 2**). Each test drive was followed by a rest  
 21 period of one minute to re-establish the optimal pre-test psychophysical condition of the drivers (20). A  
 22 post-drive questionnaire was dispensed to collect information regarding simulator sickness and the  
 23 subjective judgment of the driving experience.

## 24 Observed variables, data collection, and manipulation

25 Data was collected at a frequency of 100 Hz, the outcomes were recorded, validated, and organized for  
 26 each of the twelve circuits. Data were analyzed at sites corresponding to the corresponding ones in Calvi  
 27 *et al.* (3) for linear deceleration terminals. The reference sections are represented in **Figure 1**: (i) the taper  
 28 start (TS), (ii) the taper-to-terminal (TT), (iii) the lane-to-terminal (LT) where the center of gravity of the  
 29 vehicle crosses the marking separating the motorway lane and the terminal, and (iv) the terminal-to-ramp  
 30 (TR) at the end of the deceleration lane where the exit ramp curve begins. Other data were collected in the  
 31 connection segment between sections TR and SC.

32 Some longitudinal and transversal driver inputs and vehicle outputs were monitored. Between the  
 33 longitudinal ones, the speed values at TS ( $S_{TS}$ ), LT ( $S_{LT}$ ), and TR ( $S_{TR}$ ) sections were taken together with  
 34 the action on pedals approaching the terminal, i.e. the station of the throttle release and the station where  
 35 the driver acted on the brake pedal to negotiate the lane change. Transversal measurements included the  
 36 diverging abscissa ( $L_{LT}$ ) which measures the distance of the LT section from the TS one, the steering  
 37 wheel angle along the entire off-ramp, and the standard deviation of lateral position ( $SDLP$ ) along the  
 38 connection between the terminal and the ramp, were used to indicate the vehicle control capability of  
 39 drivers (21).



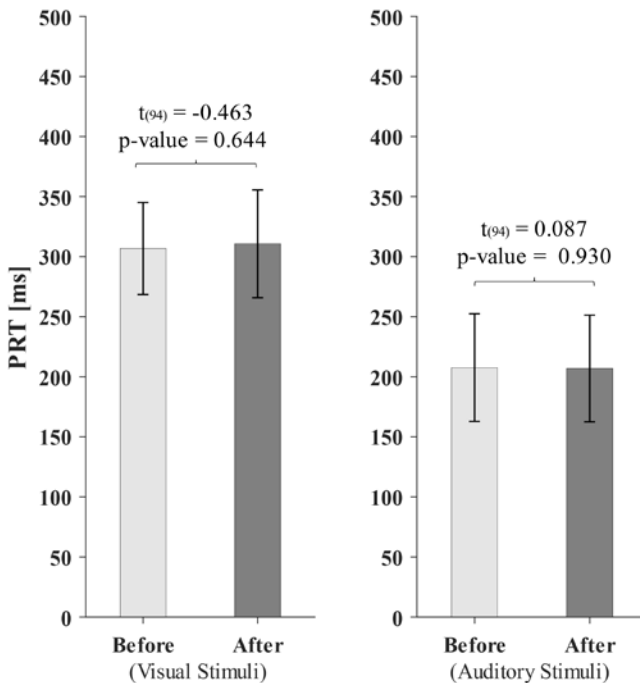
## 1 RESULTS AND DISCUSSION

### 2 Questionnaires and cognitive tests

3 The questionnaire results revealed that diverging maneuvers on curved terminals did not present the  
4 participants with any particular difficulties. Nevertheless, the curved terminals did result in some  
5 problems with the comprehension of the ramp geometry and the management of the braking phase.

6 PRT from auditory and visual stimuli (**Figure 3**) carried out before and after the driving session  
7 were found to be normally distributed according to the Kolmogorov-Smirnov (KS) test for normality  
8 (pre-drive visual reaction:  $D_{(48)} = .08$ ,  $p = .847$ ; pre-drive auditory reaction:  $D_{(48)} = .14$ ,  $p = .228$ ;  
9 post-drive visual reaction:  $D_{(48)} = .12$ ,  $p = .435$ ; post-drive auditory reaction:  $D_{(48)} = .17$ ,  $p = .102$ ).

10 A comparison between before and after PRT for visual and auditory stimuli did not reveal any  
11 significant variation at the 95% confidence level (**Figure 3**). As a consequence, the protocol adopted for  
12 this experiment did not affect the cognitive performances of participants during the test. However, one  
13 participant who experienced simulation sickness during the trial simulation session did not start the  
14 experiment and his place was taken by another participant of the same age and gender.  
15  
16



17 **Figure 3 Average visual and auditory reaction times before and after the driving session.**

### 18 Synthesis of results and Analysis of Variance (ANOVA)

19 The speeds at the three reference sites (TS, LT, and TR), the diverging abscissa ( $L_{LT}$ ), and the standard  
20 deviation of lateral position ( $SDLP$ ) values are reported in **Table 4**. The table shows the average and  
21 standard deviations of the values recorded for the different combinations of the experimental factors  
22 (2 motorway radii  $\times$  3 terminal lengths  $\times$  2 traffic volumes  $\times$  2 connection types). Hence, a  $2 \times 3 \times 2 \times 2$   
23 ANOVA (**Table 5**) was conducted to assess whether these independent variables lead to statistically  
24 significant variations in the dependent ones. The driving speeds, the diverging abscissas, and the  $SDLP$   
25 data were found to be normally distributed as per the KS test for normality.  
26  
27  
28  
29

1 **TABLE 4** Descriptive statistics for speeds recorded at TS ( $S_{TS}$ ), LT ( $S_{LT}$ ) and TR ( $S_{TR}$ ) sections,  
 2 longitudinal abscissa of the diverging point ( $L_{TL}$ ), and standard deviation of lateral position ( $SDLP$ ).  
 3 (Notes: M = Mean value; SD = standard deviation).

Terminal length, m ( $L_t$ )	200				250				325				
Traffic volume, pc/h ( $V$ )	1000		3000		1000		3000		1000		3000		
Motorway radius, m ( $R$ )	964	437	964	437	964	437	964	437	964	437	964	437	
<b>Continue terminal</b>													
$S_{TS}$ , km/h	M	100.3	103.2	104.4	103.7	107.2	104.7	102.8	103.7	111.7	104.5	109.8	100.8
	SD	15.9	18.3	7.7	14.4	17.0	18.9	13.4	9.9	14.1	19.2	14.4	11.7
$S_{TS} - S_{LT}$ , km/h	M	3.4	2.7	2.7	4.6	5.0	3.0	1.3	2.8	5.0	4.4	2.6	3.5
	SD	2.1	2.4	2.6	3.1	2.9	2.1	1.7	1.9	2.9	6.6	2.9	3.5
$S_{LT}$ , km/h	M	96.9	100.4	101.7	97.1	102.1	101.7	101.5	100.9	106.7	100.1	107.2	97.3
	SD	15.3	18.0	9.1	14.3	17.5	18.6	13.5	9.7	13.6	18.2	14.3	11.2
$S_{LT} - S_{TR}$ , km/h	M	20.1	15.2	16.8	13.8	25.9	13.2	20.7	13.1	24.1	17.9	22.2	15.9
	SD	9.7	10.5	7.6	8.5	8.7	6.1	7.1	5.7	10.0	7.4	9.3	7.5
$S_{TR}$ , km/h	M	76.8	85.2	84.9	83.3	76.3	88.6	80.8	87.9	82.6	82.2	85.0	81.3
	SD	16.3	21.0	7.6	17.4	17.8	16.9	15.1	12.5	16.5	15.1	17.4	12.4
$L_{LT}$ , m	M	37.9	53.2	51.2	57.0	62.4	44.6	35.1	42.2	56.0	32.3	63.7	39.7
	SD	21.1	14.7	27.8	26.8	21.1	19.8	17.3	13.7	28.7	56.5	48.8	31.2
$SDLP$ , m	M	0.37	0.32	0.39	0.27	0.25	0.36	0.32	0.30	0.37	0.32	0.25	0.23
	SD	0.25	0.15	0.18	0.16	0.08	0.24	0.21	0.10	0.23	0.14	0.11	0.06
<b>Reverse terminal</b>													
$S_{TS}$ , km/h	M	112.6	103.3	101.7	113.3	118.9	99.6	108.8	104.1	113.8	105.7	106.4	103.8
	SD	15.7	13.6	14.7	19.8	13.4	11.6	16.4	17.0	14.7	11.5	19.8	15.1
$S_{TS} - S_{LT}$ , km/h	M	9.8	8.4	7.9	11.4	9.4	12.0	10.8	10.1	8.2	5.3	5.6	9.9
	SD	15.3	7.7	6.7	11.4	6.9	11.6	9.9	8.7	6.1	4.0	4.7	8.3
$S_{LT}$ , km/h	M	102.8	94.9	93.8	101.9	109.4	87.6	98.0	94.0	105.6	100.4	100.9	93.9
	SD	17.8	16.6	16.3	17.7	14.8	17.0	15.4	12.8	16.0	12.0	17.7	15.3
$S_{LT} - S_{TR}$ , km/h	M	14.4	13.9	10.0	10.2	14.9	11.4	10.8	12.9	13.6	15.0	11.2	9.4
	SD	9.9	10.3	6.6	5.4	8.3	15.7	6.8	8.5	8.9	8.7	8.6	8.7
$S_{TR}$ , km/h	M	88.4	81.0	83.8	91.8	94.6	76.3	87.1	81.1	88.4	85.4	89.6	84.5
	SD	18.9	14.0	13.2	21.0	15.3	16.0	17.2	13.8	18.9	12.0	21.0	13.4
$L_{LT}$ , m	M	90.2	85.7	87.6	101.2	105.8	109.6	136.7	93.2	138.6	101.7	95.7	142.1
	SD	76.3	33.3	66.8	47.3	52.0	63.6	78.9	63.2	75.0	90.7	102.5	120.7
$SDLP$ , m	M	0.55	0.39	0.60	0.39	0.48	0.50	0.58	0.42	0.58	0.38	0.49	0.49
	SD	0.17	0.17	0.13	0.18	0.08	0.22	0.16	0.16	0.10	0.17	0.09	0.22

4  
 5 **TABLE 5** Analysis of Variance (ANOVA), main and significant interaction effects (significant  
 6 values in bold).

Factors	$S_{TS}$		$S_{LT}$		$S_{TR}$		$L_{LT}$		$SDLP$	
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
<b>Main effects</b>										
$R$	5.66	<b>0.018</b>	6.97	<b>0.009</b>	0.37	0.543	0.51	0.474	13.74	<b>&lt;0.001</b>
$L_t$	0.45	0.639	0.91	0.404	0.17	0.843	1.28	0.279	0.51	0.604
$V$	1.32	0.252	0.93	0.335	0.29	0.590	0.11	0.739	0.46	0.498
$CT$	3.14	0.077	2.06	0.152	2.79	0.064	75.87	<b>&lt;0.001</b>	80.55	<b>&lt;0.001</b>
<b>Interactions</b>										
$R \times V \times CT$	4.62	<b>0.032</b>	4.22	<b>0.041</b>	4.68	<b>0.032</b>	0.23	0.633	0.38	0.538
$R \times CT$	0.51	0.476	0.81	0.368	6.86	<b>0.009</b>	0.04	0.842	6.06	<b>0.014</b>
$R \times L_t$	1.87	0.156	1.61	0.201	0.85	0.429	0.84	0.432	3.31	<b>0.045</b>
$R \times V \times L_t$	0.39	0.679	0.86	0.424	0.13	0.875	1.31	0.272	4.10	<b>0.018</b>

7

## 1 Longitudinal driver behavior

2 Drivers adopted an almost constant speed when approaching the continue curved terminal along the  
3 motorway. **Table 4** indicates that speeds at TS and LT sites were very similar in terms of both mean and  
4 standard deviation. For example, along the continue terminal with  $R = 437$  m and  $L_t = 250$  m, mean  
5 values differed by only 3 km/h, with  $M(S_{TS}) = 104.7$  km/h, and  $M(S_{LT}) = 101.7$  km/h, and standard  
6 deviations of  $SD(S_{TS}) = 18.9$  km/h, and  $SD(S_{LT}) = 18.6$  km/h respectively. Similar differences for mean  
7 and standard deviations were found for the other combinations of experimental factors (**Table 4**).

8 In contrast, reverse curved terminals showed a higher speed differential ( $S_{TS} - S_{LT}$  in **Table 4**),  
9 thus indicating that this terminal type causes significant speed variations along the motorway lane. This  
10 fact has consequences in terms of safety and level of service: when speed variations occur in the through  
11 lane rather than in the terminal, the traffic flow on the motorway is disrupted due to exiting vehicles  
12 compelling the drivers behind who wish to proceed straight ahead to decelerate.

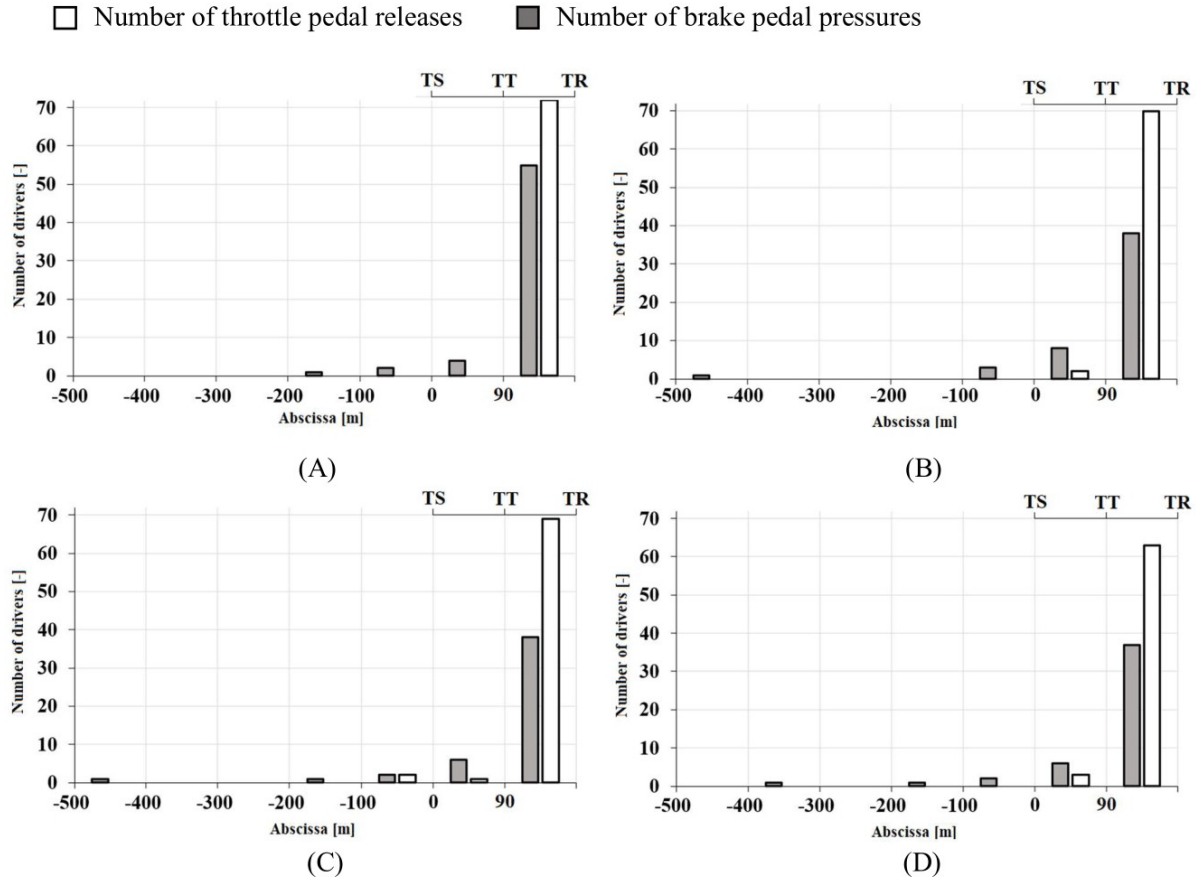
13 The speed differential between the LT and TR sections ( $S_{LT} - S_{TR}$  in **Table 4**) was found to be  
14 higher in the continue than in the reverse connection type. This confirms that the main speed variation  
15 maneuver was correctly performed along the terminal in the continue type but, incorrectly (i.e., unsafely),  
16 along the reverse one. In fact, in the latter case most drivers reduced their speed in the through lane rather  
17 than in the terminal.

18 Observations in linear parallel terminals made by Calvi *et al.* (3) indicate that speed values in TS  
19 and LT sites are similar. They attributed this finding to the fact that drivers choose their diverging speed  
20 before the terminal and maintain same until they move into the deceleration lane. However, speeds  
21 decrease significantly along the through lane before entering the diverging lane. Livneh *et al.* (22)  
22 confirmed that the average speed of exiting vehicles at the beginning of the deceleration lane was lower  
23 than that of through vehicles. Further corroboration from driving simulation studies comes from Bella *et al.*  
24 *al.* (5): in that study, the average speed differential between exiting drivers and through drivers was  
25 around 10 km/h. In this study, the same behavior was observed in continue terminals: the average speed at  
26 the TS site was 19% lower than that of autonomous vehicles traveling in the motorway.

27 **Figures 4A** and **Figure 4C** indicate that along continue terminals some drivers decelerated before  
28 the taper. In fact, a few drivers even release the accelerator pedal up to 500 m before. Similarly, some  
29 drivers used the brake pedal before the taper. Speeds recorded at the end of the deceleration lane (TR  
30 section) were 28% and 48% higher than the design speed of the exit ramp curve for the continue and  
31 reverse terminals respectively. Albeit with a different magnitude, these results are in accordance with  
32 observations along linear terminals (3,23,24).

33 Although **Figures 4B** and **Figure 4D** for reverse terminals show a similar pattern to that of  
34 **Figures 4A** and **Figure 4C** for continue ones, reverse terminal speeds at TS and LT are significantly  
35 different at the 95% confidence level ( $F_{(143,143)} = 0.93$ ,  $p = 0.33$ ;  $t_{(286)} = 4.91$ ,  $p = 0.001$ ). This outcome is  
36 contrary to that observed in both continue and linear terminals. In fact, Calvi *et al.* (3) found that speeds at  
37 LT and TS sites were quite similar. In this experiment, along reverse terminals there was an 18%  
38 variation in the average speed between the traveling flow and the exiting flow at the TS site. Moreover,  
39 the speeds recorded at the TR site were significantly higher than the posted speed limit along ramps (set at  
40 60 km/h).

41 The ANOVA (**Table 5**) revealed that the speeds at TS and LT sites were significantly influenced  
42 not only by the motorway radius ( $R$ ), but also by traffic volume and connection type. This result confirms  
43 the impact of road geometrics on driver speed choice. Furthermore, the connection type (continue or  
44 reverse) also has an impact because of the different perspective afforded to the driver. In the case of a  
45 continue spiral, the driver needs to look beyond the carriageway boundaries to see where the terminal  
46 begins, and he/she also has to look at the roadway ahead and maintain awareness of surrounding vehicles  
47 (**Figure 2A**). In comparison, the reverse connection is less demanding because drivers can see both the  
48 terminal and the surrounding traffic in a smaller view angle, as clearly depicted in **Figure 2B**. The  
49 relatively simple driving task required in a reverse terminal-to-ramp connection helps to boost driver  
50 confidence vis-à-vis the road scenario, and can result in the acceptance of higher risks when performing  
51 the maneuver (25).



1  
2 **Figure 4** Number of drivers that release the throttle pedal and use the brake pedals in significant  
3 sections along continue (A, C) and reverse (B, D) terminals, with  $R = 964$  m (A, B) and  $R = 437$  m  
4 (C, D).  
5

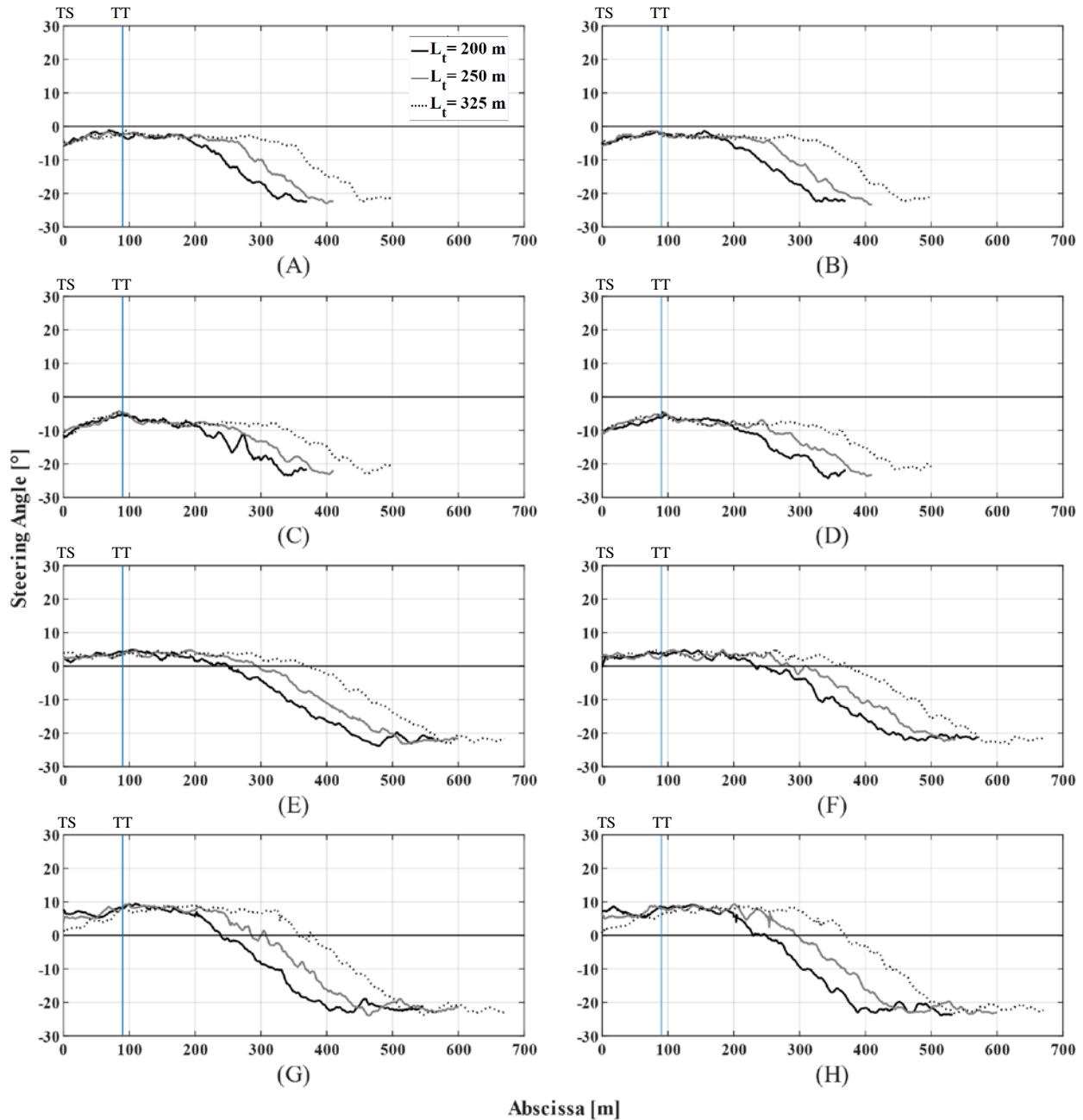
6 The ANOVA also reveals that the terminal length and traffic flow do not impact on driver speed  
7 choice. This outcome is contrary to that of Calvi *et al.* (3) in which statistical differences in driving speed  
8 are attributed to traffic volume. Specifically, their studies demonstrated that an increment in traffic flow  
9 along the freeway diverging area causes a decrease in exiting speed. The differences between this study  
10 and (3) must be attributed to the different spacing used between autonomous vehicles in simulated traffic.  
11 In this study, we opted for a random variation in spacing with values following a gamma distribution,  
12 while Calvi *et al.* (3) used fixed values of 40, 80, and 120 m for 3000, 1500, and 1000 pc/h respectively.  
13

#### 14 Transversal driver behavior

##### 16 *Steering wheel angle variations*

17 An overview of the steering behavior of drivers along the terminal (from TS to TR), the spiral connection  
18 (from TR to SC), and ramp (from SC to CS) is shown in **Figure 5**. The graphs exhibit the average curves  
19 of the steering wheel angle values along the entire off-ramp starting from the TS section for the 12  
20 circuits. Each curve represents the average of twelve data, and each graph contains three different curves  
21 associated with the different terminal length ( $L_t$ ) values investigated here.

22 Along continue terminals (**Figure 1A**), drivers maintain the steering wheel angle rotated on the  
23 right side (negative values in the graphs); conversely, in the case of reverse terminals (**Figure 1B**) the  
24 steering wheel angle passed from the leftward motorway curve (i.e., initial positive steering wheel angle  
25 values) to the rightward exit ramp (i.e., final negative values).



1  
 2 **Figure 5** Steering wheel angle values in continue (A, C, E, and G) and reverse (B, D, F, and H)  
 3 ramp terminal connections. Cases A, B, E and F refer to  $V = 1000$  pc/h, cases C, D, G and H to  
 4  $3000$  pc/h. Cases A, B, C and D refer to  $R = 964$  m, cases E, F, G and H to  $R = 437$  m. The  
 5 acquisition frequency of the data was  $100$  Hz (Notes: TS = terminal start, TT = taper-to-terminal).  
 6

7 **Figure 5** suggests that continue terminals require drivers to perform a simpler steering task with a  
 8 limited variation in the steering wheel action. Furthermore, in the case of reverse design, the steering  
 9 wheel rotation was prolonged due to the longer connecting section between the terminal and the ramp (i.e.  
 10 the distance between the TR and SC sections in Figure 1): it was  $125$  m for the continue connection  
 11 (**Figure 1A**) and  $260$  m for the reverse one (**Figure 1B**).  
 12

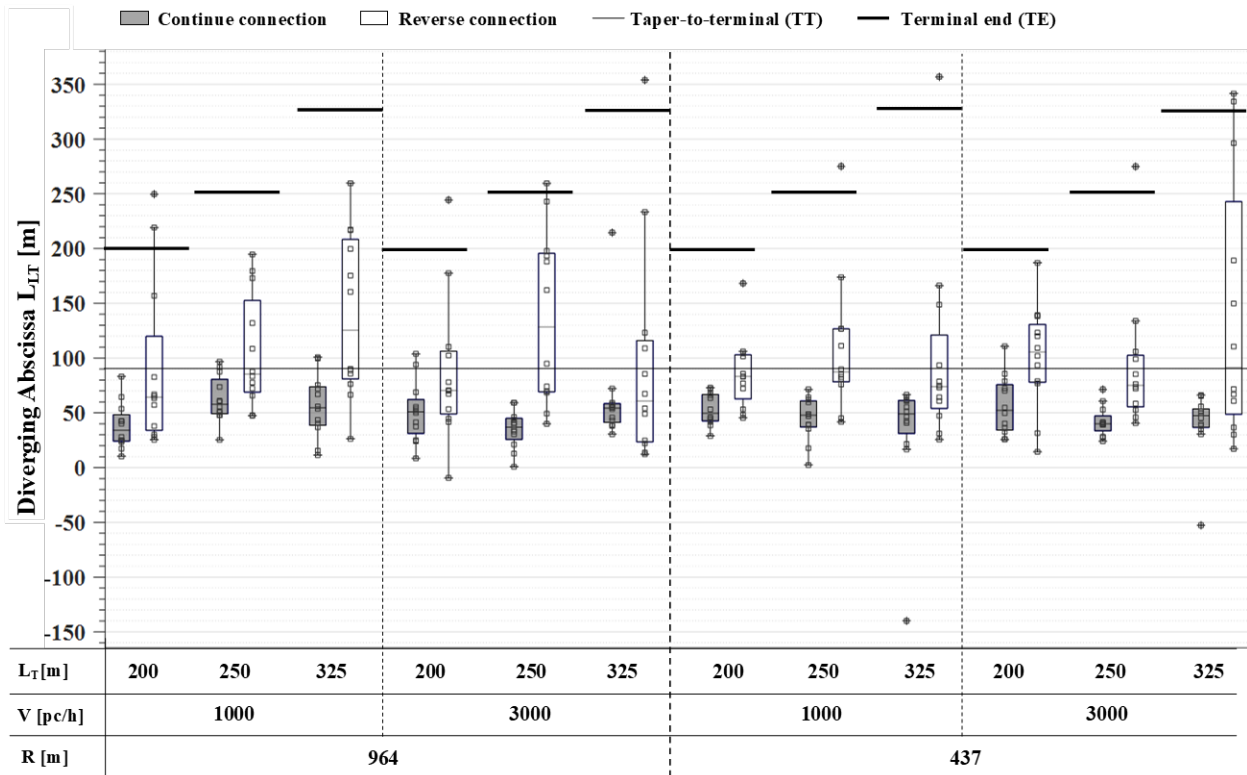
1 *Effects on the diverging abscissa ( $L_{LT}$ )*

2 As part of the transversal behavior, the diverging abscissa indicates where drivers passed from the  
 3 motorway through lane to the terminal. Data synthesized in **Table 4** are illustrated in the boxplots of  
 4 **Figure 6**, with the y-axis representing the diverging abscissa and the zero placed at the TS section. In  
 5 **Figure 6**, the thin lines represent the taper end (TT section), and the thick lines indicate the ends of the  
 6 terminals (at 200, 250, and 325 m respectively, i.e. at the TR section).

7 Along continue terminals, drivers were all able to complete the diverging maneuver within the  
 8 terminal, albeit most of them did so along the taper. This fact, combined with previous results on speed,  
 9 demonstrates that continue terminals perform better than reverse ones and is consistent with what was  
 10 previously observed in the case of straight terminals. Calvi *et al.* (3) and Bella *et al.* (5) observed that all  
 11 drivers completed the diversion maneuver in the terminal independently of its length.

12 In this study, the ANOVA confirms this result, indicating that  $L_t$  does not have a significant  
 13 impact on the merging abscissa ( $F_{(2,23)} = 1.28, p = 0.279$ ). ANOVA also confirms the non-significant  
 14 effect of the motorway radius on the diverging abscissa. However, **Figure 6** also reveals that two drivers  
 15 passed from the lane to the shoulder before the start of the taper (TS section). Although this would be an  
 16 example of hazardous behavior in real driving conditions because of the possibility of colliding with  
 17 broken-down vehicles occupying the shoulder, in this experiment drivers benefited from a wide field of  
 18 vision since there were no traffic barriers on the roadside. This early exit can be attributed to the erection  
 19 of vertical signs located 1000 and 250 m before the taper.

20



21  
 22  
 23  
 24  
 25

**Figure 6** Abscissa of the LT section that measures the traveled path along the lane from the TS section before the lane change (Note: the thin solid line indicates the TT section, the thick solid line the TE one).

1 In the case of reverse terminals, a completely different transversal behavior was observed.  
 2 Drivers changed lane in a wider spectrum of  $L_t$  values, with a total of ten lane changes occurring after the  
 3 terminal end. This evidence contrasts with observations on both continue curved terminals and linear  
 4 terminals (3). ANOVA outcomes confirm that this result is influenced exclusively by the connection type  
 5 ( $F_{(1,23)} = 75.87$ ,  $p \leq 0.001$ ) because of the different perspectives from the driver point of view. In line with  
 6 previous comments on longitudinal behavior, the reverse terminal provides drivers with greater visibility  
 7 making them more likely to delay the lane change maneuver and decelerate to exit the motorway at the  
 8 last moment. This study evidences that reverse terminals do not have a positive effect on drivers, since  
 9 most of them tend to exit the motorway by crossing the chevron markings in the neutral area that separate  
 10 the ramp from the motorway through lane. This is most definitely a hazardous maneuver because of the  
 11 serious conflict that can occur with vehicles that have already, and correctly, occupied the terminal.

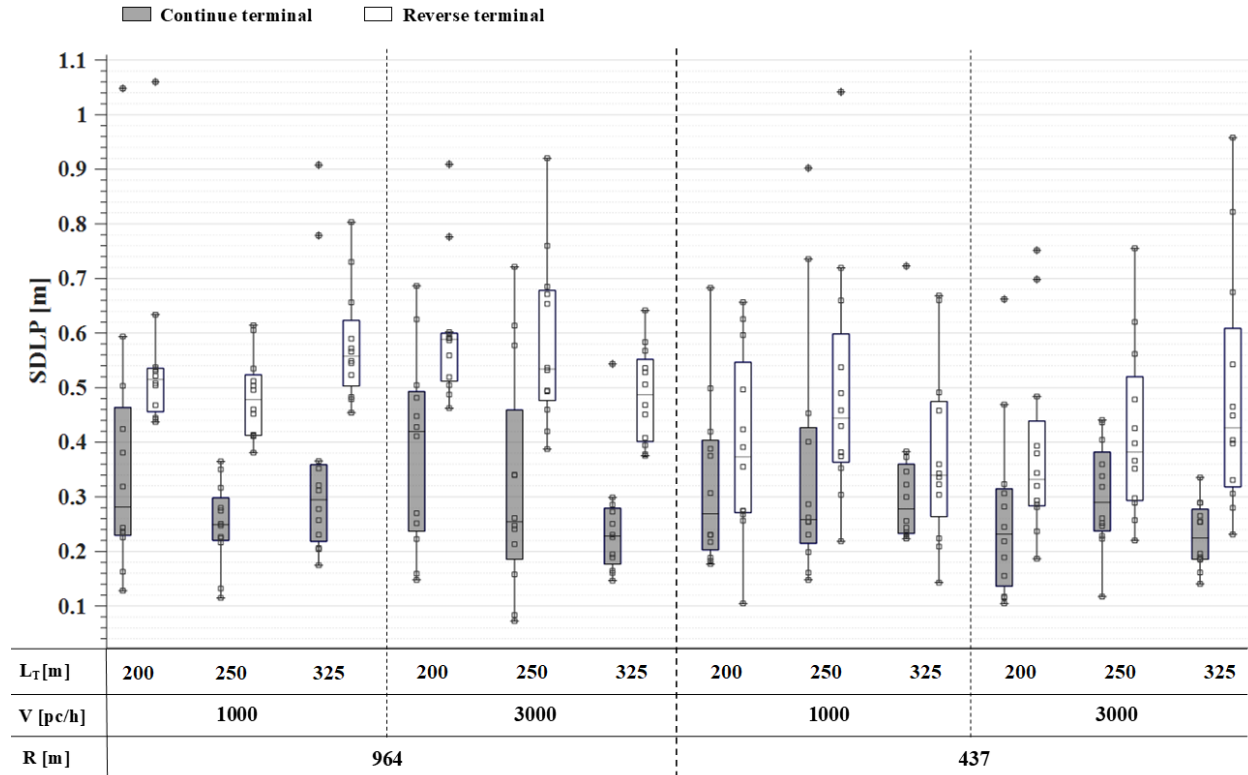
12 Finally, ANOVA evidences that the traffic volume on the motorway does not influence the lane  
 13 change abscissa ( $F_{(1,23)} = 0.11$ ,  $p = 0.739$ ). A similar conclusion was drawn by Calvi *et al.* (3) in the case  
 14 of linear terminals.

#### 15 *Effects on the Standard Deviation of Lateral Position (SDLP)*

16 *SDLP* depicts the transversal weaving of the car (20) and is widely used in driving studies to assess the  
 17 degree of control drivers have over their vehicles (4). High *SDLP* values suggest difficulties in staying  
 18 aligned with the lane centerline. Conversely, low values indicate minor trajectory oscillations, i.e. greater  
 19 control of the vehicle. As such, *SDLP* does not give an absolute figure, but a relative one useful to  
 20 compare driver behavior response when subject to different road geometrics. In this study, *SDLP* was  
 21 calculated along the continue and reverse spirals (between the TR and SC sections only) to determine the  
 22 effects of the connection type.  
 23

24 **Figure 7** shows the *SDLP* values as a function of the investigated independent factors. A clear  
 25 difference can be seen between the values recorded on continue (**Figure 1A**) and reverse (**Figure 1B**)  
 26 terminals, as confirmed by ANOVA. The boxplots in **Figure 7** show that the reverse spiral design  
 27 produces more vehicle weaving than the continue one. This result can be explained by: (i) the wider  
 28 steering wheel action required to negotiate the reverse terminal geometry, and (ii) the wider weaving of  
 29 those drivers who entered the reverse terminal-to-ramp connection passing through the neutral area (see  
 30 previous Section). In the latter case, it should be pointed out once again that drivers in the continue  
 31 connection made a proper use of the terminal unlike those who drove the reverse one.

32 ANOVA confirms that the *SDLP* is heavily influenced by the motorway radius ( $F_{(1,23)} = 13.74$ ,  
 33  $p \leq 0.001$ ) and the connection type ( $F_{(1,23)} = 80.55$ ,  $p \leq 0.001$ ). In the case of radius, this could be the  
 34 result of an indirect effect produced by the lower speeds associated with the lower radius value in this  
 35 experiment (437 m), with drivers generally having superior lateral control of their vehicles at lower  
 36 speeds. Regarding the connection type effect, along the continue one drivers had a simplified steering task  
 37 that led to a reduced weaving movement of the vehicle (**Figure 5**).



**Figure 7** *SDLP* results estimated in the terminal-ramp connection for the two terminal types (continue and reverse).

### CONCLUSIONS

To better understand the factors influencing driver behavior along curved ramp terminals of motorway interchanges, a driving simulation experiment involving forty-eight participants was conducted. Compared to linear ones, curved parallel terminals pose particular difficulties for drivers who have to maintain a curved trajectory involving a significant variation in speed.

The geometry of a terminal has a significant impact on drivers involved in the diverging maneuver. More specifically, the motorway radius (which also determines the radius of the terminal lane) has a predominant impact on speeds where the terminal begins and where the driver passes from the motorway lane to the terminal one. However, smaller terminal radii compel drivers to adopt more prudent speeds, with the results that drivers have greater lateral control of their vehicles.

The connection type between the terminal and the ramp, which can be either a continue (i.e., egg-shape) or a reverse (i.e., S-shape) spiral, influences the transversal behavior of drivers exclusively. In particular, the continue design induces an immediate lane change towards the terminal lane and a better lateral control of vehicles. Conversely, the reverse terminal leads to a delayed lane change with drivers who enter the terminal close to the theoretical gore point between the off-ramp and the through lane (i.e., the TS section in **Figure 1**). Finally, terminal length and the motorway traffic volume do not directly impact on driver behavior.

The results of this investigation confirm that visibility of the roadway ahead plays an important role in longitudinal and transversal driver behavior. Along continue terminals, drivers have restricted visibility of the exit terminal, so they adopt less risky maneuvers while taking maximum advantage of the length of roadway available. Conversely, in the case of reverse terminals, some drivers tend to stay longer in the motorway lane and reduce their speed close to the theoretical gore point (at which point they also change lane); in a number of cases, the driver crossed the chevron markings in the neutral area. The main difference between the two road scenarios lies in the different sight conditions, which are much more



1 favorable in the case of reverse ramp-terminal connections. This finding is consistent with the theory of  
2 risk homeostasis (25): in conditions where a driver perceives a lower risk, he/she is inclined to drive with  
3 less caution. This behavior is evidently hazardous and may result in conflicts with vehicles which have  
4 correctly entered the terminal, while also impeding drivers behind who wish to proceed straight ahead  
5 along the motorway lane. Finally, reverse terminals also affect the lateral control performance of drivers,  
6 with significantly higher SDLP values with respect to continue terminals.

7 This study evidences that along continue off-ramp terminals, driver behavior is similar to that  
8 along straight terminals investigated in other studies (3,5,6). In contrast, parallel reverse terminals do not  
9 promote or encourage responsible and competent driving practice as well as continue ones, so design  
10 countermeasures must be taken to compel drivers to adopt safer behaviors. For example, the adoption of a  
11 tapered design for reverse curved terminals should be evaluated in future studies.

12 The implications arising from this study merit consideration for inclusion in future technical  
13 manuals and design policies, which should place greater emphasis on the risk-taking behavior adopted by  
14 some drivers along reverse curved terminals. Furthermore, this study confirms that the kinematic model  
15 typically used to interpret the behavior of drivers negotiating a motorway exit is inadequate in its  
16 interpretation of vehicle speed reduction and actual driver decisions. Further investigations are necessary  
17 to fill the gap in knowledge that this study revealed.

18 It is worth highlighting that the results presented here depend on the geometric characteristics of  
19 the road facilities assumed for this study. New outcomes should be expected with the inclusion of  
20 additional design factors that may have a significant influence on driver performances (e.g., traffic  
21 barriers, traffic in the ramp). Further experiments should also be carried out to test whether new ADAS  
22 technologies (e.g., lateral position control, blind-spot monitor) help to improve driver behavior and  
23 performance when exiting the motorway along curved terminals.

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#### 29 30 **AUTHOR CONTRIBUTIONS**

31 The authors confirm contribution to the paper as follows: study conception and design: A. Portera, M.  
32 Bassani; data collection: A. Portera; analysis and interpretation of results: A. Portera, M. Bassani; draft  
33 manuscript preparation: A. Portera, M. Bassani. All authors reviewed the results and approved the final  
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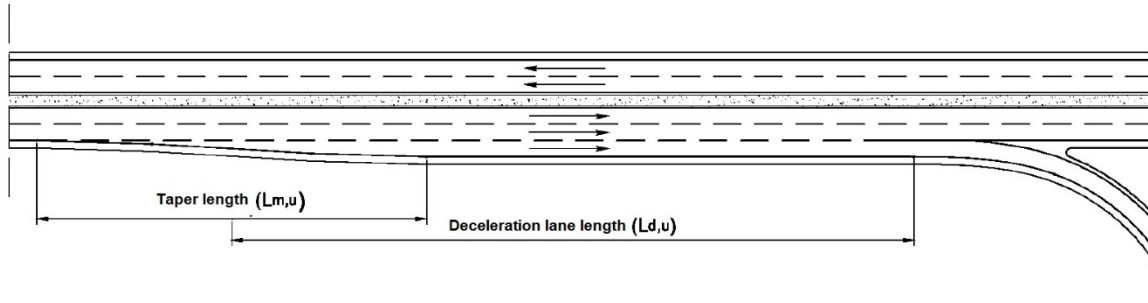
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**APPENDIXES**

**APPENDIX A: Italian Standards (2) for the design of exit terminals**

The parallel exit lane consists of the following base elements: (i) the taper ( $L_{m,u}$ ), and (ii) the deceleration lane the length of which ( $L_{d,u}$ ) includes half of the taper length ( $L_{m,u}$ ). The lane is parallel to the adjacent through lanes as indicated in **Figure A1**.



**Figure A1** Exit ramp with parallel design

The deceleration length is estimated as per the following kinematics equation:

$$L_{d,u} = \frac{v_1^2 - v_2^2}{2a} \quad (\text{A1})$$

where:  $v_1$  (m/s) is the entry speed in the deceleration segment,  $v_2$  (m/s) is the exit speed from the deceleration segment, and  $a$  (m/s<sup>2</sup>) is the deceleration rate assumed equal to 3 m/s<sup>2</sup> in the case of motorway exits. The taper length depends on the design speed ( $V_d$ ) of the motorway section (**Table A1**).

**Table A1** Length of the taper

Design speed, $V_d$ [km/h]	Taper length, $L_{m,u}$ [m]
80	60
100	75
>120	90

**APPENDIX B: Details on continue and reverse ramp-terminal connection design**

The spiral type used was the clothoid (16,17) with parametric equation  $rL = A^2$ , where  $r$  is the ramp radius (between sections SC and CS in **Figure 1**),  $L$  is its length, and  $A$  the scale factor. In all circuits,  $r$  was set equal to 150 m, and  $A$  was set at 150 m for both continue and reverse clothoids. The relationship between the geometric factors in the design was calculated according to Lorenz equations (16) for continue:

$$A^2 = 2R \cdot \sqrt{\frac{6DR \cdot \left(\frac{1-k}{k}\right)}{3 \cdot (k-1)^2 - \left(\frac{1-k}{k}\right) \cdot (1+k^2)}} \quad (\text{B1})$$

and reverse spirals:

$$A^2 = 2R' \cdot \frac{3D \left[ D + 2R' \cdot \left( \frac{k+1}{k} \right) \right]}{\sqrt{3 \cdot (k+1)^2 - \left( \frac{k+1}{k} \right) \cdot (1+k^2)}} \quad (\text{B2})$$

where  $k = R'/r$ ,  $r$  is the ramp radius,  $R'$  is the radius of the right motorway lane,  $D$  is the distance between the two circular arcs used to design the motorway curve and the ramp. For the continue spiral,  $R'$  was calculated from the motorway radius  $R$  as follows:

$$R' = R - 2 \cdot l_w - \frac{m}{2} \quad (\text{B3})$$

while for the reverse spiral it was:

$$R' = R + 2 \cdot l_w + \frac{m}{2} \quad (\text{B4})$$

where  $l_w$  and  $m$  are the lane and the median width respectively. **Equation B1** and **Equation B2** were used to derive the distance  $D$  between the circular arcs involved in the design. The terminal lengths ( $L_t$ ) were selected starting from the standard value of 250 m estimated according to **Equation A1** (2).