

Article

Synthetic Drivers' Performance Measures Related to Vehicle Dynamics to Control Road Safety in Curves

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Abstract: The road alignment design relies on the knowledge of vehicle dynamics variables. However, it assumes that drivers faithfully follow the lane axis on straights and curves. Deviating from this assumption leads to unexpected outcomes and can significantly impact users' safety. In this context, vehicle speed and longitudinal acceleration play a crucial role as key references in the international standards. They provide insights into critical driving aspects; therefore, it is essential to thoroughly analyze their real trends. Broad data collection campaigns should derive synthetic indicators in order to highlight eventual significant deviations between the ideal and real dynamics. To achieve this objective, the authors propose some indexes deduced during an experimental study with a Sim-Easy driving simulator, by AVSimulation. Importantly, these indicators can be freely applied in real driving scenarios without limitations. These indexes were tested on four different horizontal curves and proved effective in identifying relevant characteristics related to longitudinal acceleration and speed. Looking ahead, by analyzing similar data for numerous driving contexts on real roads, infrastructure managers could use this methodology to identify those sections with increased vulnerability for users' safety. Moreover, the collected data from sensors, processed using these indicators, can be filtered and transmitted to users (via ADAS tools) while driving on a specific road to provide timely warnings about potential difficulties. The indicators control the physical variable (acceleration or speed) on a certain geometric element with reference to what is prescribed by the standard. For example, the acceleration indicators are normalized with respect to a threshold value while for speed indexes, the result depends on the difference between the end control points of the geometrical element. In both cases, international regulations report prescribed or recommended reference values, so the analyst is immediately aware of any critical issues in the maneuver.

Keywords: performance measures; driving behavior; road safety; driving simulator



Citation: Bosurgi, G.; Pellegrino, O.; Ruggeri, A.; Sollazzo, G. Synthetic Drivers' Performance Measures Related to Vehicle Dynamics to Control Road Safety in Curves. *Vehicles* **2023**, *5*, 1656–1670. <https://doi.org/10.3390/vehicles5040090>

Academic Editors: Peter Gaspar and Junnian Wang

Received: 30 August 2023

Revised: 25 October 2023

Accepted: 6 November 2023

Published: 9 November 2023



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1. Introduction

For several decades, workload control has become one of the most important factors in improving road safety. Indeed, high workload can decrease the driver's attention and concentration, increasing the risk of road accidents [1,2]. Much of the applied research in the automotive and road safety field is based on some types of workload measures accepted by the scientific community, which are fundamental to understand the functioning of the human–vehicle–road system. These relationships are at the basis of the V2X technology or “Vehicle-to-Everything”, in which these components exchange information with each other to improve road safety and traffic management, with the aim of reducing accidents and improving traffic management [3]. The human factor is the most complex one within the road system, due to the great randomness of many psychophysiological variables [4–6].

The different modes in which the workload can be measured refer to subjective quantifications, which are based on the user's judgment [7–11], physiological measures such as visual activity, pupil dilation, skin conductance, heart rate, and electromyography [5,12–16], and finally, performance measures. The latter relate to the interaction with the vehicle,

through indexes related to lateral position [8,16,17], steering activity in terms of steering angle or steering speed [18–22], and those related to the longitudinal control of the vehicle, such as speed and longitudinal acceleration [23–27].

In particular, Gemou et al. [26] conducted an experimental study that compared the results of tests carried out with a semi-dynamic simulator with data extrapolated from an instrumented vehicle in real traffic conditions. Participants completed the driving tasks in three different road contexts. The authors introduced a new approach for the evaluation of some performance measures based on four different correlations useful to identify the smallest possible deviation between the different experiments. The authors found that drivers tended to drive toward the right edge of the lane more often in real traffic conditions than in the driving simulator.

Bourrelly et al. [27] highlighted the differences between autonomous driving and manual driving by studying the steering angle and both the longitudinal and lateral speeds for long and short periods (1 h and 10 min, respectively). These analyses, carried out at 60 m intervals, indicated the point in the maneuver where the driving behavior of the participants returned to high levels.

Several factors can influence driving in terms of speed or longitudinal acceleration during driving. The traffic flow is one of the main factors: when it is high, it can induce sudden slowdowns or, conversely, may encourage an increase in speed and acceleration incompatible with road safety [28].

Driving along a curve is correlated with multiple factors, such as geometry, vehicle characteristics, driver experience, presence or absence of obstacles, and the general environmental conditions [29]. Usually, the driver can adopt different strategies, although most behavioral responses are functions of speed and visibility [30–32].

Furthermore, in general, the involved variables, thanks to the large amount of data collected by modern high-frequency sensors, appear as continuous functions, often of complex form and difficult to synthesize through a single number. For this reason, the subsequent utilization of these data (e.g., for statistical analysis) requires synthetic indicators, which, in many cases, are represented by mean and variance [33–35].

Considering the mean or the maximum value in the complexity of a section that includes straights circular and transition curves risks hiding the user's behavior that deviates from the real one [36–38]. This may normalize the influence of potential risk factors such as road curvature, longitudinal slope, proximity of objects on the roadside, etc. It is clear that the driver's strategy depends on many factors that have perceivable consequences on speed and longitudinal acceleration, which can, therefore, be used as representative indicators of road safety.

Road safety also depends on the readiness with which any information is communicated to users. For this reason, it is not conceivable to record all the signals detected by the sensors, but intelligent sampling must be carried out, since these data could then be transmitted to a web platform or to a control center. In this regard, Tonguc et al. [39] proposed the architecture of a drivers' information system that uses data from accelerometers whose value is crossed with the climatic conditions and the speed of the vehicle to deduce any critical situations for users. The interesting aspect of this study is that the physical variables are related to other conditions (in this case climatic) of the road context which, when critical, could have negative consequences on road safety.

In this context, the aim of this study is to investigate certain issues that have often been overlooked or not critically and thoroughly analyzed, which may lead to distorted results or neglect of important aspects. Therefore, in this paper, a comparative analysis was carried out between the ideal trend and the actual trend followed by the driver concerning two performance variables: longitudinal acceleration and speed. To this end, through a study carried out with a car driving simulator, the authors proposed synthetic indexes relating to the dynamics of the vehicle to highlight any critical issues during driving.

Among the results of the illustrated literature, numerous indicators were also proposed, deduced from the variables measured by the sensors (accelerometers, gyroscopes, etc.), whose acceptability judgment depends on subjective thresholds which rarely led to great reliability. Furthermore, these indicators do not take into account the specificity of the geometric element traveled (straight line, circular curve, transition section).

Therefore, the objective of the present study was to identify performance indicators which are not a simplistic sampling of the data coming from the sensors, but which have a precise physical meaning with reference to the geometric element of the road traveled. For example, a low value of lateral acceleration could be neglected but, if it is recorded in the end part of the straight, it could be a sign that the driver is anticipating the steering maneuver because he has poorly understood the following curve geometry.

2. Methodology

The experimentation was carried out in a simulated environment, with a users' group consisting of young individuals with similar behavioral characteristics. The sample of users, made up of 21 young people aged between 22 and 26, was subjected to a very rigid procedure which can be summarized in the following bulleted list:

- Pre- and post-drive questionnaire (including informed consent).
- Drive on a training road (the duration of this step was subjective depending on the ability of the drivers).
- Drive on the main track (for about 10 min).

From the questionnaires, it emerged that, on average, the age was 23.9 years, the number of accidents was 0.2, the years of holding a driving license were 4.9, eye pathologies (slight myopia) affected 30% of users while only 3 drivers experienced car sickness.

The driving simulator (Figure 1) belongs to the Digital Laboratory for Road Safety (DiLaRS) at the University of Messina. It is a compact, static type with an ergonomic driving position, traditional driving controls (clutch, brake, and throttle, with manually adjustable passive force feedback and 7 + 1 manual gearbox), and a steering wheel characterized by an active force feedback system, with three monitors representing the external scenario to the driver.



Figure 1. The driving simulator.

The software used is Scanner Studio[®] rel. 2022.2, a suite that allows for full control of the driving environment in terms of vehicle, road geometry, pavement characteristics, traffic, and environmental conditions. Furthermore, the software allows for the recording of telemetry data, concerning variables such as position, speed, and acceleration in all directions of space, activity on the pedals and steering, steering rotation speed, lateral position of the vehicle with respect to lane axles or of the road or other reference points, visualization through graphs, with the possibility of exporting these data externally. It is also possible to program driving events using the Python programming language.

The road type used in the experimentation is a local rural road (type F) according to the Italian standards [40]. The cross-section consists of two lanes and two shoulders with a total width of 9 m, while the alignment presents a succession of curves with radii of 60 m and 100 m and is approximately 5000 m long (Figure 2). The residual straights between the 60 m radius curves are 106 m long and those between the 100 m radius curves are 61 m long.

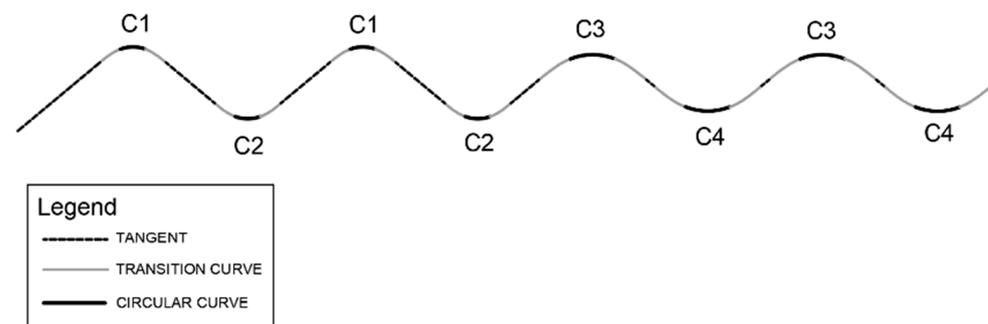


Figure 2. Scheme of the experimental test road. The symbols on the curves mean, respectively: C1 $R_c = 60$ m and right direction; C2 $R_c = 60$ m and left direction; C3 $R_c = 100$ m and right direction; C4 $R_c = 100$ m and left direction.

The detailed characteristics of the curves are given in Figure 2 and Table 1, in which are depicted the three different parts of the entire curve (green for tangent, red for clothoids, and blue for circular) and the following variables are considered:

- R_c —curve radius.
- α —central angle.
- Tan —tangent of the circular arc.
- L —total length of the geometric element.
- N —clothoids' shape parameter.
- A —clothoids' scale parameter.
- τ_F —deviation angle of the clothoids' end point.
- T_1 —long tangent.
- T_k —short tangent.

According to the Italian standards for road design [40], the driving test was conducted without traffic. This deliberate choice of scenario was aimed at limiting the number of variables in the problem and reducing their inherent randomness.

Before starting any activity on the driving simulator, all participants read and possibly sign an informed consent where the nature of the experimentation and the potential risks are explained in detail. After having given his consent, the user travels a stretch of road which constitutes the training phase, to get used to the driving controls and the simulator interface. After this phase, when the user feels confident with the simulator, the experimentation begins on the road of interest. At the end of his driving activity, the user must declare any physical discomfort accused during his performance and, if any, the test is discarded.

In the following, only the experimental data of a single driver will be presented, since the aim of this preliminary phase of the research is to define appropriate and representative performance indexes. The real driving context was discarded for several reasons, such as increased risks to the trial participants, lack of control over certain variables (lighting, weather, traffic), and higher costs for instrumenting the vehicle. The benefits of a more realistic scenario were deemed unnecessary, as the primary focus in this initial phase of the research was on defining the methodological aspects without regard to the overall results.

Obviously, it is not possible to identify a general behavior from such limited tests, without a necessary validation in a real environment and, moreover, with only one subject. Only after having illustrated in detail the method of quantifying the individual indexes, so that the scientific community can understand their potential and effectiveness, will they be applied to specific cases of particular interest, in a real or simulated environment. The aim of the authors, therefore, is to focus the reader's attention on the representativeness of the proposed indexes and not on the value of the final result, the entity of which is not of interest in this first research step.

Table 1. Geometrical parameters of the road curves.

		$R_c = 60$	$R_c = 100$
Circular	α [°]	40.2176	43.3307
	Tan [m]	21.97	39.72
	L [m]	42.12	75.63
Clothoid	N	1	1
	A	50	80
	L [m]	41.66	64
	τ_F [°]	19.8912	18.3346
	T_I [m]	27.95	42.9
	T_k [m]	14.05	21.54

The Performance Variables

In this section, the authors explain the methodology through which, starting from the study of the performance functions, 6 different synthetic indexes, relating to longitudinal acceleration (AccX) and speed (SP), were proposed.

The objective of these indicators is to evidence any difference between the ideal theoretical trend of the performance variable and the real one measured while driving.

In the following, "TANGENT" will refer to the straight section preceding the transition curve, "A" to the ingoing and outgoing transition curves (clothoids), and "R" to the circular curves.

Figure 3 depicts the ideal trend of longitudinal acceleration (AccX) in different sections. Specifically:

- [TANGENT and A]: According to the Italian standards [40], speed variations are allowed on straight sections of roads and, when of small extent, on transition curves. In this regard, a typical ideal value of acceleration at singular points or far from intersections is indicated by the Italian standards and is equal to $Acc_{Std} = 0.8 \text{ m/s}^2$. Near intersections or singular points, this value could reach 1.5–2.0 m/s^2 . Beyond these thresholds, this variable may be symptomatic of sudden maneuvers or unexpected scenarios (sudden obstacles or insufficient visibility distances).
- [R]: Along circular curves, AccX should be zero as these elements should be traveled at a constant speed. Any different value should be considered as a potential criticality unless due to random and periodic steering movements.

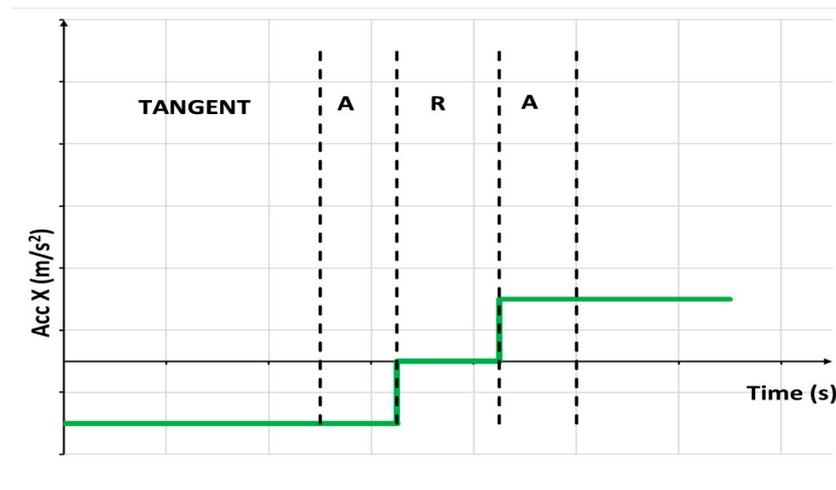


Figure 3. Theoretical trend of the longitudinal acceleration when the vehicle follows the axle of the lane in correspondence with the various geometric elements of the road (tangent, transition curves A, circular arc R). The dash lines indicate the starting and ending points of these geometric elements.

The following indexes have been identified for this performance measure:

- Along transition curves, conditions of uniformly accelerated motion should happen, and thus, the indicator should represent and evaluate the constancy of the longitudinal acceleration. For the ingoing clothoids, an indicator named $AccX_{A(In)}$ is proposed. In detail, $AccX_{A(In)}$ is the ratio between the average of the absolute values of $AccX$ along the ingoing clothoids and Acc_{Std} (Equation (1)). When it is equal to or greater than 1, the user has accelerated along this section at least by the quantity provided by the standard. Lower values represent reduced acceleration and, therefore, a preferable behavior. The same reasoning has been applied to the outgoing clothoids, identifying the corresponding indicator, named $AccX_{A(Out)}$ (Equation (2)).

$$AccX_{A(In)} = AVE | AccX_{A(In)} | / Acc_{Std} \tag{1}$$

$$AccX_{A(Out)} = AVE | AccX_{A(Out)} | / Acc_{Std} \tag{2}$$

- Along circular curves, similarly, an index named $AccX_R$ is proposed. It is equal to the ratio between the average of the $AccX$ absolute values along the circular curve and Acc_{Std} (Equation (3)). The ideal value of this indicator should tend to zero, evidencing quite uniform motion conditions.

$$AccX_R = AVE | AccX_R | / Acc_{Std} \tag{3}$$

Even if they are not included among the proposed indexes, in the exposition of the results, reference will be made even to the maximum value assumed by the longitudinal acceleration along the curve in general, $MAX AccX_{(Curve)}$, and $MAX AccX_{(R)}$ in the circular arc.

The ideal trend of the speed (SP) in the different sections is shown in Figure 4. In particular:

- [TANGENT]: SP absolute values along tangents should be compared with the speed design (S_d) and/or operative speed values, as well as the speed limit. In this way, appropriate attention and alarm thresholds could be established. It is also important to study the effective trend of the function. If the previous elements allow the driver to reach higher SP values than that allowable on the circular curves, except for special cases, the approach speed to the curve should have a decreasing trend, in agreement

with the adjacent transition curve. This, in truth, represents the most common scenario in rural roads in the Italian context.

- [A]: According to the Italian standards, only small speed variations may be permitted along transition curves (below 10 km/h). Moreover, regarding the SP trends, as in the case of tangent sections, decreasing speed in the ingoing clothoids and increasing speed in the outgoing ones are expected.
- [R]: The theoretical reference value of the design speed S_d , along circular curves, can be derived from the limit equilibrium conditions, as reported in many international standards. Alternatively, the V85 value could be obtained from empirical laws reported in the literature. In any case, in ideal conditions, the trend should be constant throughout the entire circular arc development.

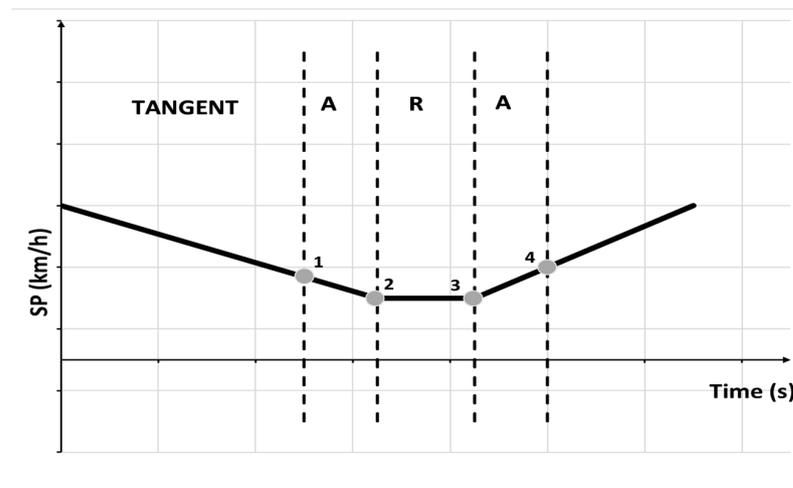


Figure 4. Typical schematic trend of the speed along a curve. Points 1 to 4 represent control points at the end of every different geometrical element (transition curves and circular arc). The dash lines indicate the starting and ending points of these geometric elements.

The following indexes have been identified for this performance measure:

- In the previously described scenario, the ingoing clothoids section should be driven in deceleration to adjust the speed from the straight to the circular curve, along which it is constant. Then, an index named $SP_{(AIn)}$ is proposed, representing the speed difference between the initial (1) and final points (2) of the clothoids (Equation (4)). This speed variation should be limited to 10 km/h to avoid discomfort to the user:

$$SP_{(AIn)} = (SP_1 - SP_2) \tag{4}$$

- Analogously, along the ongoing clothoids, the speed should instead increase, which means that the user has perceived the exit from the curve and adjusts the speed for the next straight section. Also, in this case, the speed variation should be limited to 10 km/h to avoid disturbing the user; then, an analogous index, named SP_{AOut} , is proposed, considering the speed difference between the initial (3) and final points (4) of this transition curve (Equation (5)):

$$SP_{(AOut)} = (SP_4 - SP_3) \tag{5}$$

- Finally, for the circular section, an index named SP_R is proposed. It is equal to the ratio between the mean of the SP absolute values along the circular section and the maximum of the absolute values (Equation (6)). The ideal value of this indicator should be close to one, evidencing potential uniform motion conditions:

$$SP_R = AVE |SP_R| / MAX |SP_R| \tag{6}$$

As for AccX, in the results, the value of the maximum speed measured the circular curve ($MAX SP_{(R)}$) is also reported.

A summary flow chart of the proposed indexes with their respective validity ranges is provided in Figure 5.

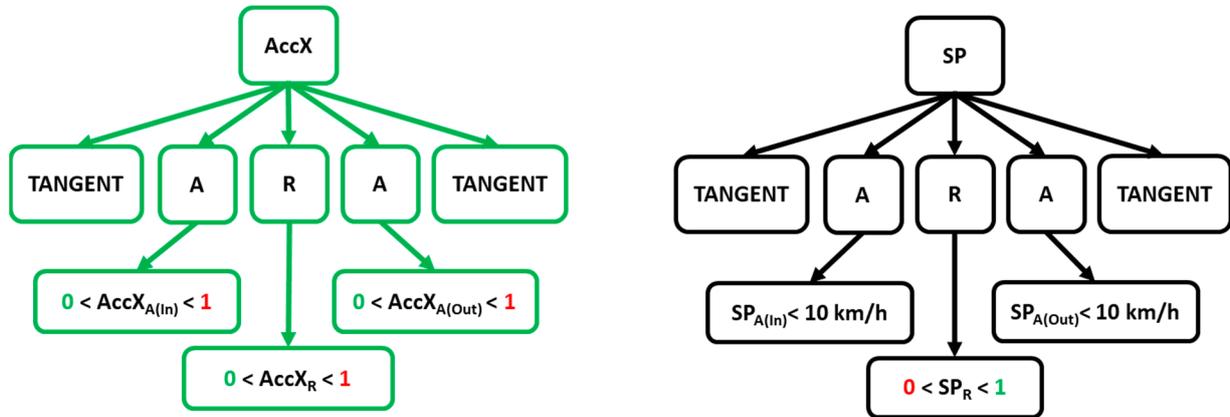


Figure 5. Simplified diagrams showing the detected variable (longitudinal acceleration or speed), the geometric elements on which the indexes are calculated, and their domain of existence. The number in green indicates the best end of the range. The red one, the extreme to avoid.

3. Results

As previously stated, this paper analyzed two vehicle dynamics performance parameters, i.e., AccX and SP, considering the values derived from a simulated driving test using a reference user on four curves of the road. The choice of a single driver, for this preliminary phase concerning the index methodological characterization, was deliberate to ensure uniform performance across all the curves, to correlate any difference to the geometric characteristics of the curves only. Specifically, the four curves (from C1 to C4) vary in terms of R and travel direction:

- (C1) $R_c = 60$ m and right direction.
- (C2) $R_c = 60$ m and left direction.
- (C3) $R_c = 100$ m and right direction.
- (C4) $R_c = 100$ m and left direction.

The graphs of the functions measured during the simulated driving test are, respectively, depicted in Figure 6 (AccX) and Figure 7 (SP), while the results of the various indicators previously defined are presented in Table 2.

Table 2. Numerical values of the longitudinal acceleration and speed indicators with reference to the functions shown in Figures 6 and 7 and calculated in the elements of interest (see Figure 5).

INDEXES		C1	C2	C3	C4
AccX [m/s ²]	MAX AccX _(R)	0.46	0.80	0.33	0.12
	MAX AccX _(Curve)	0.57	0.80	0.37	0.35
	Acc X _{(A)In}	0.38	0.07	0.29	0.14
	Acc X _{(A)Out}	0.60	0.49	0.35	0.16
	Acc X _(R)	0.18	0.72	0.32	0.05
SP [km/h]	MAX SP _(R)	70.94	76.99	75.95	78.36
	SP _{(A)In}	−2.24	0.06	−2.64	1.13
	SP _{(A)Out}	3.02	−2.12	2.89	1.31
	SP _(R)	1.00	0.98	0.98	1.00

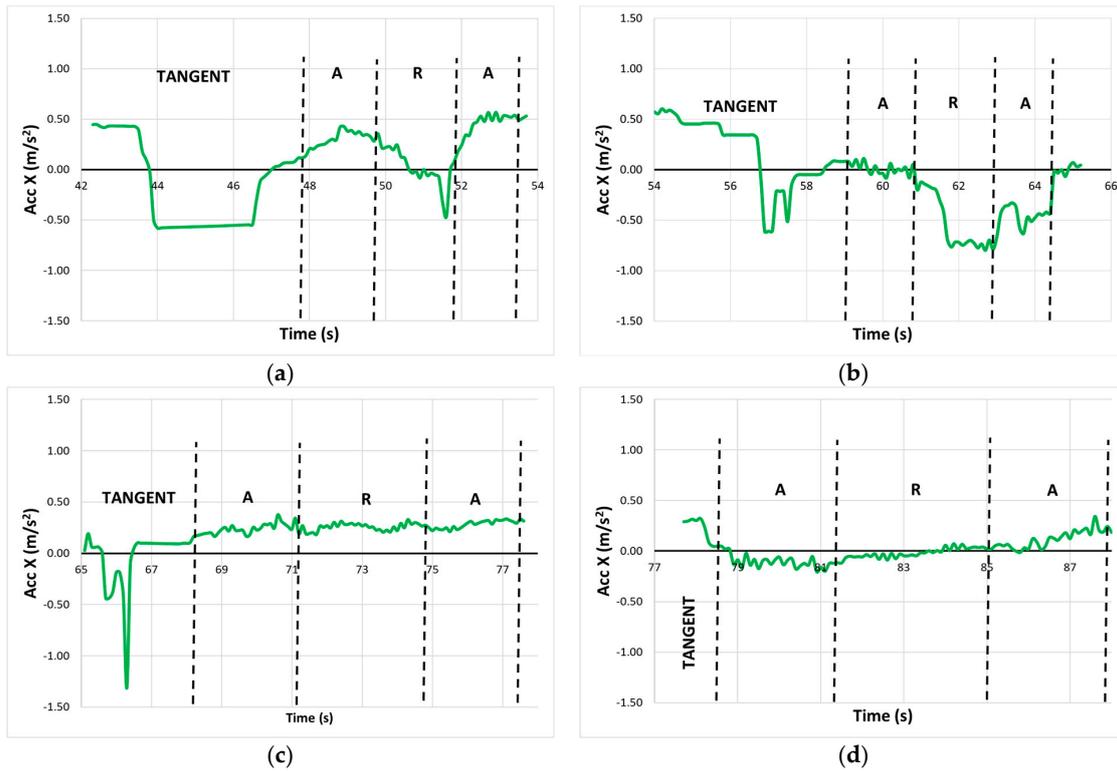


Figure 6. Real trend of longitudinal acceleration when the vehicle follows a generic trajectory within the lane in correspondence with the various geometric elements of the road (tangent, transition curves A, circular arc R) on C1 (a), C2 (b), C3 (c), and C4 (d). The dash lines indicate the starting and ending points of these geometric elements.

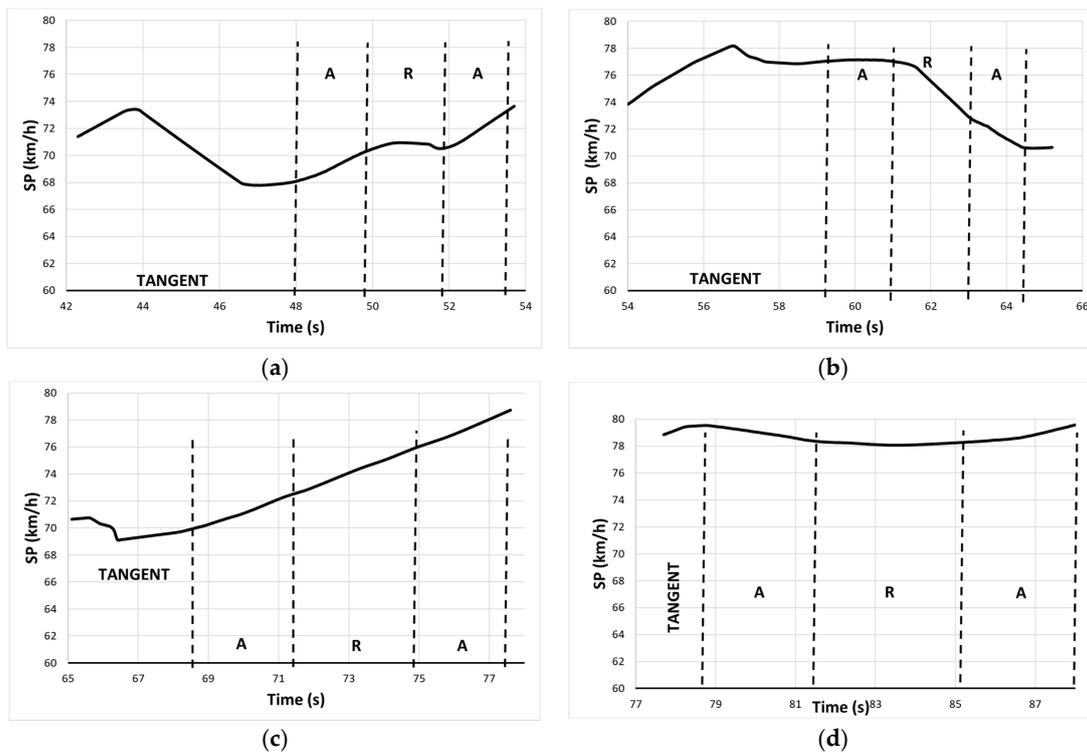


Figure 7. Real trend of the speed along a curve in correspondence with the various geometric elements of the road (tangent, transition curves A, circular arc R) on C1 (a), C2 (b), C3 (c), and C4 (d). The dash lines indicate the starting and ending points of these geometric elements.

4. Discussion

The purpose of this study is to suggest synthetic indexes related to the vehicle dynamics that can represent the driver's performance on a specific road segment.

The simulator (Sim-Easy by AVSimulation) used in this study has very basic hardware technology but excellent software capable of representing every aspect of the driving context in detail.

The correspondence in terms of the results between the simulated and real environment has long been debated inside the scientific community but, in the case of this study, it does not matter. The telemetry data obtained from the trial of the simulated vehicle were used to define new indicators, useful for understanding the maneuver. These data can also be provided from real vehicles too and the indicators will continue to have their physical meaning.

This study focused on four curves driven by a single driver since the primary objective was to propose such performance indicators rather than verify universally valid behavior. Furthermore, including a larger number of drivers in the study would have made it challenging to present the data and comprehend the outcomes.

4.1. Longitudinal Acceleration ($AccX$)

The value that characterizes all the four curves is below 1 m/s^2 , respectively, equal to 0.57, 0.80, 0.37, and 0.35 m/s^2 .

The three indicators calculate the ratio between the average $AccX$ within the incoming and outgoing clothoid sections, and within the circular arc section, respectively, and the maximum acceleration limit set by the Italian standards. The related values reveal a longitudinal acceleration close to 0 only in the ingoing clothoids of C2 (Figure 6b) and higher values, ranging from 0.14 to 0.7, in the other cases. In the circular arc, relatively low values are obtained for C1 and C3 (equal to 0.18 and 0.32, Figure 6a,c), close to zero in C4, and higher in the second curve (Figure 7b, $AccX_{(R)} = 0.72$). Even if the ideal value within the circular arc should be zero, the measured values are always exiguous and, therefore, sufficiently acceptable.

For C3 (Figure 6c), the indicators have very similar values, indicating that the function is sufficiently constant, thus satisfying the hypothesis of uniformly accelerated motion. Regarding $AccX$, calculating the maximum value is still of fundamental importance as it serves as an alert: if its value exceeds certain thresholds (for example, 2 m/s^2), the trend of the $AccX$ function should be further investigated. Conversely, if the absolute values are low, there is no need to investigate the user's behavior while traveling that specific curve.

Regardless of the numerical values of the indexes, it is possible to highlight a different behavior between the first two curves ($R = 60 \text{ m}$) and the other two ($R = 100 \text{ m}$). It should be remembered that the tangent between the first two curves is 106 m long, while that between the others ($R = 100 \text{ m}$) is 61 m long (Figure 2). In the first two curves, the driver can achieve greater acceleration but then he has the constraint of a curve whose radius is quite small. In the second case ($R = 100 \text{ m}$), the straight is considerably shorter and does not allow him to accelerate as in the first case. Moreover, the greater radius (100 m) compared to 60 m does not force the user to slow down excessively. The result of this different driving strategy can be appreciated by examining Figure 7: in the first two curves, $AccX$ is quite irregular, while in the last two, it is smoother. However, the absolute acceleration values remain very limited and within the allowable range for users' safety.

4.2. Speed (SP)

The first two indexes related to SP aim to highlight speed differences on the clothoids, and in this case, the sign is extremely important, given that acceleration is expected along the ingoing clothoids, while deceleration is expected along the outgoing ones. Beyond the limit values, therefore, a positive sign indicates that the motion is in compliance with the road geometry, while a negative value indicates a situation contrary to what was expected.

The last proposed index, $SP_{(R)}$, should ascertain the constancy of the function trend on the circular arc.

In the examined case, negative values are obtained for the ingoing clothoids in C1 (Figure 7a), the outgoing clothoids in C2 (Figure 7b), and the ingoing clothoids in C3 (Figure 7c). However, the speed differences are extremely small (between -2.12 and -2.64 km/h) and well below the values suggested by the regulations ($10 \div 15$ km/h). At this purpose, the Italian standard for road design [40] specifies two distinct cases:

- (1) If the maximum speed is greater than or equal to 100 km/h, the design speed difference must not exceed 10 km/h, otherwise it is advisable not to exceed 15 km/h.
- (2) If the maximum speed is less than 100 km/h, the design speed difference must not exceed 5 km/h, otherwise it is advisable not to exceed 10 km/h.

The case in question is that relating to point (1) but the maximum design speed of the road is never reached. Therefore, the speed difference between two successive bends should be less than 15 km/h.

The last indicator related to the circular arc presents values very close to one, which would suggest an optimal and essentially constant trend. This occurs for C1 and C4 (Figure 7a,d) but not for the other two curves, where a linear trend is found (Figure 7b,c).

However, the speed variation at the ends of this linear segment is minimal, indicating a positive outcome. Furthermore, it is observed that the maximum speed recorded in the analysis of the four curves remains nearly constant, ranging from 70 to 78 km/h. This suggests that the curve radius, whether it is 60 m or 100 m, does not significantly affect this performance parameter.

In the case of SP , the comments are analogous to the case of the $AccX$ variable. In this instance, the different behavior can be seen especially with regard to curves 1 and 4, the first characterized by a certain speed variability, while the last by a substantially uniform motion (Figure 7).

As already mentioned previously, the numerical comparison with the state of the art is not simple, as scientific production has proposed indicators which, in the opinion of the authors, present two critical issues: the first is that the performance variable analyzed is not linked to the geometrical characteristics of the road and, therefore, does not help to interpret the physical phenomenon. The second is that the data collected by the sensors of a great number of vehicles could constitute an unsustainable burden for any maintenance control center after a very short time. The data must be sampled intelligently, extracting only those strictly necessary that provide useful information for understanding the phenomenon and discarding all the others. From this point of view, this study surpasses the existing ones with respect to this problem.

The value assumed by the acceleration indicators $AccX(A)In$, $AccX(A)Out$, and $AccX(R)$ allows for making a double consideration: by virtue of the presence of a standard value in the denominator, it represents the deviation from the threshold we have introduced. In the case of this study, the indicators are all less than 1, a sign that the driving behavior is very virtuous (the maximum value reached by $AccX(R)$ on curve 2 is 0.72, while on curve 4, it is equal to 0.05). However, a certain difference should be noted in the indicators of the first two curves ($R = 60$ m) compared to the other two ($R = 100$ m). In curves 3 and 4, in fact, the maximum indicator is $AccX(A)Out$ on curve 3 (0.35), while in all other cases, the value is lower. This means that the aforementioned indicators also allow a judgment to be made on the consistency of the route, at least in terms of longitudinal accelerations.

In terms of speed, the differences between the two pairs of curves ($R = 60$ and $R = 100$) are less perceptible, given that they are essentially traveled at the same speed (between 71 and 78 km/h). The curve radius, therefore, has a modest effect in terms of the speed on driving behavior, at least within certain limits. The speed differences are always very limited (at most, 3 km/h), meaning completely safe travel. In conditions of great inconsistency of the road geometry, these indicators would take on very relevant values and should alert the control center as soon as possible.

5. Conclusions

The current study addresses the need to create appropriate indexes that can synthesize complex functions associated with vehicle dynamics. Typically, these are summarized using mean and standard deviation values only, which, in some circumstances, are not sufficiently representative of the observed phenomenon.

We believe that the large amount of raw data produced by modern tools need to be significantly reduced in order to be used effectively at a higher level of management. The objective of this study, therefore, is to filter such data in an intelligent way, without losing important information but, on the contrary, interpreting the phenomenon investigated to add further knowledge for the benefit of subsequent users.

It is, therefore, necessary to calibrate specific indicators that can represent in detail the driving strategies of the user's respect for the main geometric elements of a road (curves, straights). It is also essential that these indicators could highlight drivers' incorrect behavior, for example, by making reference to the values prescribed or recommended by international standards.

It should be emphasized that the purpose of this paper, in this phase of the research, is to propose some user performance indexes, illustrating in depth the methods of quantification. Only after these have been recognized as valid by the scientific community can they be applied to specific cases, where a certain road context (real or simulated) will have to be traveled by a suitable sample of users. In this phase, it will be possible to propose general laws capable of contributing to the improvement in road safety in that specific case.

In particular, the indexes, regarding some performance variables (longitudinal acceleration and speed), have been tested to verify their effectiveness in a simulated context considering four curves and only one user.

The quantification of the indexes is crucial as it enables the results to be used for further analyses (like the statistical ones) that require single numerical values instead of functions.

In this regard, there is another aspect that needs to be highlighted. The proposed indicators can be easily verified by also carefully evaluating the trend of the AccX and SP functions. This check can be performed only in this case, because only four curves and a single driver were examined. For large-scale experimentations, this type of verification is much more complicated or impractical. It is more convenient, then, that the index quantification is understood and validated in a preliminary phase of the research, before the effective experimentation.

The future steps of this research can be summarized as follows:

- Compare the results obtained using mean and standard deviation values.
- Formulate a comprehensive synthetic indicator for each performance metric.
- Implement the indicators on data collected from experienced drivers to identify any disparities.
- Investigate whether deviations from the ideal trend are exclusively linked to the geometric attributes of the curves.

This study was carried out in Italy and, therefore, some principles that led to the formulation of the indexes were based on Italian road standards. However, the Italian one is characterized by having a substantial similarity with all international road regulations, especially the American "Green Book" from which it is inspired. Furthermore, the applied formulas refer to well-known physical phenomena (longitudinal and transversal acceleration, steering, etc.) of general validity. Therefore, the proposed indexes can be applied to any international context.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, all authors have participated in the same measure. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been partially funded by the European Union (NextGeneration EU), through the MUR-PNRR project SAMOTHRACE (ECS00000022).

Institutional Review Board Statement: Not applicable for studies where the impact on humans is substantially absent.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Some of the data used in this study may be available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

Glossary

Symbol	Geometric characteristics of the road
Rc	Curve radius
α	Central angle of the circular angle
L	Total length of the geometric element
N	Transition curve shape parameter
A	Transition curve scale parameter
TANGENT	Straight section before or after a curve
A	Ingoing and outgoing transition curves
R	Circular arc of the curve
C1	Right curve with 60 m radius
C2	Left curve with 60 m radius
C3	Right curve with 100 m radius
C4	Left curve with 100 m radius
	Performance Indexes
AccX	Longitudinal acceleration
MAX	Maximum value
AVE	Average value
MAX AccX _(R)	Maximum value of the longitudinal acceleration indicator for the circular arc
MAX AccX _(Curve)	Maximum value of the longitudinal acceleration indicator for the curve
AccX _{A(In)}	Longitudinal acceleration indicator for ingoing transition curves
AccX _{A(Out)}	Longitudinal acceleration indicator for outgoing transition curves
AccStd	Typical ideal value of acceleration reported on the Italian standard (0.8 m/s ²)
AccX _R	Longitudinal acceleration indicator for the circular arcs
SP	Speed
MAX SP _(R)	Maximum speed measured the circular curve
SP _(AIn)	Speed difference between the initial (1) and final points (2) of the ingoing transition curves
SP _(AOut)	Speed difference between the initial (1) and final points (2) of the outgoing transition curves
SP _R	Average of SP absolute values along the circular section

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