Road Geometrical Design Out of Standards: A Preliminary Study in a Simulated Context

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Abstract

When a road design solution is quite out of standards for the presence of insurmountable constraints, there is the need for an objective procedure aimed at achieving a certain level of safety for drivers.

To avoid issues on judicial responsibility, designers aim to fully satisfy the existing standards, possibly without any exception. Traditional methodologies based on previous experience or road administrators' guidelines generally caused problems due to the high subjectivity involved in the analysis.

In this paper, to overpass these issues, a rational procedure based on vehicles telemetry data in a simulated environment is proposed. This process, through synthetic indices, allows the analysts to compare two road geometries, similar but different, because one includes curves with shorter residual circular arcs than threshold values imposed by Italian standards.

The main results, derived from a two-way ANOVA with subsequent contrast analysis, suggest that a certain deviation respect to the standards did not determine any decay in the driver's performance.

Compared to the existing literature, in this study a full objective procedure was proposed, based on a totally new indicator, which can be easily adapted to any context, involving driver, road and vehicle at the same time.

Introduction

The existence of appropriate road standards assures that, already in the design phase, it is possible to confer to an infrastructure an ensemble of proper physical and geometrical features to avoid potentially dangerous contexts and situations. But compliance with standards is not a trivial operation and, in any case, it does not protect against further unforeseen critical issues, detectable only through subsequent deepening (Rizaldi et al., 2017). On the other hand, there could be deviations from these requirements with a sufficiently safe driving behaviour (Weekley et al., 2016).

When satisfying all the standard prescriptions is too expansive, the problem of determining any criticisms for drivers' safety arises (Pellegrino, 2009, 2011; Montella et al., 2012). In these cases, some standards provide specific indications to the designer while others propose only generic advice. In Italy, for instance, a certain design flexibility beyond imposed thresholds is permitted, as this choice must be supported by opportune safety analyses that have never been specified (MIT, 2001).

The idea of taking in remarkable consideration important environmental, economic, or constructive constraints led to rethink mandatory and strictness of the regulations for building new roads or for maintaining existing ones. USA, around the 2000s, reported the studies on design flexibility in a wide research sector called Context Sensitive Solutions, in which there are all those situations that, for their complexity, abound in particularly anthropized territories (FHWA, 2004; NCHRP, 2004; Bosurgi et al., 2011). Their principle is that deviations from standard thresholds, admitted only when needed, do not necessarily induce a decay in users' safety but, instead, may represent the occasion for a better management of the overall process through the optimization of all the involved variables (NCHRP, 2003; WSDOT, 2005). Other countries, such as Great Britain, already for several years have proposed, beyond traditional "desirable minimums", less strict design scenarios, named Relaxations or Departures, for which a specific application field is defined (TD 9/93, 2002).

Some procedures are characterized by a remarkable empiricism, as in the case of Road Safety Audits (Huvarinen et al., 2017), where it is assigned a certain safety level to the infrastructure, according to a team of experts and some supporting manuals. Whether this level is difficult to reach, they have also to propose appropriate maintenance operations or activities for mitigating dangers or limiting the traffic.

Compared to this undeniable subjectivity, even though duly qualified, there is the need of applying analytical procedures for quantifying the users' performance, in real conditions representing the analysed scenario, often not predictable by road standards. In the recent past, with the progress of vehicle on board sensors, the estimation of the driving behaviour performance was entrusted to some indices able to synthetize the performance on a homogeneous element of the road that, preferably, was the horizontal curve (Chen et al., 2022; He & Donmez, 2022). At this regard, one of the most used variables in the scientific research was the Lateral Position (LP), as the trajectory in curve directly influences the values of the lateral acceleration and steering and, in turn, the manoeuvre safety. Then, the need to obtain a single value representative of the driving along a homogeneous geometric element (for instance, a curve) imposed the adoption of synthetic indicators such as the standard deviation or the average of LP, named SDLP and µLP respectively (O'Hanlon, 1984; Ramaekers, 2003; Coutton-Jean et al., 2009; Verster & Roth, 2012; Brookhuis, 2014; Hu et al., 2017; Kazemzadehazad et al., 2019).

In recent years, other indicators related to driving behaviour have been proposed, such as the so-called Time to-Line Crossing (TLC), determining the minimum time for the vehicle to overpass a marginal line, without any corrective action (Godthelp et al., 1984; Van Winsum et al., 2000). However, this function is very complex and its average or standard deviation does not permit to interpret the actual driving behaviour. This index does not fit to statistical analyses, but it can help to simplify a descriptive interpretation of the observed phenomenon.

Among the literature models derived from LP, it is interesting that one proposed by Cerni & Bassani (2017), concerning an index for "dimensionless average curvature difference", that is the difference between the curve radius and the trajectory followed by the vehicle.

It is clear that the horizontal curve represents one of the most critical geometric elements in terms of safety (Bìl et al., 2019; Elvik, 2019). Calvi (2015) analysed in a simulated environment the relationship between the driving behaviour and the curve features, like the radius, presence of clothoids, visibility, or transversal section. In particular, he measured the driving performance by means of some indicators, such as mean and standard deviation of speed, with other recently proposed (Calvi, 2010; Calvi & D'Amico, 2006; 2013) as the Pathologic Discomfort (PD) and the Dispersion of Trajectory (DT). As known, the lateral acceleration, when the user follows the trajectory represented by the lane axis, is only a function of radius (R) of the lane and speed (V) values – i.e., $a_L = V^2/R$. If its real measure exceeds this value, then the trajectory is different respect to the axis and, probably, there has been an incorrect interpretation of the curve by the driver. The analytical expression for PD consists in a subtraction between the two functions: the theoretical a_L and the actual values measured by the telemetry. DT index has the same meaning, as it measures the deviation of the real trajectory from the theoretical one (i.e. the axis of the lane) along the curve.

Before the introduction of the driving simulators, speed prediction was performed through regressive model often based on survey campaigns performed only on few points of the road. Some basic hypotheses, such as constant speed on homogeneous elements, were highly limiting and unrealistic. For this reason, Montella et al. (2015), relying on experiments in a simulated environment, deduced the trends of speed and longitudinal acceleration, proposing a piecewise linear regression model, able to predict the operative speed trend on the entire alignment, identifying start and end points of constant speed sections. The results, in macroscopic terms, permit to deduce the operative speed variation law along curve as a function of the radius.

Finally, it is relevant to underline how a large part of the recent scientific production focuses on specific conditions of the road environment, in order to solve strongly localized problems, and thus, the results are impractical to be used in other contexts (Boruah et al., 2020).

The proposed literature review evidences some limitations that should be overpassed:

- Several road administrators rely on empirical procedures for controlling infrastructure safety, strongly based on experts' judgment and suggested by government offices.
- When analytical procedures are applied, the research has focussed to a single component of the road system (man, vehicle or road), neglecting the others and, mainly, their mutual interactions. Performing tests on roads is the unique way for verifying road safety in general terms, considering real or simulated environment in which all the elements interact.
- Synthetic indicators, required for statistical analyses, are only partially representative of the actual phenomenon to interpret.
- The proposed procedures are very often tested in very specific environments and may not be generalized.

This research responds to some of these critical issues, through the proposal of an analytical procedure allowing the analysts to verify the impact on safety when some legislation requirements are not satisfied. In detail, the driving behaviour in terms of trajectory along some horizontal transition curves was investigated. Some of the curves were perfectly in compliance with Italian standards, while other – almost similar – presented the residual circular arc shorter than imposed minimum values. The experimentation was performed in a simulated environment on a sample of 21 users. The authors analysed the results, even in terms of proper synthetic indicators, partly innovative respect to existing literature. These indicators went through appropriate statistical procedures for evidencing any critical criticisms in the driving behaviour.

However, even if the methodology is easily generalizable in any type of context, the results of this preliminary study are not yet applicable on a large scale since there is still a need to expand the experiments appropriately.

Methods

Synthetic indicators representative of the trajectory.

As anticipate in the last part of the Introduction section, some researches on vehicle trajectories applied indicators as SDLP and mLP, neglecting some evident critical issues (Bobermin et al., 2021). Probably, these indicators contribute to a certain knowledge of the phenomenon, but do not permit an objective and valid quantification of the observed behaviour in all the situations.

To evidence these issues, in Figure 1 three hypothetical trajectories (in truth they are sinusoids) in a road lane and shoulder for overall 4.5 m wide, from which the following considerations are deduced:

- Trajectories 1 and 2, despite the same mLP, are deeply different, as the first shows higher amplitude and, thus, a higher potential danger for lateral elements (obstacles, barriers, or opposite vehicles).
- Trajectories 1 and 3, instead, have the same SDLP. It is evident that trajectory 3 is moved towards the opposite lane and, thus, it is more dangerous in terms of a potential frontal collision.
- The deviation of trajectory 3 (or 1), whether pointing toward the right side of the curve, would not involve high risks, owing to the absence of obstacles (beyond the barrier), but mLP nor SDLP provide any useful indications in this perspective.
- INS FIG

At this regard, for right curves and with sufficiently wide lanes, the driver often voluntary moves toward the centre of the curve, for driving on a shorter trajectory. Then, the ideal indicator should consider the left deviation only, as it causes potential negative effects. For this, it would be sufficient to delete right deviation data respect to the lane axes, as represented in Figure 2.

Consequently, the previous indicators may be redefined as $SDLP_L$ and mLP_L, to indicate that only left deviations respect the lane axes will be considered.

Finally, it is fundamental to assess for how long time or space the driver moves on the left of the axes. This information may be easily derived, referring to the integral of the left deviation function, representing the area between the left part of the trajectory and the lane axes (Figure 3). The novel index is identified with the symbol INT_L. The authors think it is appropriate then to consider the three indicators (INT_L, $SDLP_L$ and mLP_L) together, for deducing any deficit in driving along a road, as hardly one of them alone is representative of all the observed phenomena.

Opportunities of the simulated environment

Road safety, as anticipated in the Introduction section, should consider all the components of the road system, i.e. the driver, the vehicle and the road context. Performing tests on real roads or accurate simulated environments represent the only ways for involving them simultaneously. For this research, the second option is selected, according to generally discussed reasons evidenced in literature (Maxwell et al., 2021):

- Users' safety during tests.
- Repeatability and homogeneity of the investigated scenarios in terms of weather condition, light and traffic, hard to obtain in real contexts.
- Complete control of vehicle telemetry, pavement condition and main driver's psycho-physiological factors (Graichen et al., 2022).
- Possibility of testing particular geometric elements not yet realized.
- Accurate design of the road geometry.
- Proper choice of the variable that may influence the road environment, at this regard, the external disturbance was limited (absence of elements that may distract the driver or represent an obstacle to visibility, absence of traffic, fully plan alignment, etc.) to refer eventual irregularities in the driver behaviour to the geometrical characteristics of the alignment only.

Obviously, the use of a driving simulator also has some disadvantages such as the absence of kinaesthetic feedback, eventual simulator sickness, need for results validity respect to real context, driver's motivation and perceived risk level (Kuiper et al., 2020, Chinazzo et al., 2021).

Regarding a total fidelity respect to real conditions, it should be noted that the proposed study has been based on a commercial and very performing software (SCANeR↓), widely adopted in recent years by many automotive manufacturers. Furthermore, the deducted conclusions concern the comparison between scenarios present only in the simulated environment, avoiding comparing mixed conditions.

The driving simulator at University of Messina

The experimentation has been performed using the driving simulator named SimEASYâ, produced by AVSimulation, available in the Digital Laboratory for Road Safety (DiLaRS) of the University of Messina (Fig. 4). This simulator has the following features:

- Three 29-inch full HD screens (1920×1080 pixels each) with a horizontal field of view of 130° and a frequency higher than 50 Hz.
- A steering wheel characterized by a force feedback sensor to simulate the rolling motion of wheels and shocks.
- Sound effects reproduced through several speakers and subwoofers.

- The SCANeRâ studio software, used to design tracks, generate the environmental context and run trials.
- Data collected with a frequency of 10 Hz.
- A family car powered by a 130 hp gas engine, with six manual gears and automatic clutch.

Features of the alignment

The experimental road is represented by about 5 km long alignment, characterized by a succession of 18 transition curves, all including in and out transition curves and a residual circular arc.

The road belongs to the type called F (local rural) in the Italian standard and consists of two lanes in each direction of travel 3.50 m wide each and two shoulders of 1.00 m each.

The first 9 curves can be divided in 4 curves, with a 60 m radius (called R60), followed by other 5 curves with radius equal to 100 m (R100). They are in compliance with Italian standard and, in particular, with the minimum imposed length of the residual circular arc, defined as the space driven by the driver moving at the design speed for 2.5 seconds. This means that for R60, as the design speed is equal to 45 km/h (12.5 m/s), the minimum length is equal to 32 m. Analogously, for R100 the design speed is 56 km/h (15.5 m/s) and, thus, the minimum length of the circular arc is 39 m.

Without discontinuities, the alignment continues with other 9 curves, in this case not in compliance with standards, in terms of residual circular arc length. The first 4 of these curves again have radius equal to 60 m (called R60out) and the following 5 equal to 100 m (R100out). The related residual circular arcs (provided in Table 1 and Figure 5) are not in compliance with standards, being excessively lower than previously indicated thresholds.

Therefore, in total, there are then 4 types of curves, named R60, R100, R60out e R100out, the features of which are listed in Table 1 and Figure 5.

Table 1 – Main characteristic of the curves included in the alignment

	Track according to Italian road standard		**Track out of standard**	
Type of curve	R60	R100	R60out	R100out
Arc Radius	60 m	100 m	60 m	100 m
Arc Length minimum	32 m	39 m	32 m	39 m
Arc Length Real	42 m	75 m	0.3 m	6 m

In this experiment, the radii of the curves equal to 60 m and 100 m were used as they are the most frequent in this type of road (local rural) and, at the same time, they are sufficiently different from each other in order to highlight particular drivers' behaviors dependent on the radius of the curve.

The R60out and R100out curves are characterized by arc lengths close to zero (0.3 and 6 m, respectively), caused by a reduction in the angle of deviation from 80° to 40° (Figure 5).

It should be emphasized that these curves are arranged along a circuit and the starting point of each of the drivers is not fixed but random so as not to create a dependence of the results on the succession of curves. Finally, it is specified that the experimentation was carried out in the absence of traffic, given that the Italian legislation refers to an isolated vehicle.

The road markings are made up of continuous lines both at the edge and in the middle of the cross section and the surrounding terrain is flat in such a way to not constitute a barrier for sighting.

The drivers' sample.

The driving tests involved 21 users, between 22 and 26 years old (Parmet et al., 2015), selected in such a way as to constitute a homogeneous sample with respect to age, number of years of driving license, presence of light visual impairments as myopia (below two dioptres), number of accidents experienced, eventual car sickness recorded after the activity driving to the simulator. This research complied with the American Psychological Association Code of Ethics and an informed consent was obtained from each participant.

In the table 2, the main results have been reported and in the bottom row, the standard deviation shows a good consistence of the sample.

Table 2 – Data about the drivers. The "Accidents" column includes both accidents suffered and caused. The "License" column relates to the number of years of possession of the driving license. The "Myopia" column includes only values of 1 (presence of myopia less than 2 dioptres) or 0 (no pathology). In the same way, the "Car sickness" column includes only values of 1 (the driver got a little nauseous while driving) or 0 (no problem).

Driver	Age	Accidents	License	Myopia	Car sickness
1	23	0	4	0	0
2	24	0	5	0	0
3	22	1	3	0	0
4	25	0	6	1	1
5	24	0	5	1	0
6	23	0	4	0	0
7	26	0	7	0	0
8	22	2	3	1	1
9	24	0	5	0	0
10	25	0	6	0	0
11	23	0	4	0	0
12	24	0	5	1	0
13	24	0	5	0	1
14	26	0	7	0	0
15	22	1	3	0	1
16	24	0	5	1	0
17	25	0	6	0	0
18	23	0	4	1	0
19	24	0	5	0	0
20	25	0	6	1	0
21	24	0	5	0	0
std dev	**1,18**	**0,51**	**1,18**	**0,48**	**0,40**

The experimental phase was characterized by the following steps:

a) Complete a pre- and post-drive questionnaire.

b) Drive on a first pre-selected track (the duration of this step was subjective since the driver keeps driving until felt comfortable with the driving commands).

c) Drive on the main track (for about 10 minutes).

The calculation of the sample size should derive from considerations related to the variance and the magnitude of the confidence level which, generally, is assumed to be 95%.

Given the good homogeneity of the selected drivers (see table 2), the sample size was calculated as a function of the desired precision P and the expected frequency F using the formula below.

$$n = \frac{1.96^2 \cdot F(1-F)}{P^2} = 18$$

In the present study, the expected frequency F was set at 5% and the absolute precision P at 10%, obtaining a minimum number of 18, lower than the actual sample size, equal to 21.

Two-ways ANOVA

Since each user is measured more than once under all levels, the authors performed an ANOVA factorial design within subjects with the following factors:

- Type of curve (4 levels: R60, R100, R60out, R100out, according to Table 1 and Figure 5).
- Direction (2 levels: Left, Right)

The response variable (or Dependent Variable DV) is represented by the performance indexes already introduced: INT_L, mLP_L, $SDLP_L$.

The reliability of the results depends on the satisfaction of the assumptions based on ANOVA analysis. In this case, the assumptions regard the following:

- The dependent variable must be measured at the continuous level. In our case, the measures of the indexes are expressed in squared meter for INT_L, and in meter for mLP_L and $SDLP_L$, i.e. in a continuous way.
- The two within-subjects' factors (i.e., two independent variables) should consist of at least two related groups that indicates that the same subjects are present in both groups. They have been divided in 4 levels (the Type variable: R60, R100, R60out, R100out) and 2 levels (the Direction variable: Right, Left), respectively.
- The observations are independent, without relationship between the observations in each group or between the groups themselves.
- Absence of significant outliers.
- Tests for normality by means of residuals.
- Check the sphericity, i.e. the variances of the differences between all combinations of related groups, were equal. When these conditions are violated, the Mauchly tests for sphericity was performed, adjusting the analysis by a correction criterion as the Greenhouse-Geisser method.

Since the authors have to perform a two-way ANOVA and there is the effect of two independent variables and the effect of the independent variables on each other, there are three pairs of null or alternative hypotheses, as following:

- H_0: The means of all Type groups are equal.
- H_1: The mean of at least one Type group is different.
- H_0: The means of the Direction groups are equal.
- H_1: The means of the Direction groups are different.
- H_0: There is no interaction between the Type and Direction.
- H_1: There is interaction between the Type and Direction.

However, if an ANOVA test shows significant results, it cannot say where those differences lie. In these cases, the post-hoc Tukey's HSD (Honestly Significant Difference) test was run to find out which specific groups' means (compared with each other) are different.

Results

Figure 6 represents LP of user 1 along curve 4 (left R60). It is possible to notice that the zero of the ordinate axis coincides with the lane axis, while the unit of the abscissa is the time. Since the curvature is measured in the time domain, its trend shows irregularities as the speed is not constant along the curve.

The synthetic indicators, representing the ANOVA's dependent variables, were calculated for each curve and each user. In total, a dataset with 2 independent variables (type and direction of the curve) and 3 DVs (INT_L, μLP_L, $SDLP_L$) with 378 records (21 users x 18 curves) was defined (Table 3 is referred to only a driver).

Table 3
– Data base regarding only the User 1. Twenty-one drivers contributed to build the overall data set, useful to perform the ANOVAs. The Independent Variables are Type and Direction and the Dependent Variables are the indexes INT_L, μLP_L, $SDLP_L$.

Observation	Subject	TYPE	DIRECTION	INT	µLP	SDLP
1	User1	R60	R	0.154	0.024	0.081
2	User1	R60	L	0.770	0.124	0.148
3	User1	R60	R	0.002	0.000	0.003
4	User1	R60	L	1.943	0.341	0.408
5	User1	R100	R	0.000	0.000	0.000
6	User1	R100	L	2.293	0.276	0.245
7	User1	R100	R	1.994	0.262	0.491
8	User1	R100	L	1.079	0.138	0.239
9	User1	R100	R	0.030	0.004	0.023
10	User1	R60out	R	0.282	0.066	0.155
11	User1	R60out	L	0.558	0.186	0.161
12	User1	R60out	R	0.415	0.130	0.221
13	User1	R60out	L	1.516	0.474	0.434
14	User1	R100out	R	0.027	0.005	0.024
15	User1	R100out	L	0.948	0.202	0.156
16	User1	R100out	R	0.046	0.010	0.030
17	User1	R100out	L	0.850	0.174	0.211
18	User1	R100out	R	0.080	0.019	0.054

Three different two-ways ANOVA were performed, in which the DV in turn was represented respectively by INT_L, MLP_L, $SDLP_L$. All the assumptions listed in the Methods section were verified. For example, in Fig. 7 the quantiles of the residuals are plotted to verify the normal distribution. The normal probability plot of the residuals should approximately follow a straight line and in the case of INT_L this hypothesis is quite satisfacted. The other DVs (μLP_L and $SDLP_L$) present similar trends and for the sake of brevity have not been inserted. In the following the results of the three ANOVA are reported.

Two-way ANOVA with Dependent Variable INT_L.

There is a significant difference in the average, both for Type variable [$F(3,270) = 30.37$, $p = 0.000$], for Direction [$F(1,270) = 651.94$, $p = 0.000$] and, last, for their interaction [$F(3,270) = 13.97$, $p = 0.000$]. As evidenced in Table 4, the Tukey's post-hoc test did not reveal significant differences in driving along the 4 types of right curves (p-value in couple comparisons between 0.4088 and 0.9991), while in left ones R60 induces a different driving behaviour than other curves (p-value < 0.0001). Figure 8, concerning the estimation of the marginal averages of the various levels of the independent variables, shows a substantially homogeneous driving behaviour in right curves, regardless of radius or length of residual arc. Among left curves, R60 presents an average INT_L value equal to 2.77 m^2, higher than other curves that, instead, exhibit not significant differences.

Table 4
– Contrasts between all the levels of the Independent Variables. The p-value adjustment has been determined by means of Tukey method. This table is referred to the Dependent Variable INT_L.

Direction R		
Element 1	**Element 2**	**p-value**
R60	R100	0.6537
R60	R60out	0.4088
R60	R100out	0.4912
R100	R60out	0.9790
R100	R100out	0.9939
R60out	R100out	0.9991
Direction L		
Element 1	**Element 2**	**p-value**
R60	R100	< .0001
R60	R60out	< .0001
R60	R100out	< .0001
R100	R60out	0.0158
R100	R100out	0.0740
R60out	R100out	0.9377

- *Two-way ANOVA with Dependent Variable μLP_L.*

Also in this case there is a significant difference in the average both for variable Type [$F(3,210) = 27.96$, $p = 0.000$], for Direction [$F(1,210) = 827.48$, $p = 0.000$] and their interaction [$F(3,210) = 18.19$, $p = 0.000$].

In Table 5, the Tukey's post-hoc test was reported: it did not reveal significant differences in driving along 4 right curve types (p-value in couple comparisons between 0.7121 and 1.0000), while in left ones there is a different behaviour between couples R60-R100, R60-R60out and R60-R100out (p-value < 0.0001). Furthermore, in this case too, there is a relevant difference between right and left curves. Figure 9 evidences a substantially homogeneous behaviour for driving along all right curves, while for R60 and R100 left curves different behaviours than other 2 types were measured.

Table 5
– Contrasts between all the levels of the Independent Variables. The p-value adjustment has been determined by means of Tukey method. This table is referred to μLP_L.

Direction R		
Element 1	**Element 2**	**p-value**
R60	R100	0.7121
R60	R60out	0.7475
R60	R100out	0.7196
R100	R60out	0.9999
R100	R100out	1.0000
R60out	R100out	1.0000
Direction L		
Element 1	**Element 2**	**p-value**
R60	R100	< .0001
R60	R60out	0.1327
R60	R100out	< .0001
R100	R60out	< .0001
R100	R100out	0.0290
R60out	R100out	0.0107

- *Two-way ANOVA with Dependent Variable* $SDLP_L$.

Similarly, in this scenario there is again a significant difference in the average for Type [$F(3,270) = 10.47$, $p = 0.000$], Direction [$F(1,270) = 433.77$, $p = 0.000$] and their interaction [$F(3,270) = 3.92$, $p = 0.000$]. Again, the Tukey's post-hoc test (Table 6) did not show significant differences for the 4 types of right curves (p-value in couple comparisons between 0.3864 and 0.9991), while in the left ones there is a different behaviour between couples R60-R100 and R100-R60out (p-value between 0.0004 and 0.0007). Moreover, in this case too, right and left curves determine different behaviours. Figure 10 shows a substantially homogeneous trend in driving along right curves, regardless of radius or compliance with standards for length of residual arc. Considering left curves, R60 curves present very similar behaviours, while R100 presents minor deviations.

Table 6
– Contrasts between all the levels of the Independent Variables. The p-value adjustment has been determined by means of Tukey method. This table is referred to the Dependent Variable $SDLP_L$.

Direction R		
Element 1	**Element 2**	**p-value**
R60	R100	0.3864
R60	R60out	0.5891
R60	R100out	0.5037
R100	R60out	0.9873
R100	R100out	0.9973
R60out	R100out	0.9991
Direction L		
Element 1	**Element 2**	**p-value**
R60	R100	0.0004
R60	R60out	0.9988
R60	R100out	0.0595
R100	R60out	0.0007
R100	R100out	0.3905
R60out	R100out	0.0851

Discussion

The proposed methodology aims to overpass limitations due to the extreme experts' judgement subjectivity, by proposing an analytical procedure for determining the safety level of a road when its geometrical/constructive features are not perfectly in compliance with limitations imposed by standards. It should be underlined that the results previously reported are not directly generalizable, even because they reflect some specific characteristics of this experimentation, hardly of common interest. However, the presented method may be applied to almost every scenario in which quantifications on infrastructure safety level are required, both in absolute terms and in comparative analyses.

The advantages obtained through this procedure may be listed in the following:

- Reproducibility and repeatability of tests, guaranteed by the homogeneity of the driving scenario for all users.
- Final considerations derived from the real driving of drivers and not from purely theoretical hypotheses of the standards, that are far from reality (for example, the coincidence between lane axis and trajectory).
- Objective procedure based on telemetry data, focusing on variables specifically indicative of the observed phenomenon. In this case, the attention is on trajectory, as it would be assumed that a too short circular arc would cause a more complex manoeuvre for the driver.

The statistical analyses referred to synthetic indicators is able to quantitatively represent the driver's performance in terms of his trajectory on a specific curve. They relied on the following features of the vehicle motion:

- Capacity of discerning right and left deviation from the axes. In the first case, the crossing of the axis line of the lane can be fully voluntary to reduce the travel distance. On the contrary, a left deviation could cause a danger against vehicles driving in the opposite direction.
- "Meandering" from the lane axes represents a danger only if its amplitude is relevant. In any case, its average value may lead to an underestimation of the danger (Fig. 1, Fig. 2)
- The time/space in which the vehicle deviates from the lane axes. A short deviation, followed by a quick fix, is almost physiological and does not cause any critical issue for safety (Fig. 3).

The considerations reported at the end of the Introduction section evidence that there is not a perfect synthetic index, and the best solution is considering more than one. For these reasons, novel indicators, as INT_L, μLP_L e $SDLP_L$ were proposed, representing the DVs for the three different two-ways ANOVA. The exam of the results confirms that focusing on left deviations has led to similar results with the 3 indicators, evidencing only the most critical phenomena for safety. In all the analyses H1 hypothesis was confirmed, i.e. at least one of the averages of the groups is different from the others. However, this result is not interesting from an engineering point of view, since it does not deepen the relationship between the dependent variables (INT_L, MLP_L o $SDLP_L$) with the single levels of the two independent variables (Type e Direction). In this case, a multiple comparison test among the averages of the involved groups permitted to complete the information required to interpret the phenomenon, as noticed in Tables 4–6 and Figs. 8–10.

In particular, there is not a remarkable difference in driving along right curves, regardless of radius or residual circular arc length. For INT_L, not only the averages are very similar (Table 4, where right curve couple comparisons have values between 0.4088 and 0.9991), but also the averages of the dependent variable are very low (between 0.07 and 0.34 m^2, Fig. 8) and this indicates a good vehicle performance during curve driving. This behaviour is confirmed with the other indicators too.

In the second elaboration, averages of μLP_L for right curves are very similar (p-value between 0.7121 and 1.0000 in couple comparisons – Table 5) and the averages of DV are very low (between 0.02 and 0.04 m - Fig. 9), indicating a good performance of the vehicle while driving along curve. $SDLP_L$ presents the same trend for right curves (p-value between 0.3864 and 0.9991 in couple comparisons - Table 6) and, even in this case, the averages of the dependent variable are very low (between 0.03 and 0.06 m - Fig. 9), indicating again a good performance of the vehicle along curve.

In left curves, instead, the driving behaviour is completely different.

First of all, larger deviations are measured than right direction. Further, there are also quite different values between different curves, despite not always statistically significant. For example, for INT_L there is a different trajectory (p-value < 0.0001) between R60 and the other three (R60out, R100 e R100out), while these show a very similar behaviour (p-value between 0.0158 and 0.9377) or, however, not statistically significant differences. It should be underlined that the averages present higher values for right curves (between 1.37 and 2.78 m^2 - Fig. 8) as left curves are harder for drivers. This phenomenon may be easily explained: while driving along curves, the driver gazes the internal marginal point, with higher curvature. For right curves, it coincides with the barrier or other non-overpassing elements, still easily to be recognized, determining great confidence in curve interpretation. In left curves on two-ways roads, the internal margin is only represented by the markings – whether clearly visible. However, this element is not seen by the users as a fixed and non-overpassing obstacle. This prerogative, with the possible influence of opposite vehicles, produce more spread trajectories for left curves.

The μLP_L and $SDLP_L$ indicators, for left curves, present slightly different values than INT_L, as more criticisms emerge in driving along R60 and R60out curve respect to R100 and R100out (Fig. 9 and Fig. 10). Statistically, for μLP_L there is a significant difference between couples R60-R100, R60-R100out e R100-R100out (p-value < 0.0001) with average values of deviations between 0.18 e 0.37 m (Fig. 9). A different outcome appeared for $SDLP_L$, where significant different behaviours are noticed only for couples R60-R100 and R100-R60out (p-value between 0.0004 and 0.0007). Even in this case, the averages present higher values than right curves (between 0.15 and 0.22 m - Fig. 10), proof of a higher driving difficulty.

Although couple comparisons are extremely interesting, the aim of this research is to evidence any critical issues in curves not in compliance with guidelines in terms of length of residual circular arc, in identical radius or direction conditions. For this reason, the most interesting comparisons are between couples R60-R60out and R100-R100out. As already said, no difference raised for right curves. This means that the violation of the minimum value imposed by the standards did not induce any negative effect on driving behaviour, at least with the geometry of this road. It is recalled that the Italian standards fix a minimum length equal to m 31.46 and 38.95 m respectively for R60 and R100. Instead, R60out residual circular arc was only 0.3 m long, while that of R100out was 6.0 m long, remarkably below than admitted values. For left curves, INT_L does not evidence any difference between R100-R100out curves but does evidence one between R60-R60out (p-value < 0.0001). However, the most unfavourable situation in terms of deviation from axes was measured for R60. The other two indicators, instead, did not evidence any significant difference between compliance and violation scenarios. Overall considering these results, for this experimentation, it is possible to assess that deviation from standards, regarding the selected limit, does not produce any negative effect in terms of trajectory.

Conclusions

This study proposed a methodology to analytically quantify road safety, based on check on synthetic indicators on the observed phenomenon. In this case, the problem was to verify a design solution not in compliance with Italian standards in terms of minimum length of the residual circular arc in transition curves. The results proved that even excessive deviations from the minimum thresholds did not produce statistically significant effects on homogeneous drivers' sample.

Some of the limitations of existing literature (presented in the Introduction section) may be considered satisfied:

- This methodology does not apply empirical procedures (such in Context Sensitive Solutions or Road Safety Audits) but purely analytical ones, based on vehicle telemetry data.
- All the components of the road system (driver, context, vehicle) have been simultaneously involved, not separately but considering their mutual interactions, through tests on road in a simulated environment.
- The proposed methodology may be generalized to any type of verification or condition (design or existing road). The analyst should only identify the most appropriate dependent variable. Using several dependent variables, as in this research, may help the decision maker in obtaining a more robust result.
- In contrast to the common μLP and SDLP widely used in literature, the proposed ones are more adapt for curve driving, evidencing some issues on left deviations from trajectories, more and more dangerous than right ones because of possible collisions against opposite vehicles.
- A novel index named INT_L, representing the time/space in which the user overpasses the lane axes on the left, was introduced.

In conclusion, this approach is more useful for practitioners, as it provides an objective response to frequent problems in road design or upgrading of existing ones, when territorial constraints cannot be overpassed and the only available solution is not-compliance with regulatory limits, often too severe. This research may also help from a theoretical perspective, as it guides the choice toward specific curve geometry (or of other elements) considering the real driving behaviour of the user, renouncing to the hypothesis of perfect overlap of theoretical and effective trajectories for some dynamic functions.

Declaration

DATA AVAILABILITY STATEMENT

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Figures

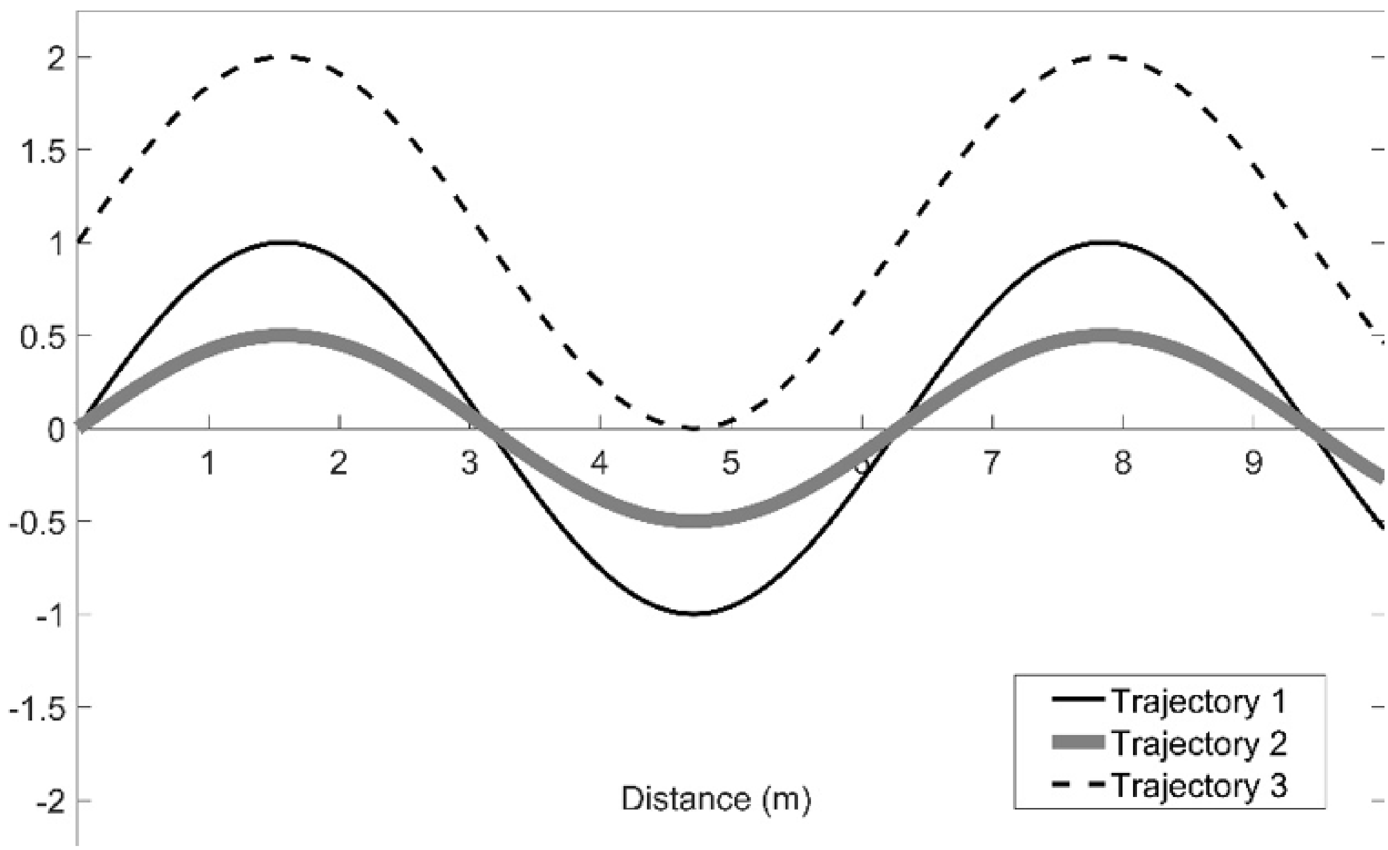

Figure 1

Hypothetical trajectories along a general section, where the lane width (m 4.50) is reported as ordinate axis.

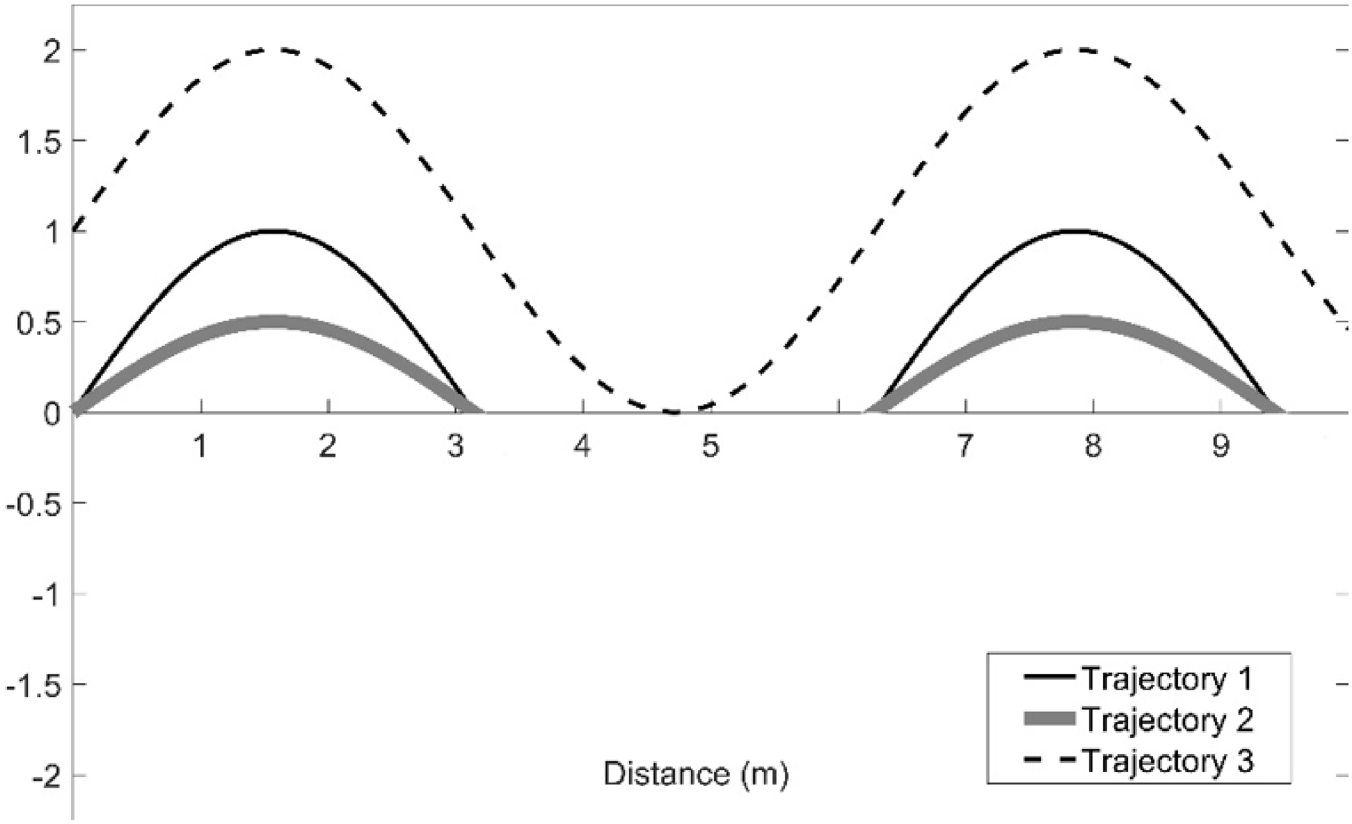

Figure 2

Hypothetical trajectories along a general section, where the lane width (m 4.50) is reported as ordinate axis. The trajectories on the right side of the lane were deleted.

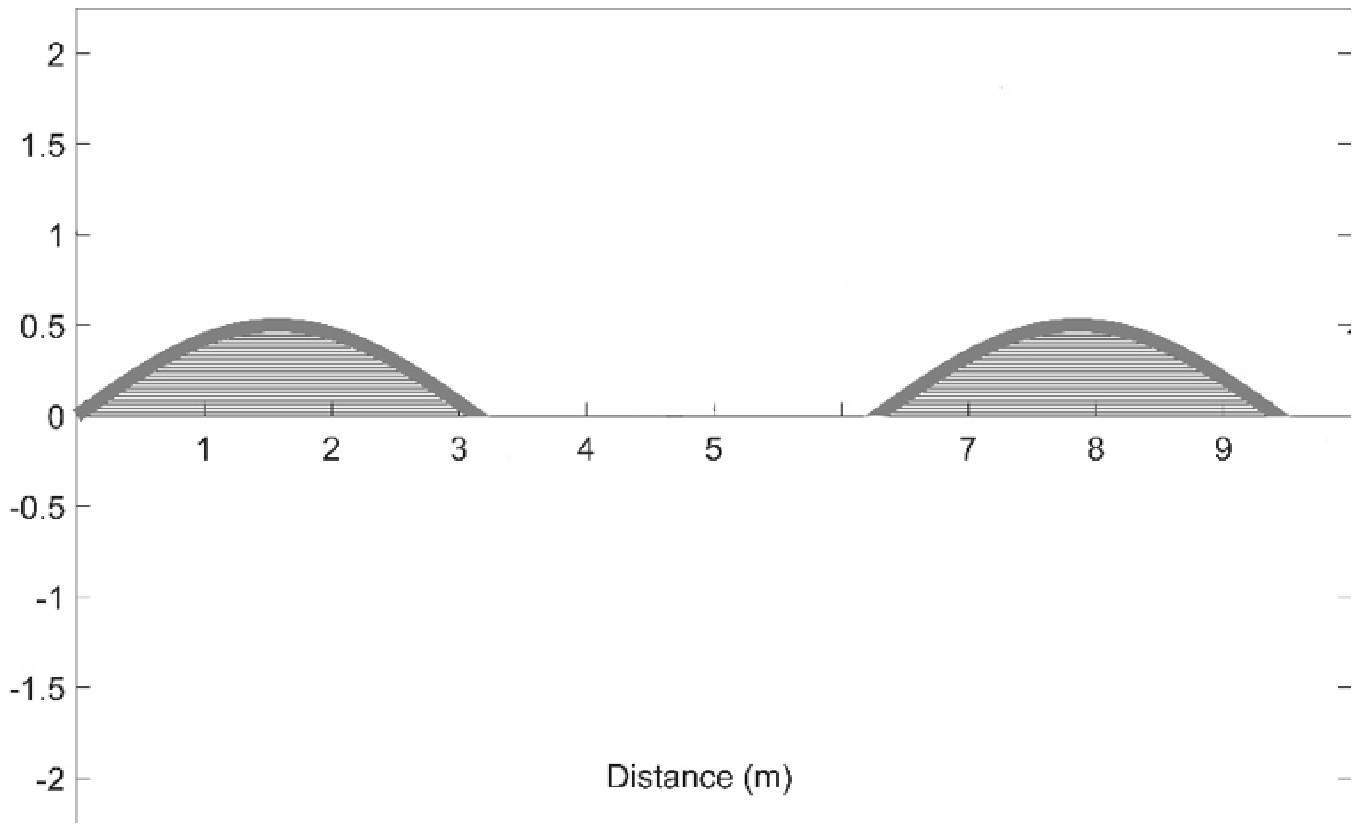

Figure 3

Integral referred to the area delimited by the trajectory on the left of the axis and the same axis. As the Figure 2, the trajectories on the right side of the lane were deleted.

Figure 4

The driving simulator of the Laboratory of Road Infrastructure in Messina (Italy).

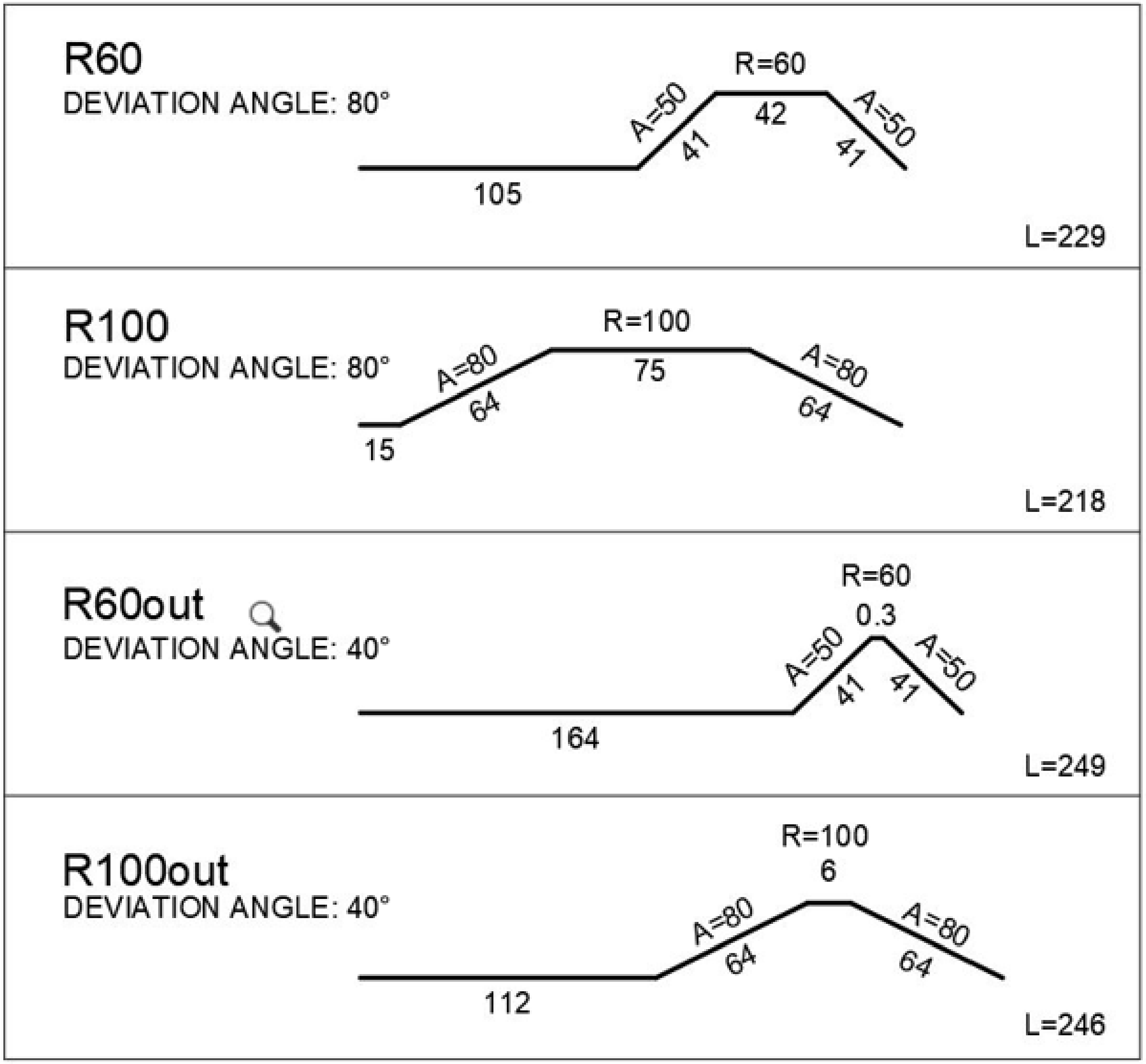

Figure 5

Geometrical scheme of the four types of curves used in the experimentation. The first two were built in accordance with the legislation while the last two do not respect it in relation to the length of the circular arc. In every configuration, the shape parameter A of the transition curve and the radius R of the curve have been indicated. The overall length of the alignment consisting of a tangent, a first transition curve, a circular arc and a second transition curve is shown on the extreme right of each row. All lengths are in meters.

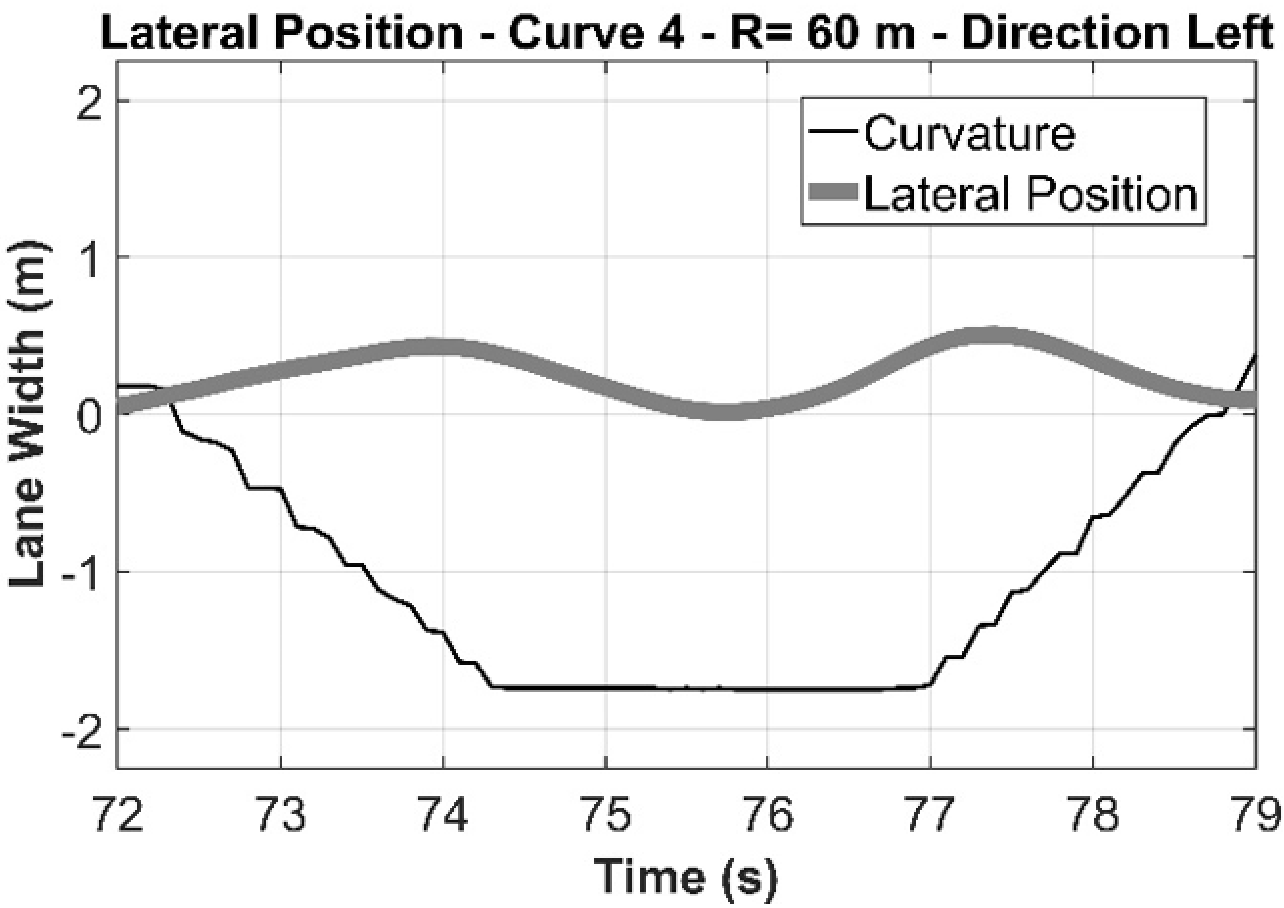

Figure 6

A typical trend of LP in correspondence of a curve. The curvature diagram is not regular and symmetric because is in the time domain. The lane and shoulder width are 4.5 m and the origin of the reference system is positioned in the axis of the lane.

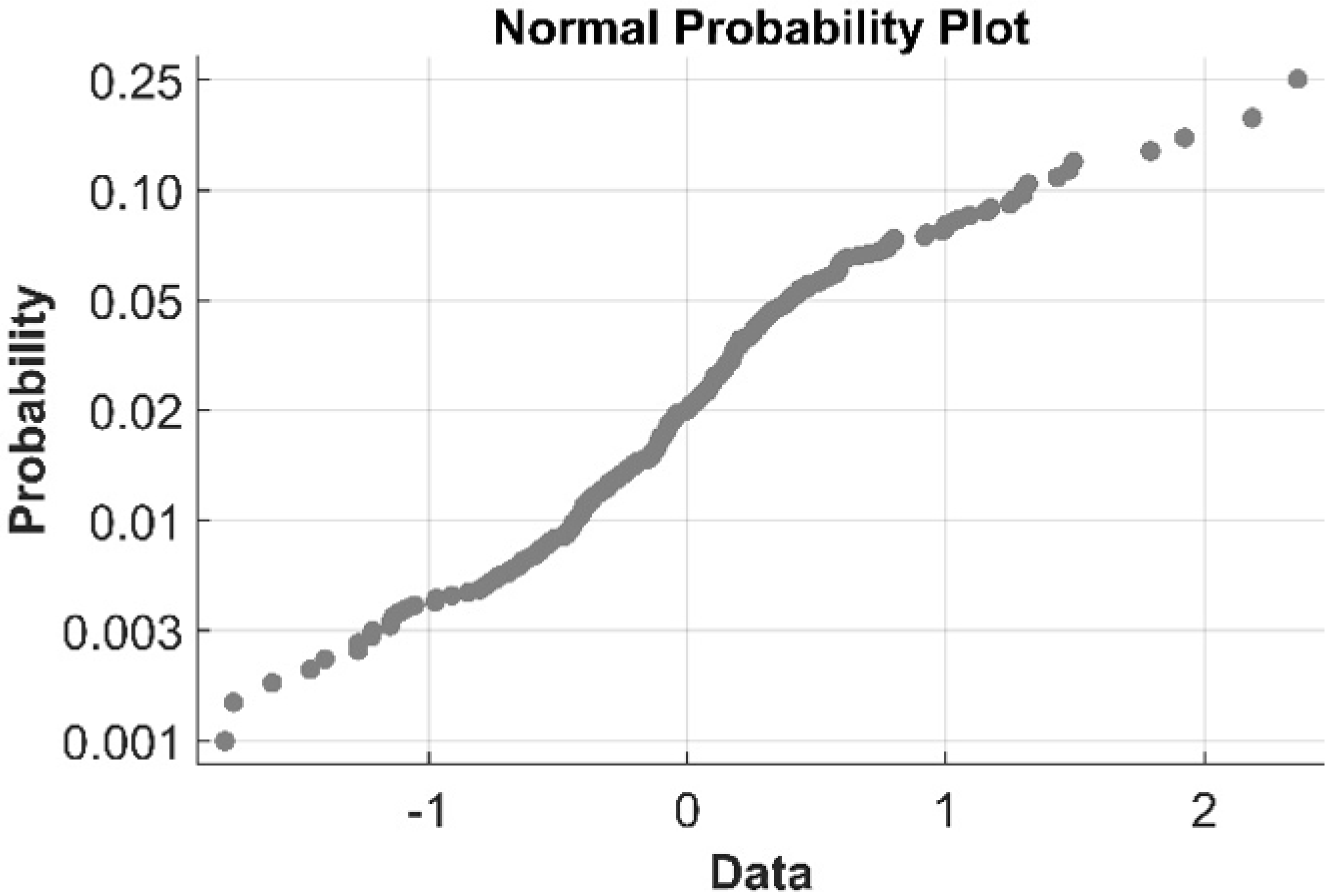

Figure 7

Normality plot of the residuals referred to INTL.

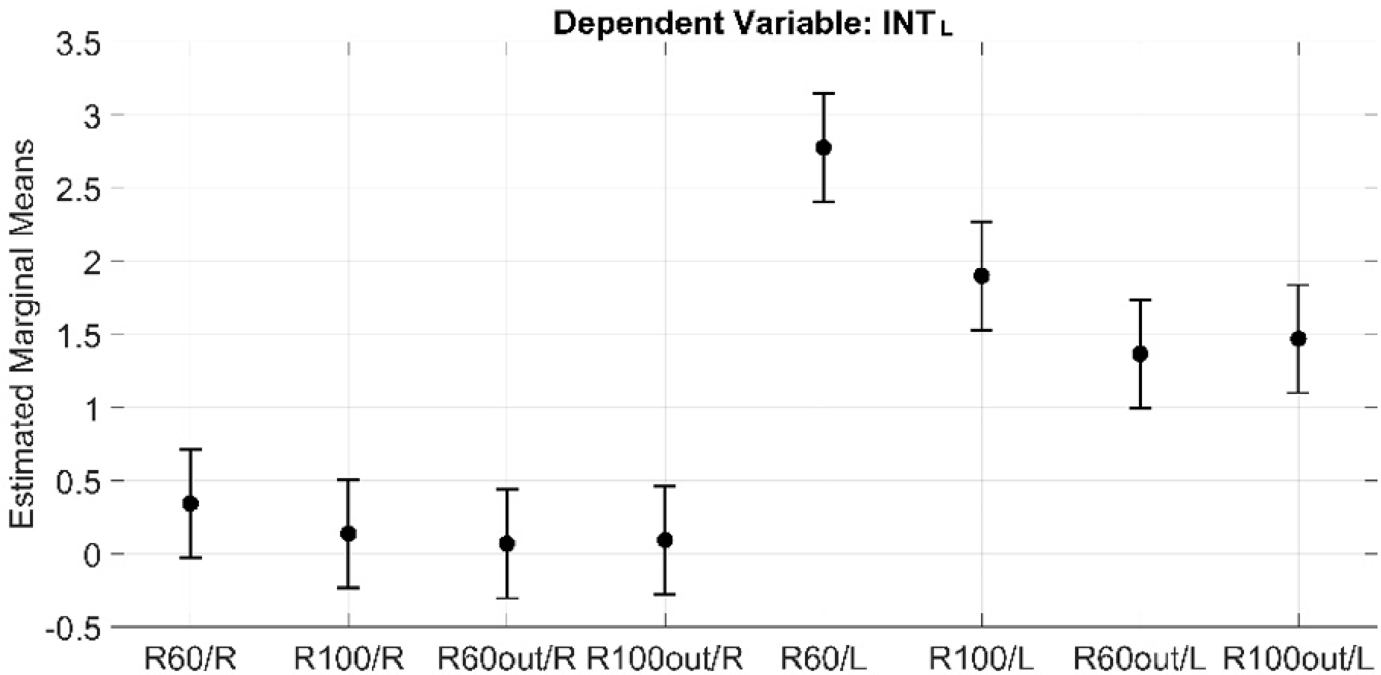

Figure 8

Estimated Marginal Means for the Dependent Variable INTL. The circular black marker indicates the mean value, while the interval represents the confidence level used (0.95).

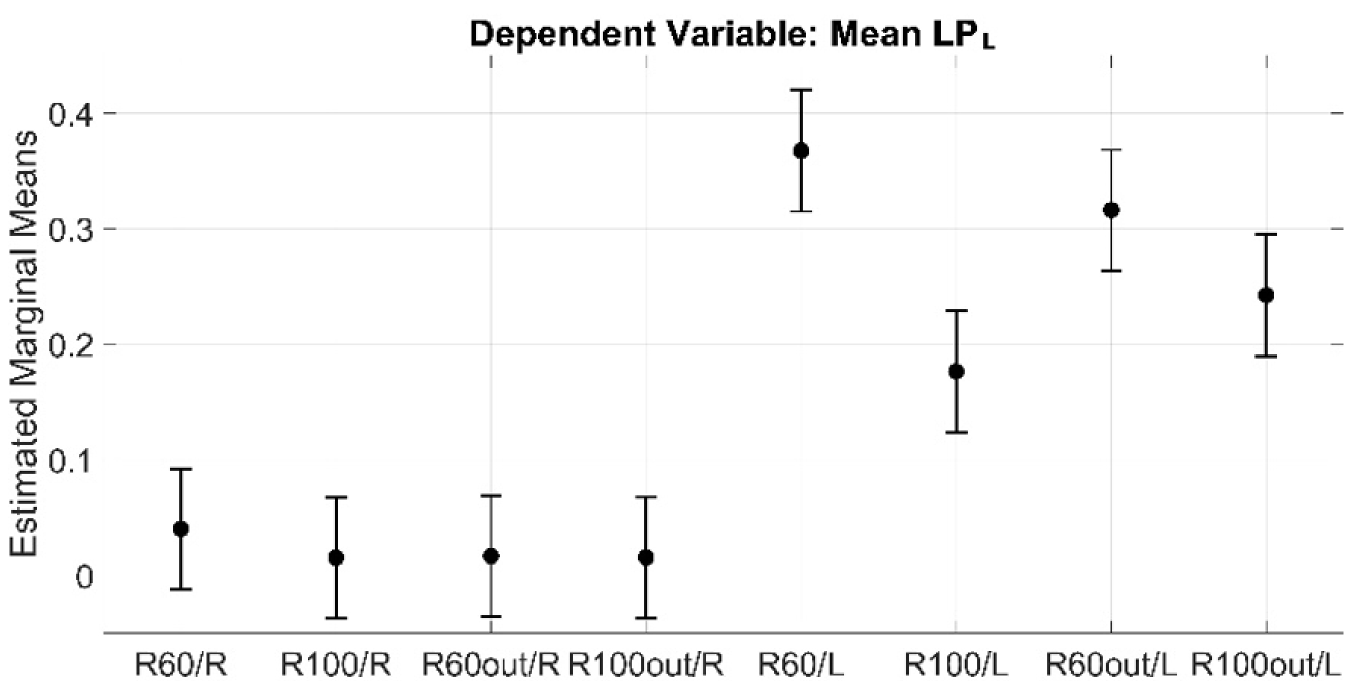

Figure 9

Estimated Marginal Means for the Dependent Variable mLPL. The circular black marker indicates the mean value, while the interval represents the confidence level used (0.95).

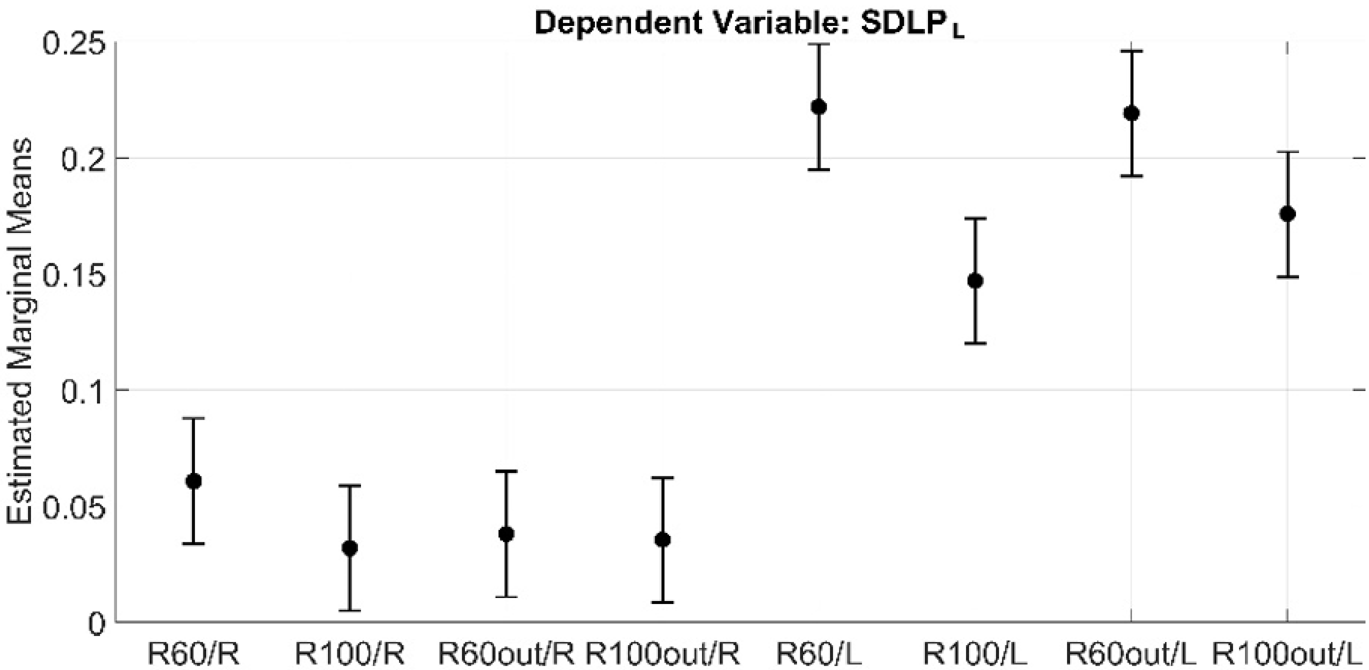

Figure 10

Estimated Marginal Means for the Dependent Variable SDLPL. The circular black marker indicates the mean value, while the interval represents the confidence level used (0.95).