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

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ABSTRACT

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

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

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

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

INTRODUCTION

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

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

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

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

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

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

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

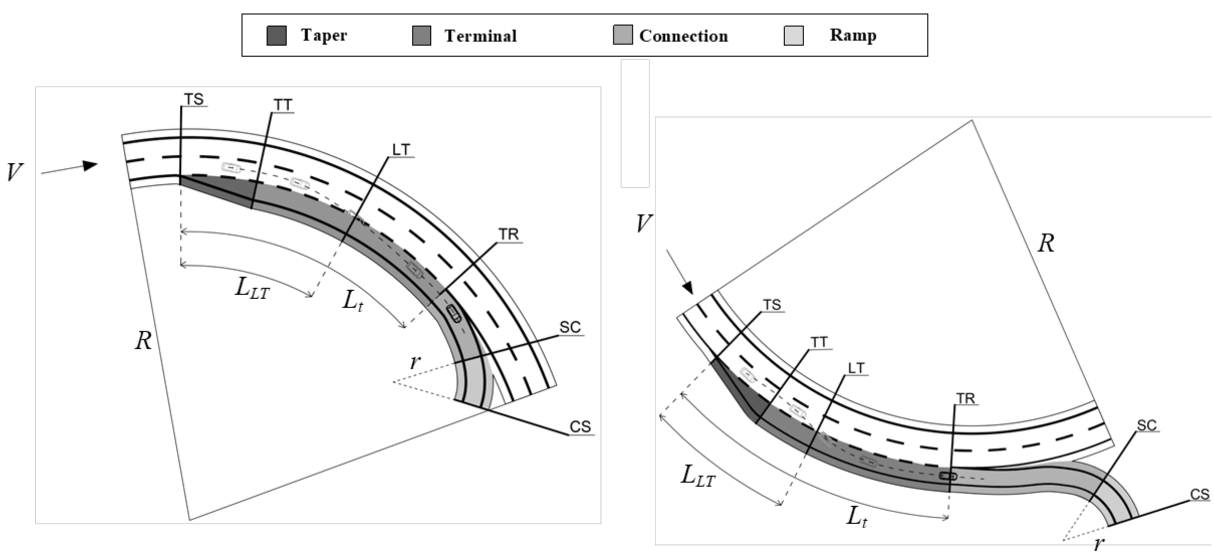
METHODS

Equipment

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

Experimental design, driving scenarios, and independent factors

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



(A) (B)

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

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

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

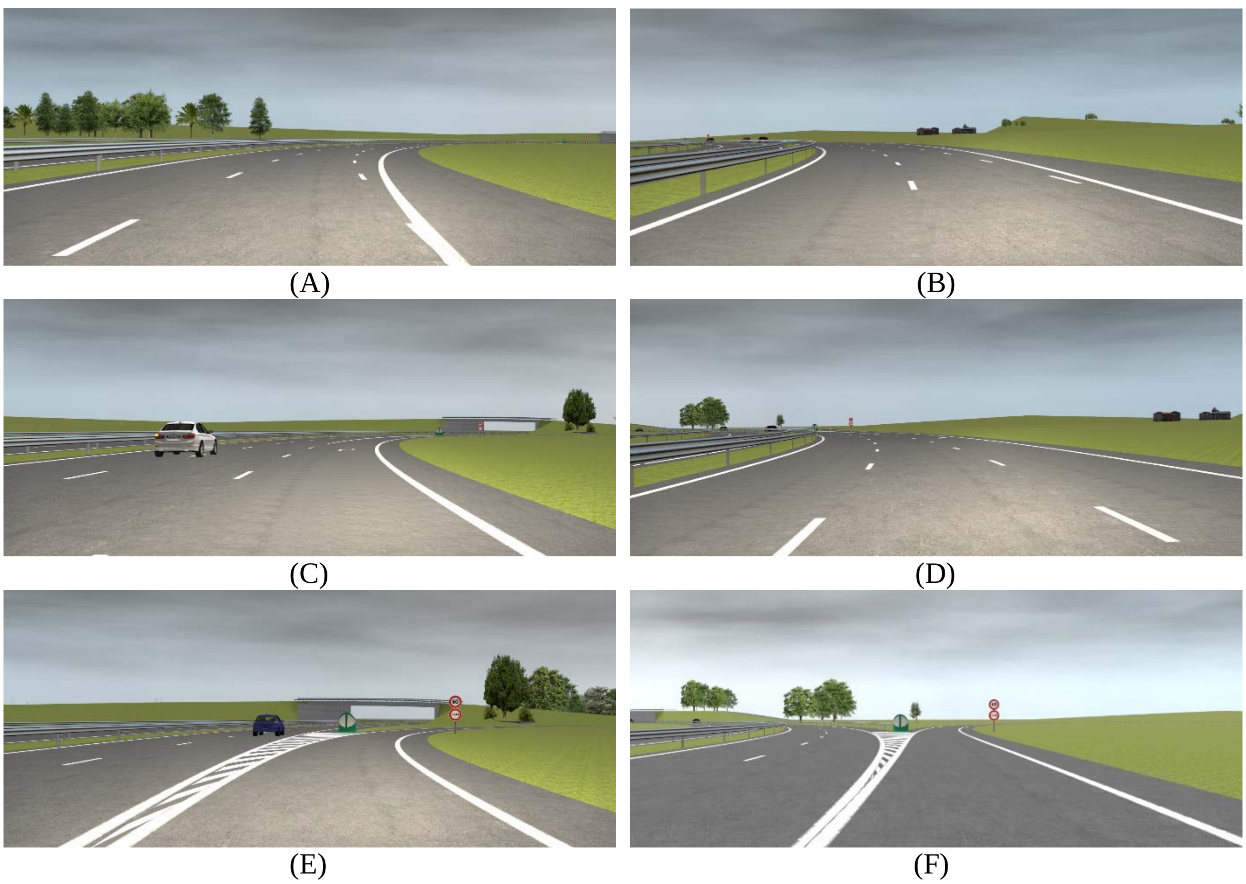


Figure 2 Frames from the simulated environment depicting the driver point of view approaching the off-ramp in the case of continue (A, C, E) and reverse (B, D, F) terminals.

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

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

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

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

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

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]
1	+1	-1	0	+1	+1	-1
2	+1	-1	+1	+1	+1	0
3	+1	-1	-1	+1	+1	+1
4	+1	+1	+1	+1	-1	0
5	+1	+1	-1	+1	-1	+1
6	+1	+1	0	+1	-1	-1
7	-1	-1	-1	-1	+1	+1
8	-1	-1	0	-1	+1	-1
9	-1	-1	+1	-1	+1	0
10	-1	+1	0	-1	-1	0
11	-1	+1	-1	-1	-1	-1
12	-1	+1	+1	-1	-1	+1

Participants

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

TABLE 3 Descriptive statistics about participants (Notes: Ave. = average value, Min = minimum 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

Experimental protocol

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

Observed variables, data collection, and manipulation

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

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

RESULTS AND DISCUSSION

Questionnaires and cognitive tests

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

PRT from auditory and visual stimuli (**Figure 3**) carried out before and after the driving session were found to be normally distributed according to the Kolmogorov-Smirnov (KS) test for normality (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: $D_{(48)} = .17$, $p = .102$).

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

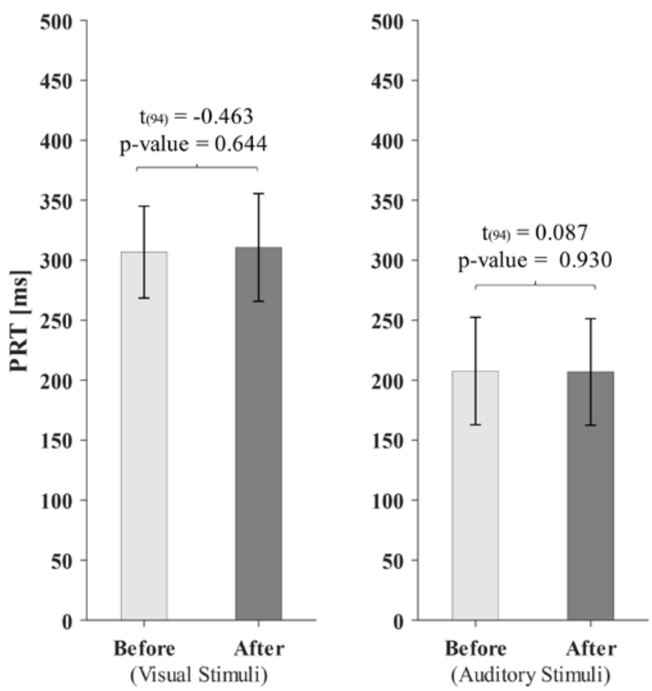


Figure 3 Average visual and auditory reaction times before and after the driving session.

Synthesis of results and Analysis of Variance (ANOVA)

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

TABLE 4 Descriptive statistics for speeds recorded at TS (S_{TS}), LT (S_{LT}) and TR (S_{TR}) sections, longitudinal abscissa of the diverging point (L_{TL}), and standard deviation of lateral position (*SDLP*). (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**
Continue terminal													
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
Reverse terminal													
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

TABLE 5 Analysis of Variance (ANOVA), main and significant interaction effects (significant 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**
Main effects										
R	5.66	**0.018**	6.97	**0.009**	0.37	0.543	0.51	0.474	13.74	**<0.001**
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	**<0.001**	80.55	**<0.001**
Interactions										
$R \times V \times CT$	4.62	**0.032**	4.22	**0.041**	4.68	**0.032**	0.23	0.633	0.38	0.538
$R \times CT$	0.51	0.476	0.81	0.368	6.86	**0.009**	0.04	0.842	6.06	**0.014**
$R \times L_t$	1.87	0.156	1.61	0.201	0.85	0.429	0.84	0.432	3.31	**0.045**
$R \times V \times L_t$	0.39	0.679	0.86	0.424	0.13	0.875	1.31	0.272	4.10	**0.018**

Longitudinal driver behavior

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

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

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

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

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

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

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

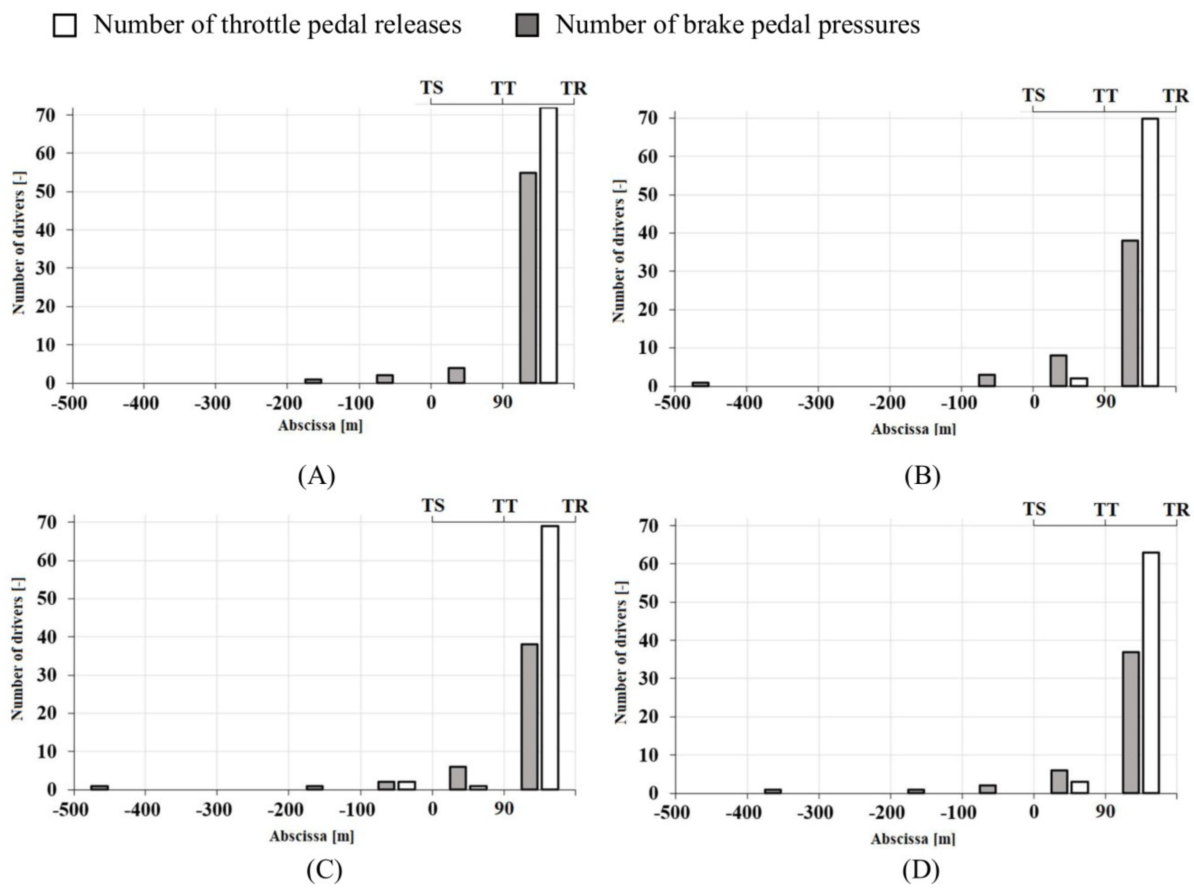


Figure 4 Number of drivers that release the throttle pedal and use the brake pedals in significant sections along continue (A, C) and reverse (B, D) terminals, with R = 964 m (A, B) and R = 437 m (C, D).

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

Transversal driver behavior

Steering wheel angle variations

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

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

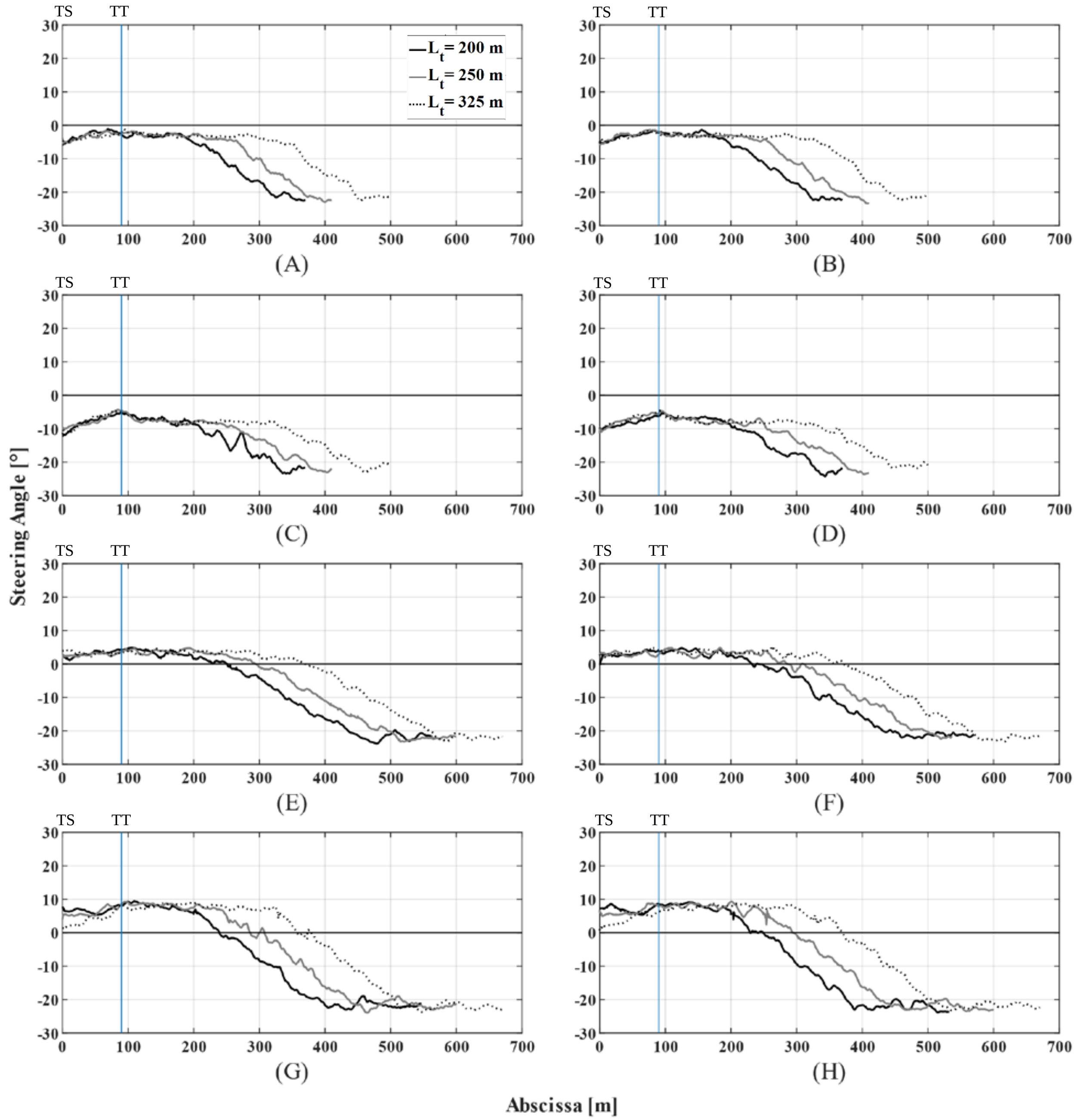


Figure 5 Steering wheel angle values in continue (A, C, E, and G) and reverse (B, D, F, and H) ramp terminal connections. Cases A, B, E and F refer to V = 1000 pc/h, cases C, D, G and H to 3000 pc/h. Cases A, B, C and D refer to R = 964 m, cases E, F, G and H to R = 437 m. The acquisition frequency of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

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

Effects on the diverging abscissa (L_{LT})

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

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

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

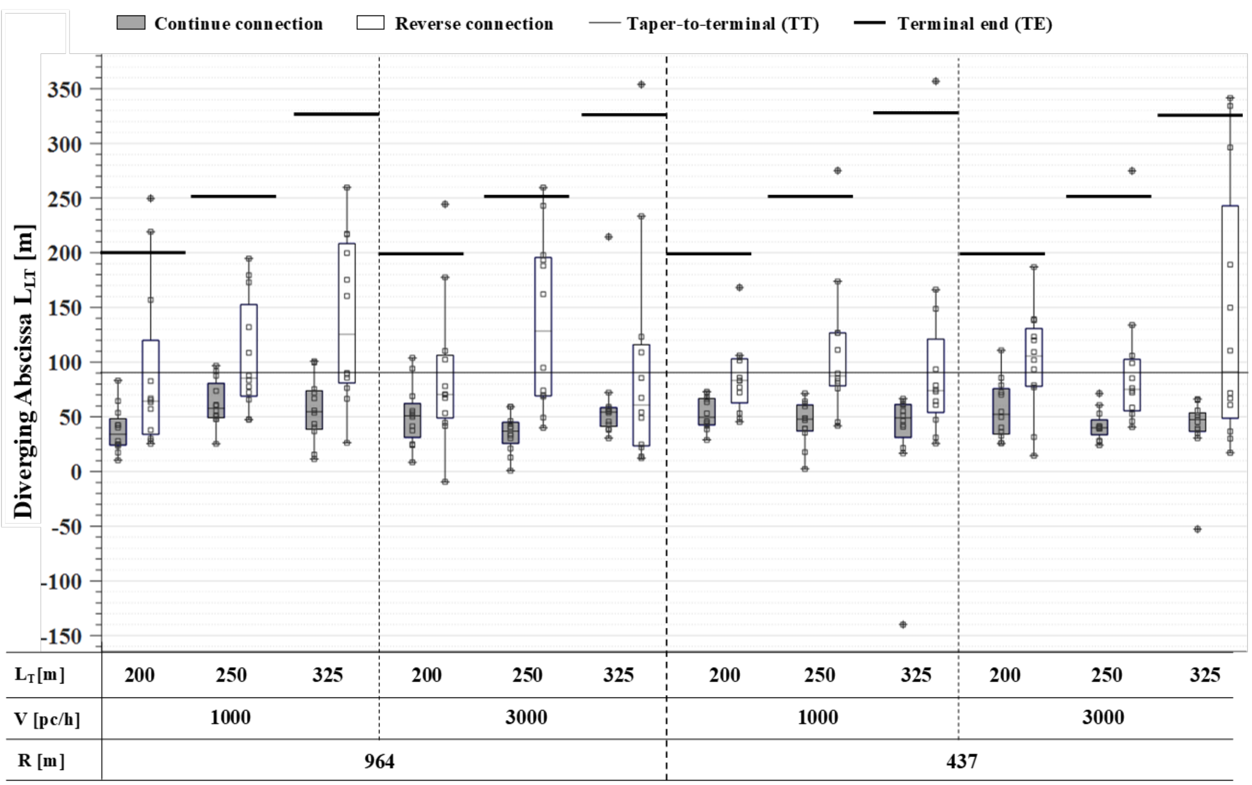


Figure 6 Abscissa of the LT section that measures the traveled path along the lane from the TS section before the lane change (Note: the thin solid line indicates the TT section, the thick solid line the TE one).

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

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

Effects on the Standard Deviation of Lateral Position (SDLP)

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

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

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

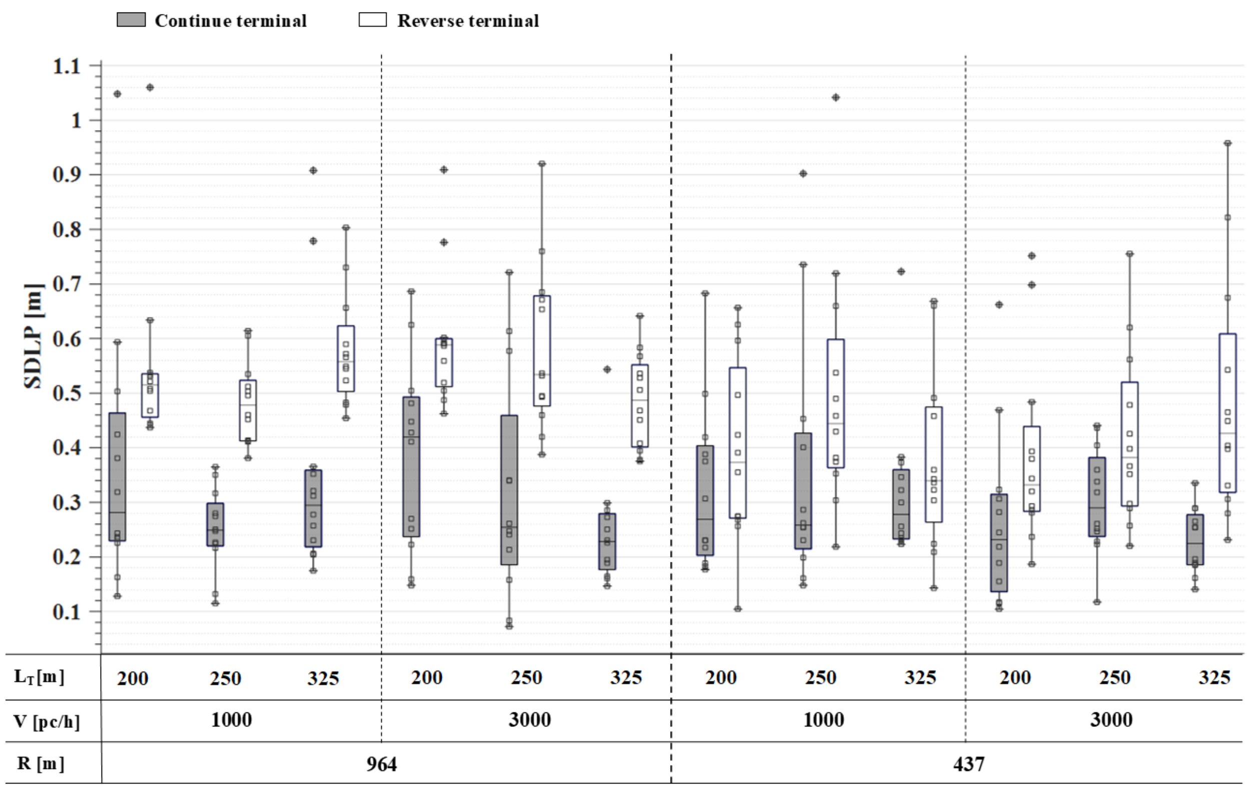


Figure 7 ***SDLP*** **results estimated in the terminal-ramp connection for the two terminal types (continue and reverse).**

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

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

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

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 of additional design factors that may have a significant influence on driver performances (e.g., traffic barriers, traffic in the ramp). Further experiments should also be carried out to test whether new ADAS technologies (e.g., lateral position control, blind-spot monitor) help to improve driver behavior and performance when exiting the motorway along curved terminals.

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AUTHOR CONTRIBUTIONS

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

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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**.

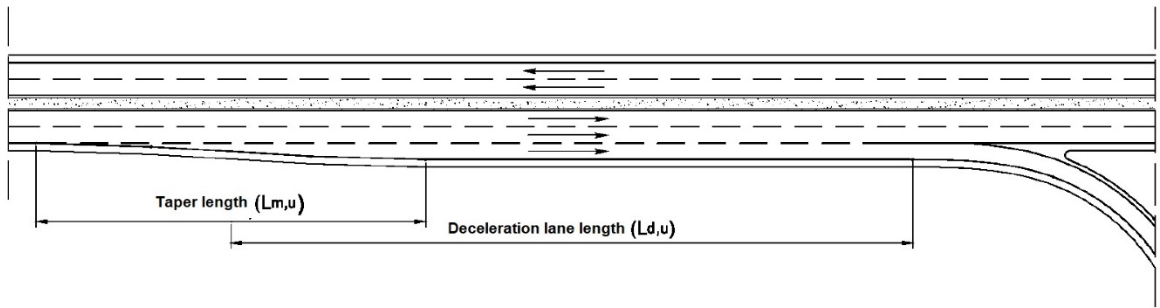

Figure A1 Exit ramp with parallel design

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

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

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^2) is the deceleration rate assumed equal to 3 m/s^2 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:

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

and reverse spirals:

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

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:

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

while for the reverse spiral it was:

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

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*).