SDS - DRIVING TESTS ON THE NEW SAPIENZA DRIVING SIMULATOR

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ABSTRACT

The drivers' behavior observation, in real context, generally introduces many operational difficulties related to safety problems, because of the necessity to take no actions on the traffic circulation. The complex installation of monitoring equipment encourages the use of alternative techniques such as virtual reality tests.
Also in the Sapienza University of Rome a driving simulator, named *SDS* (Sapienza Driving Simulator), is realized and used for this study. It allowed to reconstruct three-dimensional driving scenarios, starting from a geometric discrete model of the road, by means of a utility interface that allows the conversion of geometric data set with a specific algorithm. The discrete input, based on a sequence of three-dimensional points, allows to create the road models, independently from the nature of geometric elements that constitute the layout (real or designed road sections).
In the experimental phase, the tests are conducted on a sample of people composed 35 participants. Each participant drove on three virtual road layouts, generated in accordance to Italian standard, which also contain some design faults in order to analyze the behavioral participants' response to these defects. As an example, the trajectories of sample on tangent-curve junctions realized without spiral curve were analyzed through these tests. Also the speed profile was obtained: it allows to evaluate the continuous speed increase on tangents and wide radius curves that have a long extension. At last, it was analyzed the influences of vertical signs on drivers speed by studying effects of some road signals position (especially located in stretches of road having different geometrical characteristics).

Keywords: Driving simulators, Human factors, Road geometric layouts.

INTRODUCTION

The driving simulation techniques are used both for research purposes and to solve technical and application problems. In fact, in real context, the drivers' behavior observation introduces many operational difficulties related to safety problems, because of the necessity to take no actions on traffic circulation. The complex installation of monitoring equipment encourages the use of alternative techniques, making virtual reality tests a valuable alternative. Therefore, many international research centers are currently involved in this studies and the number of papers concerning this topic expresses the growing activities of International Scientific Committees.

Simulation Techniques

From a formal point of view, the *simulation* is defined as the virtual interactive representation of an environment and of all phenomena that occur in it. The definition of virtual environment is realized by means of computational models that formalize laws that rule simulated reality; the solution and the management of these computational models are generally done by computer systems. It is necessary to create the conditions as much as possible similar to real ones to realize the simulation models in relation to different perceptive abilities of generic user. The simulation systems designed to implement an interaction between a human subject and a virtual environment requires two different levels of emulation: the first one concerns the simulation of environment with which the test subject will interact and a second level concerns the interface that a person will use to interact with environment around him. For the latter it is sufficient to reproduce the real instruments and command interface required to interact with the simulation: these are objectively defined and remain unchanged during the entire experience. Instead, it is not so direct and easy the virtual representation of real environment that requires calculation and continuous playback of precise and interactive sensorial stimulations. The quantitative consistency and effectiveness of transposition are crucial to ensure the realistic representation and the effectiveness of the results. In fact, the changing patterns act directly on user's perception determining his sensorial and cognitive involvement in simulation.

Road Context Application

The international research on the simulation techniques is focalized on very heterogeneous development issues regarding different scientific themes. These studies concern problems of visibility on highway, Rosenthal et al. (2004), or in underground tunnels (Hirata et al., 2005; Hirata et al., 2006), in normal driving conditions or on passing conditions, Benedetto et al. (2004). Also Traffic congestion and problems of perception and visibility in areas of work are studied (Bella, 2005; Mitchell et al., 2005), as the reconstruction of trajectory in deceleration and exit lanes, Bella et al. (2007), and the consequences of use of mobile phones while driving, Muttart et al. (2005). These studies are aimed to evaluate driver behavior, or his driving skills, in relation to driving experience, Pradhan et al. (2006), age, Fisher et al. (2007), type of lighting, Garay-Vega et al. (2007), and even in case of use of drug or alcohol, Lamers et al. 2006. The observation of the influence of geometric characteristics of the track on the user's behavior remains the most diffuse theme of study, given the relevance of this correlation.
The purpose of experimental techniques that use driving simulators can be related, therefore, to different research activity:

- changes of driver behavior induced by experimental design choices;
- suitability of design constraints, or standard indications, to induce specific behaviors on drivers;
- choice among different alternatives to obtain similar safety conditions;
- training to inexperienced drivers;
- rehabilitation of drivers after violating traffic rules when driving is forbidden.

The driving simulation technique is not only an useful and innovative research tool, but it has various direct application purposes both in road engineering context as in management-regulation of transportation modes too.

In particular, in infrastructure design, one of major shortcomings in theory and design standards is a limited consideration of users-road-vehicle-environment interaction phenomena. By means of an accurate reproduction of these factors in virtual reality, it is possible to examine previously the effectiveness of different design solutions for new road infrastructures (or modifications to existing roads) and determine a predictive global quality level achievable, especially in terms of safety.

Requirement, Advantages And Limits

The user's sense involvement is very tricky, because it is mainly generated by an indirect way: visual, sound, tactile and spatial reproductions played by simulator generate indirectly the perceptions of users by means of these stimuli. In particular, the visual projection of virtual environment requires a high level of detail and the represented frames should be sufficiently fluid, played with a refresh rate greater than the frequency of human eye perception. Therefore, the video refresh rate must be at least 30Hz, because the time of images permanence on the retina is about 1/10 of second: in this way the eyes perceive a continuous sequence of images. The distance between user's eyes and visual framework must be established according to perspective parameters used in representation, in order to respect the sizes and the shape of reproduced objects. The sound reproduction also requires the presence of environmental sounds, in addition to sound effects detail related to vehicle (engine, gearbox, rolling tires). These additional sounds come from external sources, like other vehicles, road pavement irregularity or sound effects caused by presence of artifacts that modify the propagation conditions of sound waves (bridges, tunnels, and noise barriers), van der Horst and deRidder (2007). Also the spatial position of reproduced sound origin is important and it can be achieved by properly placing the speakers and using techniques for stereo playback.

The biggest advantage of virtual experiments, compared with real surveys, is the opportunity to conduct tests under the complete control of the analyst, in conditions of absolute safety and repeatability. Each test parameter is adjustable according to specific needs to achieve identical simulation conditions for each user and for each context. However, in order to investigate absolute reliability of the performance and achievable results, it is necessary to perform a rigorous validation process. It is possible to investigate the reliability of obtained results from direct comparison of data observed in real experiments and those obtained by simulation tests. Both tests must be conducted with samples of drivers having the same characteristics and same statistical representativeness. If an *absolute* validation process of the simulator is not possible, the significance of the experiment results is not generalizable because a not monitorable aleatorily is implicit in tests: it is due to uncertainty about the correct interpretation by users of simulation conditions. However, in these cases, an interpretation of test data allows to evaluate

the sample choices in a *relative* way, that means a relative comparison of the behavioral changes related to a limited number of input parameters variations.
Therefore, the comparison in users' behavior changes in relation to different geometric designs allows to consider the user's response only in a qualitative way, not quantitative, Törnros (1998).

SDS SIMULATOR

Hardware Features

The *SDS simulator* developed at DICEA - Department of Civil, Construction and Environment Engineering of *Sapienza* University of Rome is composed by five distinct subsystems:
- Driving Device (*DD*) that includes all the driving controls;
- Simulation software;
- Central Calculation Unit (*CCU*) with an Analog/Digital - Digital/Analog interface (*ADDA*);
- Video projection on frontal screen;
- Sound system.

All these subsystems are placed into an isolated room which hosts the driving tests, Figure 6.
The *CCU*, by means of the simulation software, provides solution of the equations of motion and graphic elaborations of scenarios proposed during simulation tests and it is connected to Driving Device via the *ADDA* interface Advantech PCL-1710. The *DD* repeats the driving controls of an Alfa Romeo car with steering wheel, pedals and a sequential gearbox, Figure 1. To increase user involvement also the driver seat derives by the same real car.

Figure 1 SDS driver's seat and driving controls

The acquisition device PCL-1710 converts the positions of the driving controls from analog to digital signal. This information is then analyzed by simulation software and recorded in telemetry file as an additional data.

Software Features

The simulation software is designed by the company *Vi.R.A.* (Virtual Reality Arts). Startup and development of software were supported by different PhD students who, consecutively, cooperated for the definition of input formats and in other development phases. The software consists of three modules that perform the different phases of tests:
- *EdiTech*, the 3D Editor used to configure the road environment and to displace vertical signal;
- *DriveTech*, the driving simulator software;
- *TeleTech*, the telemetry analyzer of simulation tests results.

The editor allows to insert the data of modeled layout by an ordered collection of coordinates *x, y, z* related to 12 distinctive points of cross section of the road, necessary to geometrize the model of road structure in a generic section, see Figure 2.
These points identify the limit of the distinctive elements of the road (lanes, shoulders, widening, median strip, barriers, trench faces, etc).

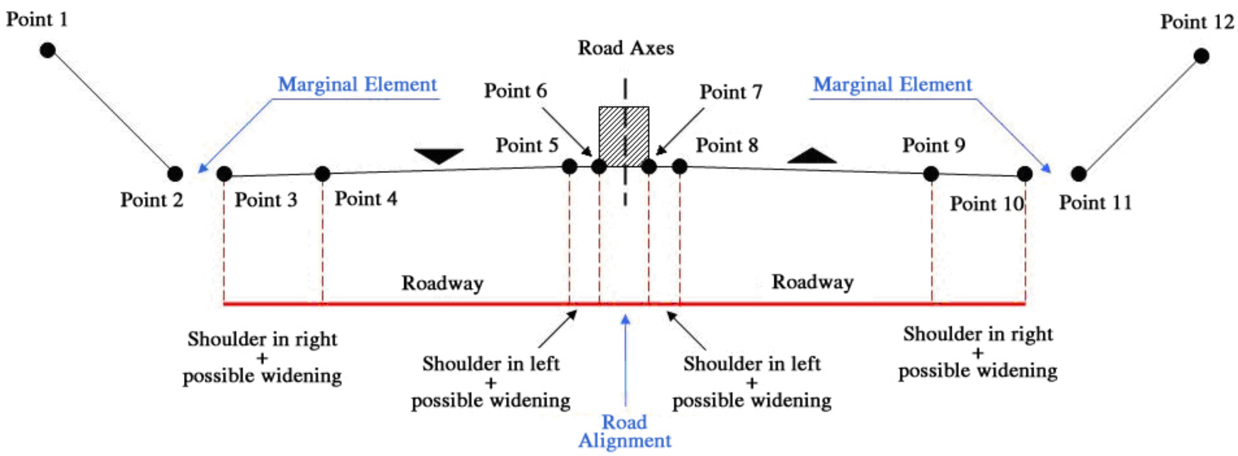

Figure 2 The twelve points that define cross section of the road model

The input coordinates are organized in a worksheet with a length equal to the number of sections used for modeling the road, which in turn depends on the length of layout and of discretization step adopted to define horizontal elements. This modeling approach requires a previous design of road layout in order to achieve coordinates of points to insert in *EdiTech*. This computational burden, that does not allow an immediate input of a new layout, has the essential advantage of its flexibility respect to the nature input data. In fact, the modeling of road layouts is independent from typical restrictions due to the formalization of geometric elements, but it can be derived from all formats of design drawings and also from surveys on existing road segments. Through the elaboration of *EdiTech* it's possible to see the layout in three-dimensions in order to get a preview of simulation environment and to provide signals, barriers and other marginal elements, as can be seen in Figure 3.
The road layouts designed for this research have been modeled by means of software *DITS*, Cantisani and Di Vito (2010), through geometric elements according to the Italian Standard: tangents, arcs and clothoids. The layout, complete in all details, is converted to *DriveTech* input format. *DriveTech* is the most important sub-system: it provides the solution in real-time of equations of motion, the reproduction of audiovisual scenario and the interaction with driver.

Figure 3 Road reconstruction and cluster visualization

The calculation of motion equations considers technical features of virtual car such as size, suspension stiffness, anti-roll bars coefficients, gear and differential ratios, aerodynamic coefficients, braking distribution, power curves and efficiency of engine, drift angles and Pacejka scaling factors that model the dynamic response of tires.
During simulation, the information on driving conditions is included in projection, summarized in the instrument cluster, Figure 3.
At the end of simulation, *DriveTech* saves monitored test data into a telemetry binary file. In this file are recorded vehicle location (x, y, z), punctual vehicle speed, load on suspensions, revolutions per minute of engine, accelerator pedal pressure, brake pedal pressure, steering wheel position and gear in use.

Data acquisition and elaboration

The telemetry data are acquired every 0.33 seconds (3Hz) and stored in a specific output file. The scan time used for the acquisition generates automatically the data, unrelatedly to vehicle's position on layout. For each stored item data it is necessary to use the center of mass coordinates of vehicle to calculate its location on the track (longitudinal position) and to determine its position on the lane (transversal position). In fact, while the analysis of single test data does not need additional precautions, the comparison of data acquired in multiple tests requires the determination of vehicle positions to define a common spatial reference and a common section of study.
A specific algorithm, named *VPR* (*Vehicle's Position Recognizer*), is developed to transform the temporal sampling of the data in a spatial reference, in order to analyze the data in every study sections.
The *VPR* algorithm is in accordance with the following bases assumptions:
1) vehicle's center of mass is always inside the edge of carriageway;
2) vehicle's center of mass is always located inside the layout length, which is between sections that determine beginning and end of the path;
3) between two consecutive layout sections, one or more stored points may appear, and, in certain circumstances, no one.

In fact, the virtual models are realized by a discretization step that varies from a minimum of 5meters (for circular curves) to a maximum of 12meters (for tangents). At a speed of 108km/h (30m/s) the data acquisition is performed every 10meters. It is easy to observe that for lower speed it is possible to have multiple acquisition points between two consecutive sections, while for higher speed the acquisition points may be absent.
The difference of operating test speed for the sample tests (*x* and *y*) represented in Figure 4 determines very different acquisition steps: 10meters for *test x* (108km/h) and 3meters for *test y* (33km/h).

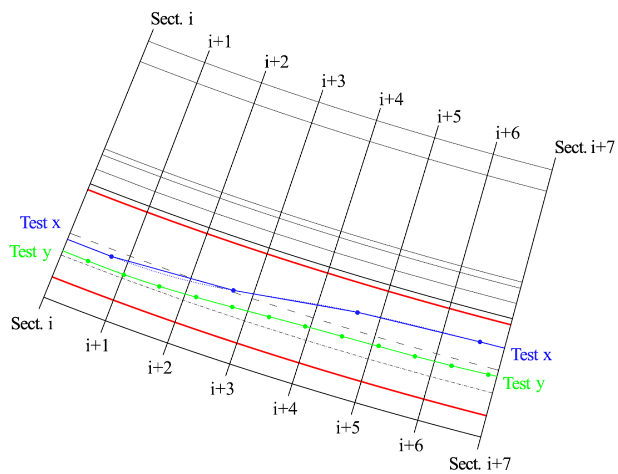

Figure 4 Example of different data acquisition steps

The determination of vehicle position is necessary because generally the trajectory does not follow the lane axis, but differs from it by a random amount. The coordinates of the vehicle's center of mass are relating to an *Absolute Reference System*; for each acquisition point the discretization sections immediately preceding and following were determined. By means of geometric considerations, all the study sections corresponding to each acquisition points and their abscissa on the alignment were so calculated. The abscissa is defined as the length of curve that defines alignment axis (or drivers' trajectory) between beginning of the path and the reference transversal section. These lengths are calculated as the sum of linear segments lengths resulting by joining the coordinates of discretization points (or of vehicle position) in each section preceding the studied sections.
The *VPR* algorithm calculates vehicle position; it is based on the following assumptions:

1) horizontal alignment between two consecutive discretization sections can be confused with the linear segment that joins the two points belonging sections and alignment, see Figure 5;
2) under the assumption 1), horizontal alignment can be considered as a broken curve, or rather a succession of linear segment (broken alignment), see Figure 5;
3) the distance ($\overline{P^I_{j,i}P_j}$ and $\overline{P^I_{j,i+1}P_j}$) between acquisition point P_j and the two nearest discretization sections *i* and *i+1* are proportional to lengths of segments identified by the transversal section related to acquisition point ($\overline{P_{a,i}P^I_j}$ and $\overline{P_{a,i+1}P^I_j}$);

4) the lengths of linear segments ($\overline{P_{a,i}P_j^I}$ and $\overline{P_{a,i+1}P_j^I}$) identified on broken alignment allow to calculate abscissa, transversal position of vehicle $\overline{P_jP_j^I}$ and transversal displacement of vehicle trajectory respect to travel lane axis;
5) the acquisition point belongs to transversal section identified by abscissa calculated on the previous hypothesis.

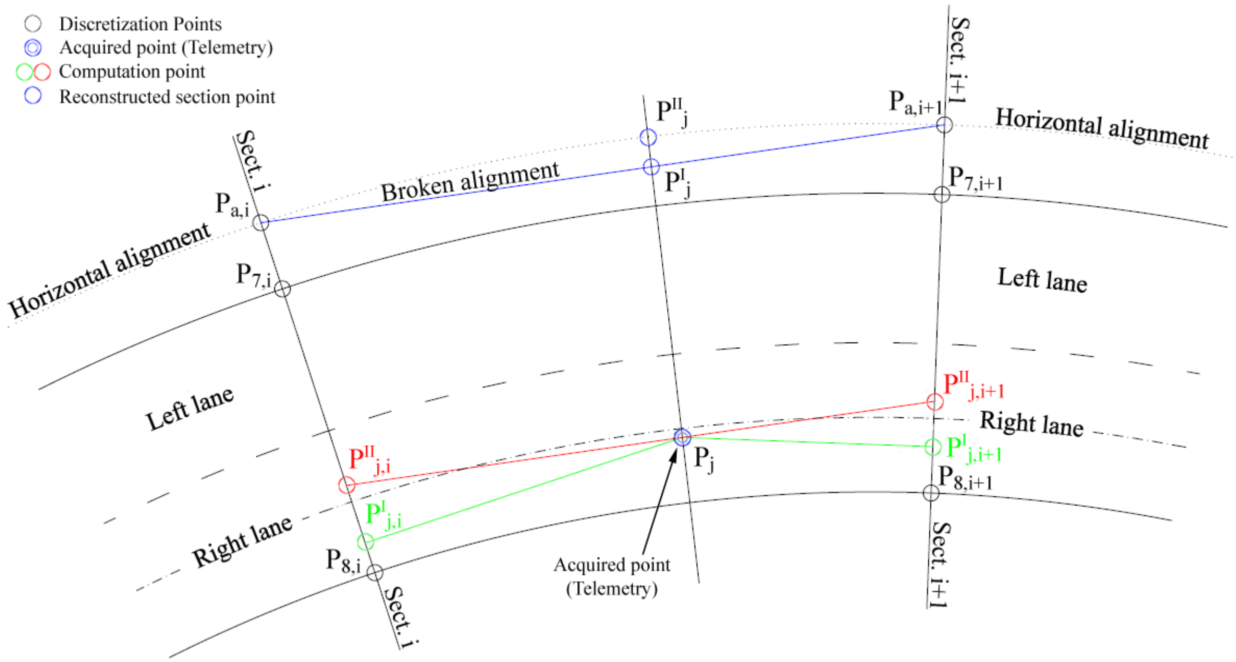

Figure 5 Section Reconstruction

The discretization step used for modeling layouts makes acceptable the first three hypotheses. In fact, the values of curve radii and the small value of discretization step make possible to confuse arc length with the length of its cord; the maximum difference resulting from this approximation is about 0.02%:

$$\frac{\overline{P_{a,i}P_{a,i+1}}}{\overset{\frown}{P_{a,i}P_{a,i+1}}} = \frac{2\cdot R\sin\left(\frac{\alpha_{\max}}{2}\right)}{R\cdot\alpha_{\max}} = \frac{2\sin\left(\frac{\alpha_{\max}}{2}\right)}{\alpha_{\max}} = 99.98\% \tag{1}$$

where the maximum value $\alpha_{\max}$ of arc central angle is:

$$\alpha_{\max} = \frac{step_{\max}}{R_{\min}} = \frac{12}{175.38} = 0.06842 rad \tag{2}$$

The abscissa of point P_j is determined by proportional relationship between the known value $P_{a,i}P_{a,i+1}$ and the calculated lengths of segments $\overline{P_{a,i}P_j^I}$ and $\overline{P_{a,i+1}P_j^I}$. The distance of vehicle from the axis of right lane is determined by calculating value and algebraic sign of the distance between the point P_j and the line passing through the points $P_{a,i}$ and $P_{a,i+1}$, obtained by the intersection between axis lane and nearest sections.

TEST CAMPAIGN

The aim of this experimental study is to observe and to evaluate the behavioral changes due to road geometry in a sample of drivers, especially related to consistency of horizontal elements of road layout. The term consistency shall mean the coherence of geometric elements to Italian standard, both in relation to specific rules as to speed diagram observation. Therefore, a first design phase of road layouts is necessary to compare drivers behavior on road stretch complying with the standard and the ones that have some design faults (with varying severity). The nature of behavioral analysis is comparative, given the absence for *SDS simulator* of an absolute validation, Törnros (1998).

Driving conditions

Driving conditions during the simulation are: isolated vehicle in daylight conditions with clean and dry pavement, which is in the best adherence. The assumption of isolated vehicle allows to observe the drivers response related to layout perception, without conditioning produced by other vehicles. For visibility conditions, is assumed absence of clouds, fog or mist. During the tests, external noise and artificial lighting are limited in order to not distract the drivers from the test execution. At the end of the test a few questions are asked to users about the sensations felt during the test and some other general information such as age, average annual distance traveled, etc. Also the attendance of game use of simulations is asked to identify possible effects due to familiarity with the virtual driving.

The visual reproduction of simulation scenario is performed on a projection screen of 1.5m×1.2m placed in front of driver, the images are projected with a resolution of 1024x768 in pixels and with a frequency variable from 30Hz to 50Hz (depending on complexity of visual picture represented).

The sound reproduction is achieved by two speakers placed in front to simulator device, without any obstacles that could limit their effectiveness. The location is chosen to obtain the best distribution of audio wave and to hide devices to user sight. Frontal position of speakers emulates sound direction of vehicle’s engine in addition to his real sound.

Sample of drivers

The survey sample submitted for testing must be sufficiently numerous and representative of the population of drivers. In particular, to observe behavior of universe of drivers on a specific layout, the sample must be as heterogeneous and numerous as possible but, if tests are aimed at behavioral changes induced by different experimental parameters, the sample must be very homogeneous in order to emphasize the differences and make them independent from the heterogeneity of sample. Obviously, the results obtained with this second approach is representative only for the driver population represented by sample and it is generally not possible to extend them to other drivers typologies by means of statistical inference techniques.

In this research, the experimental analysis is conducted on a sample composed by 35 drivers, each one having a driving license for cars and a sufficient driving experience. About 60% of participants are male and aged between 22 and 39 years, while remaining part of sample is aged between 23 and 32 years. Each user has driven on a virtual training layout of 5km long before proceeding to simulated driving on test tracks, with the aim to ensure a spontaneous response on them and to ensure familiarity with car controls and instrumentation on the screen, Yan et al. (2007). Simulation training allows to not alter the final results with behaviors not directly dependent on road characteristics. This training is performed each time the simulation tests are non-consecutive to establish an appropriate involvement in driving experience and to ensure an effective spontaneity of responses. An example of tests on three-dimensional scenario is represented in Figure 6.

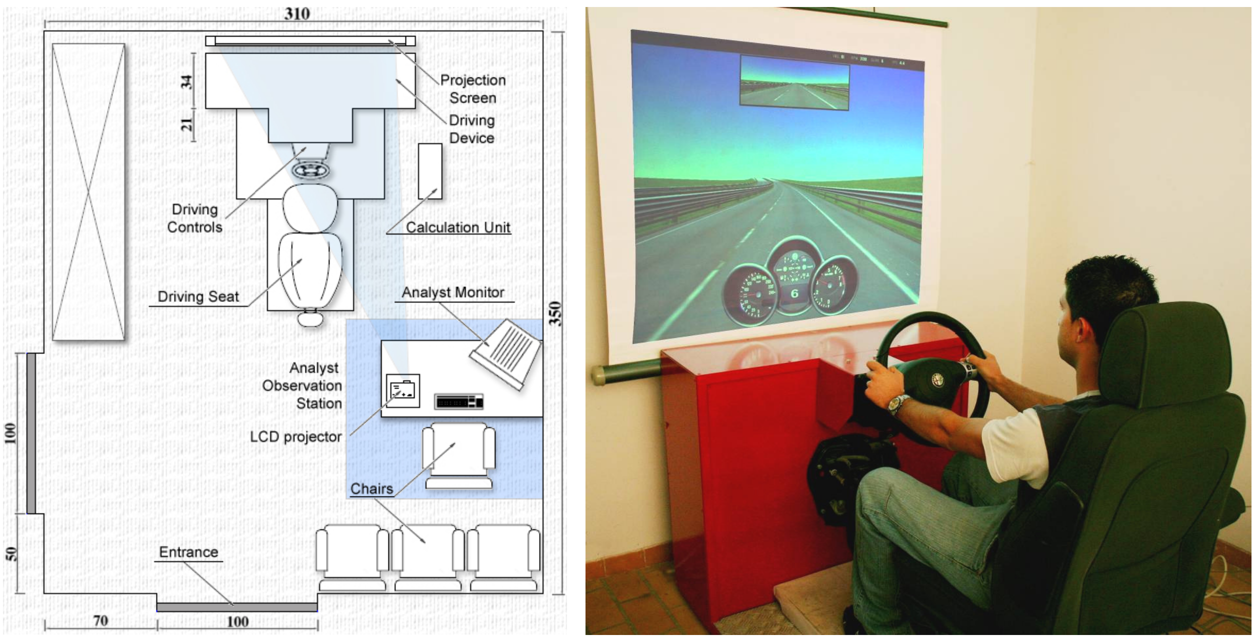

Figure 6 Simulation tests condition

Test Road Tracks

The design of road layout used for simulation tests are developed with original software *DITS*, Cantisani and Di Vito (2010). The coordinates of the 12-points needed to model virtual environment are extracted from road alignments defined by conventional elements. The original utility, developed during the research, allows to verify the road alignment and to evaluate its compliance with Italian standard: this phase is necessary to introduce localized faults on horizontal or vertical layouts. By means of a three-dimensional perspective view it is preemptively evaluable the final configuration of layout.

The discretization step is related to visual performance of simulated environments. In fact, excessively small discretization steps involving a sequence of points so thick that unnecessarily burdens calculation phases without making significant improvements to tests realism. Instead, bigger discretization steps create inaccurate visual effects, especially on lateral objects disposed on high curvature elements (such as barriers) or creating cusps on road surface marking representation.

The tests are performed on three road layouts, named *A*, *B* and *C*, similar to highway typology. Each layout has two lanes of 3.75m wide per carriageway with shoulder of 1.75m on right and of

0.50m on left. The lengths of layouts are 11.0km, 12.3km and 12.4km respectively. In each of these alignments several design faults are introduced, concerning the correct dimensional consistency between consecutive geometric elements. These imperfections cause additional faults, especially regarding the speed diagram trend. Moreover, some clothoid junctions have been omitted in order to observe the spontaneous adaptation of driver's trajectories. The three horizontal alignments are represented in Figure 14 and their geometric characteristics are listed in Table 1.

Acquired Data and Derived Data

Only a few parameters acquired by means of experimental surveys are directly used to achieve purposes of these early tests, while others are used only to understand some test results having a special complexity. Vehicle position, speed and steering wheel position are the observed data directly used in the post processing phase. From these parameters are also derived the following variables:

- Traveled distance;
- Current acceleration;
- Transversal position;
- Local curvature of trajectory;
- Normalized speed (referred to values hereinafter indicated).

The determination of derived quantities requires the definition of two distinct kind of curvilinear abscissas: the first one, *layout abscissa* $\boldsymbol{a_L}$, related to layout design and the second, *trajectory abscissa* $\boldsymbol{a_T}$, related to the vehicle trajectory, different for each simulation test. In fact, for a same road section, the traveled distance by different drivers is not the same and it also differs from the layout abscissa of the reference section, $\boldsymbol{a_L}$ value. The calculus of local acceleration and curvature values is performed by numerical methods that integrate the traveled distance and calculate the first and the second derivatives which appear in the curvature formula.

$$\rho_i = \frac{1}{R_i} = \frac{y''_i}{\left[1+(y'_i)^2\right]^{3/2}} \tag{3}$$

where:

ρ_i: local curvature
R_i: local Radius of curvature
y'_i: first derivative of vehicle trajectory in acquired point *i*
y''_i: second derivative of vehicle trajectory in acquired point *i*

This method needs $\boldsymbol{a_T}$ values for computation, but the obtained results must be related to the layout abscissa $\boldsymbol{a_L}$: in this way, it is possible to make comparisons among the data obtained in different tests.

The obtained trends are very realistic and comparable with the curvature trend of an “ideal” trajectory (that is the trajectory along the longitudinal axis of the road design) although the curvature determined by the indicated formula (3) was very approximate.

The performance of each driver is analyzed through both the recorded data and the normalized value of these variables, in particular for the speed. The normalization values are:

- average speed of a single test over the entire layout;
- maximum speed of a single test over the entire layout;
- average speed of a single test on a stretch of layout;
- maximum of a single test on a stretch of layout.

The speed analysis, performed on normalized values, can mitigate the specific driving skills of each driver and provides an additional framework to compare test results.

It is necessary to determine the factors in a spatial reference system (not in the time one) to correctly achieve the normalization. In fact, the determination of average speed cannot be directly achieved from the recorded values, because they must be weighted on the traveled lengths: as represented in Figure 7, the average value cannot be determined only considering values numerousness, but it is necessary a weighting process: otherwise the obtained average values could be lower than the real ones.

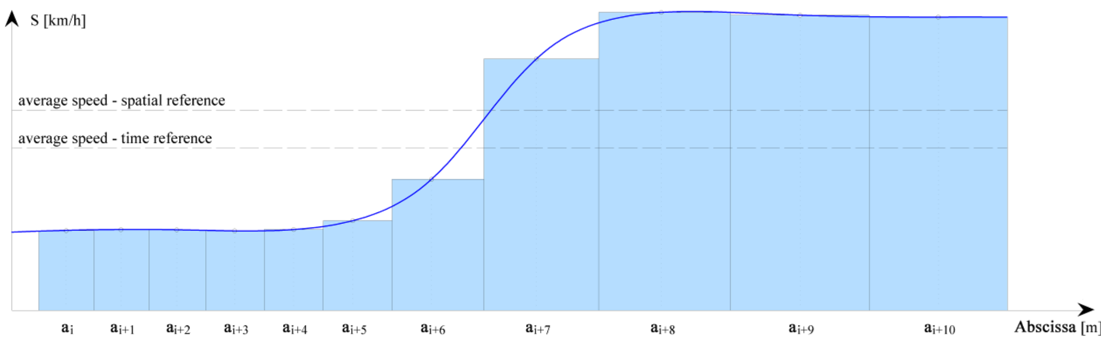

Figure 7 Weighted average of speed

Therefore, average speed values are calculated by means of a weighted average and weights are the extensions of stretches in which the speed value can be considered constant:

$$\overline{S} = \frac{1}{\sum_{i=1}^{N-1} a_{T,i}} \cdot \sum_{i=1}^{N-1} \left[\frac{(S_i + S_{i+1})}{2} \cdot (a_{T,i+1} - a_{T,i}) \right] \tag{4}$$

where:

$\overline{S}$: Average speed

S_i: Acquired speed in point *i*

a_{Ti}: Traveled distance in point *i* (abscissa)

The normalization of speed based on the maximum value is less effective and less reliable than the normalization on the average speed value because the maximum speed may be reached even once time during a test. In this case the normalization process could distort the trend by cause of an over-reduction of normalized speed values.

Abnormal changes of driving parameters due to vehicle impact on safety barriers or other events have caused, in some cases, the suspension or the end of the test. These events have led to the exclusion of acquired data from subsequent processing and final interpretations.

The average speed and the 85th percentile of speed were calculated during each study section: these values allow two kinds of comparisons on speed profiles. In particular, the 85th percentile values and speed dispersion on each section provide the statistical values conventionally used in studies on drivers' speed, because the 85th percentile is related to operating speed.

Results Discussion

The results were analyzed both comparing the data coming from all drivers and considering only two statistical parameters (average and variance or 85th percentile and variance); in fact, it is generally not exhaustive to analyze only the statistical parameters instead of an entire set of data. Some considerations about the different performed analysis are summarized below.

Speed

As previously explained, for each road section the average and the operating speeds were calculated for the considered sample of drivers. The tests results are summarized using some speed profiles that correlate the speed trend with the curvature of layout and with the *Italian Speed Diagram* (*ISD*), Italian standard (2001), as showed in Figure 8. The comparisons show an important similarity between the trend of average speeds $\overline{S}$, the operating speeds (S_{85}) and the *ISD*, for the studied road layouts. In all graphs below is omitted the representation of the first 1000m. In fact, in this stretch is enclosed the transitional phase of vehicle speed between the departure from standing start conditions and the achievement of normal driving speed.

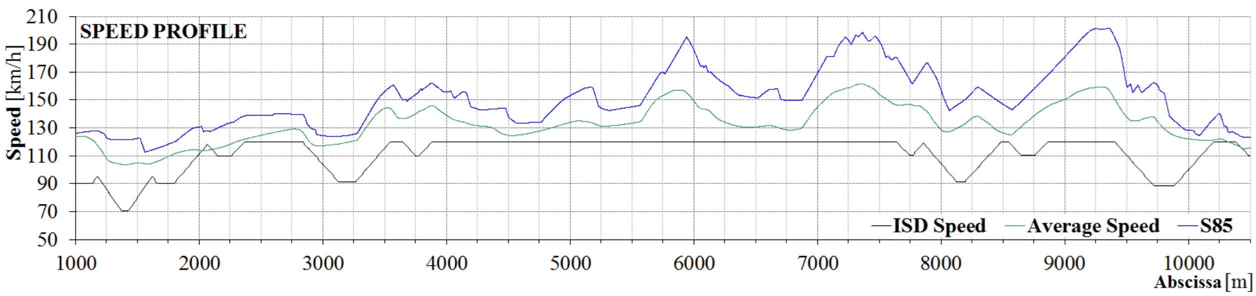

Figure 8 Speed trends comparison

The quantitative differences between different speed values are imputable to the absence of an absolute validation of SDS and consequently to the comparative nature of the experimentation. However, the concordance of speed profiles, particularly on clothoid, respect to *ISD* construction rules (based on behavioral considerations) made it possible to assert that drivers behavior showed the expected trend. The large quantitative differences and high peak values present in speed profiles depend on the absence of a refinement phase of represented scenarios. The speed limitation on tangents, included in *ISD* model, amplifies the different in trends.

The comparison of the normalized speeds shows various behavioral peculiarities: in the highlighted boxes of Figure 9 some of these behaviors are displayed. In the *Box A* two stretches of road with the same geometric characteristics are shown. These stretches are not affected by any design fault and the distance between them is about 2km. Despite the similar geometric characteristics of elements that define the highlighted stretches, the speeds on these stretches are not equal because of different nature of geometric elements preceding them. In the *Box B* the differences between acceleration and deceleration rates are represented. Despite the virtual vehicle has a sufficient engine power, the acceleration phase is less intense than braking one.

Furthermore, the traveling speed was not reduced on elements with a small radius of curvature, as if this important geometric constraint was not perceived.
Instead, on the straights and large-radius curves with considerable extension, see *Box C*, the drivers increase their speed up to stabilize it to a target value, which depends on detail level of virtual environment and on resulting realism perceived by drivers. The intrinsic ability of the simulated environment to indirectly inform about traveling speed, by using visual and sound effects, is essential to obtain realistic speed values. The details abundance, especially near road platform, increases the speed perception, while road environments with fewer details are poorly suited to represent scenarios which are covered with high speed values.

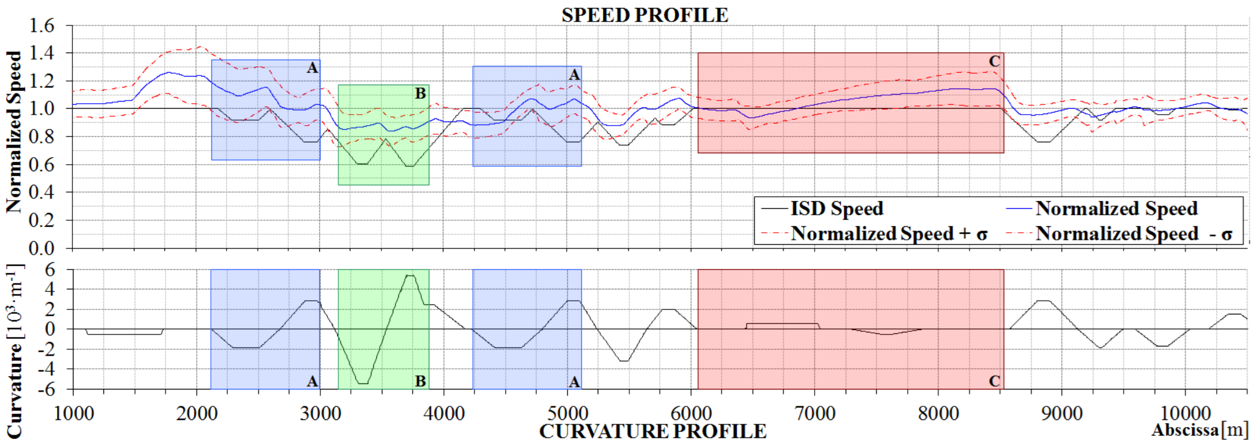

Figure 9 Behavioral consideration on Layout A

Another behavioral aspect is manifested in road stretches with low curvature values. On these elements, the drivers perceive the lower geometric constraints and they increase speed to reach a value considered appropriate. Subsequently, the drivers do not substantially reduce this speed at the beginning of circular curves with high radius values, while, on their end, they are encouraged by the favorable visibility conditions to increase their speed to higher values. This phenomenon, represented in Figure 10, occurs on circular curves with radius values between 1500 and 2000meters.

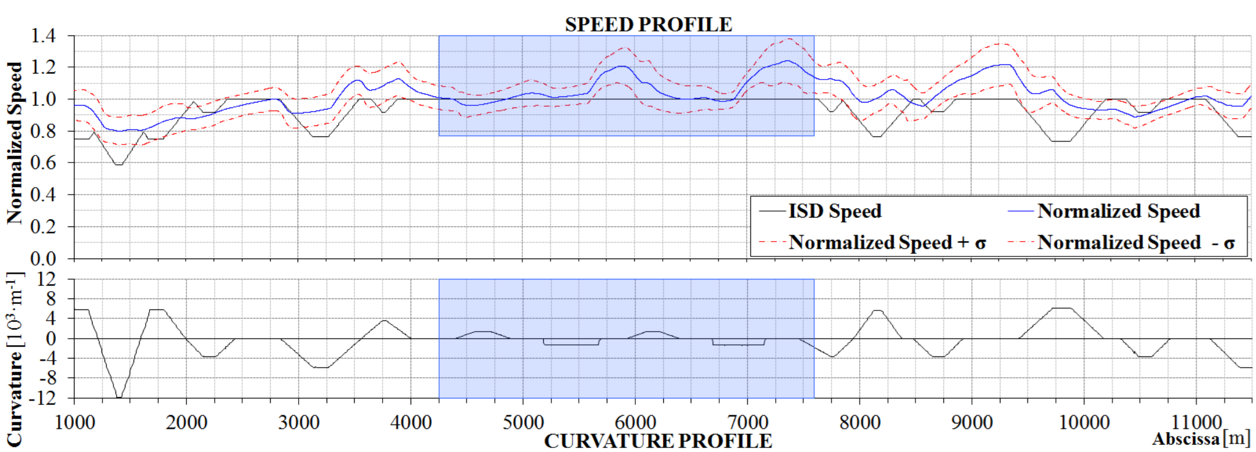

Figure 10 Behavioral consideration on Layout B

In Figure 11 is highlighted the drivers tendency to anticipate speed variations respect the points where that is required by the road geometry. This anticipation is about of 100 meters and it is probably due to unnatural driving condition on visual simulation. The study of this aspect and possible modification to apply in order to mitigate this effect are still under analysis, particularly in relation with the height of the skyline respect to driver's eyes. In fact, in comment field of questionnaires, many drivers have reported difficulties related to the difference height of skyline and driver's eyes in driving position. The most frequent comment is about a feeling of a continuous climbing slope that suggests an increase of vehicle's speed.

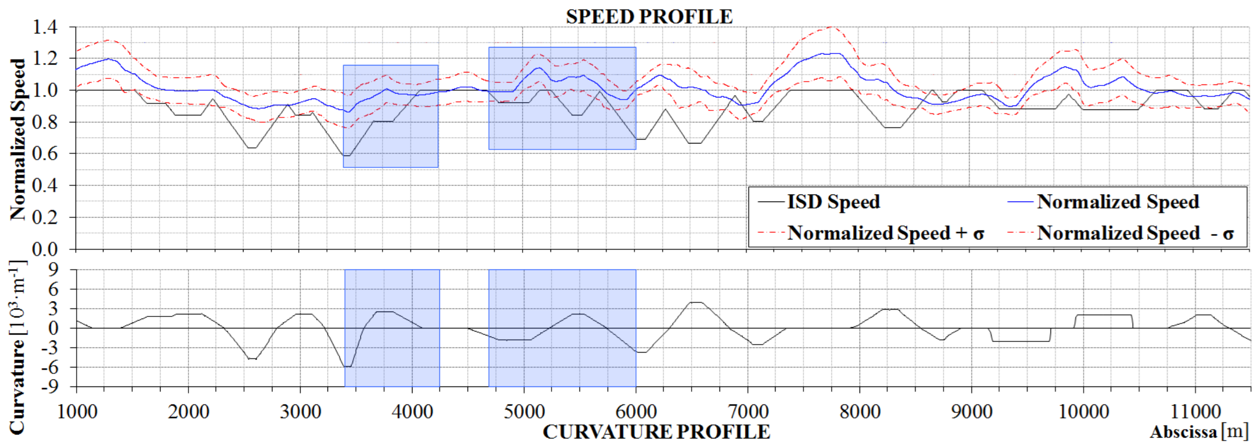

Figure 11 Behavioral consideration on Layout C

<u>Transversal Position</u>

The transversal position of vehicle during the motion depends on the capacity and sensitivity of driver. The unfamiliarity with the driving controls can cause inaccurate maneuvers and continuous adjustments to vehicle trajectory. During the tests, many users showed a natural uncertainty in maintaining transversal position of vehicle, which is attenuated only on the third test (layout C).

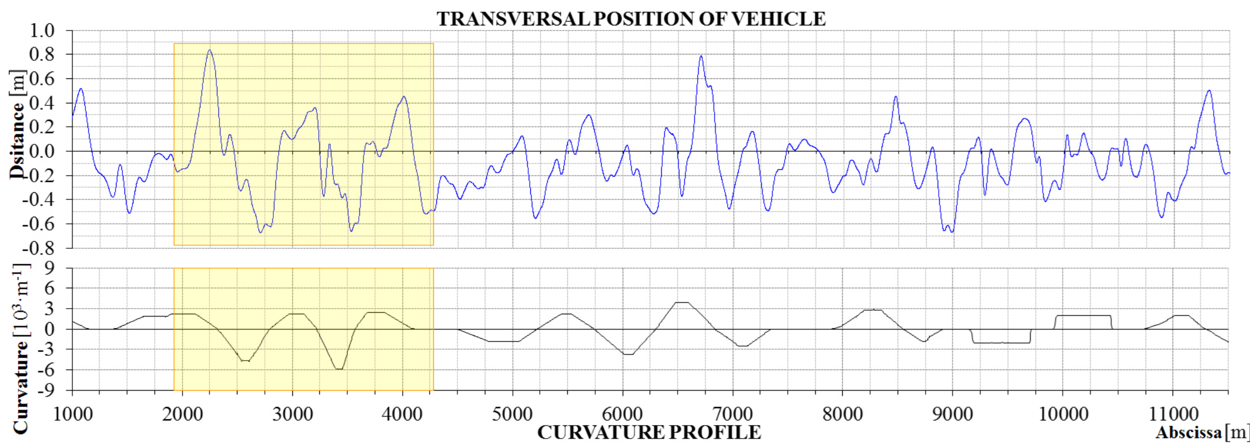

Figure 12 Transversal position in the circular curves

The greater distance of vehicle from axis of travel lane occurs on clothoid elements; that indicates the difficulty of users to maintain trajectory during steering angle increase (or decrease) phases, probably due to the delay of steering gear response respect to user expectations and consequent need to work again on this. On layout C, however, the drivers seem to change their trajectory to better inscribe vehicle in the travel lane. In fact, they approached the beginning of curve on outside border of lane and subsequently went near the inner side, as show in Figure 12. The tendency to realize this trajectory is surely due to the intention to stabilize the vehicle; it is important to note that this characteristics maneuver derives by the drivers' experience, acquired in real driving, and it reveals their involvement in simulated test. This tendency is shown despite the absence of a car cockpit; considering that the drivers establish their behavior on previous real experiences and on road surface markings; this observation demonstrates the proper transposition of real to virtual driving experience.

Curvature

The analysis of the curvature is carried out by comparing the axis of travel lane and drivers' trajectories. This comparison is made particularly on road stretches where it is omitted the clothoid in curve-tangent connection: in the transition between two geometric elements having different curvature, drivers changed their trajectories with a linear trend (constant curvature change ratio), as if they drove on a clothoidic curve, as show in Figure 13.

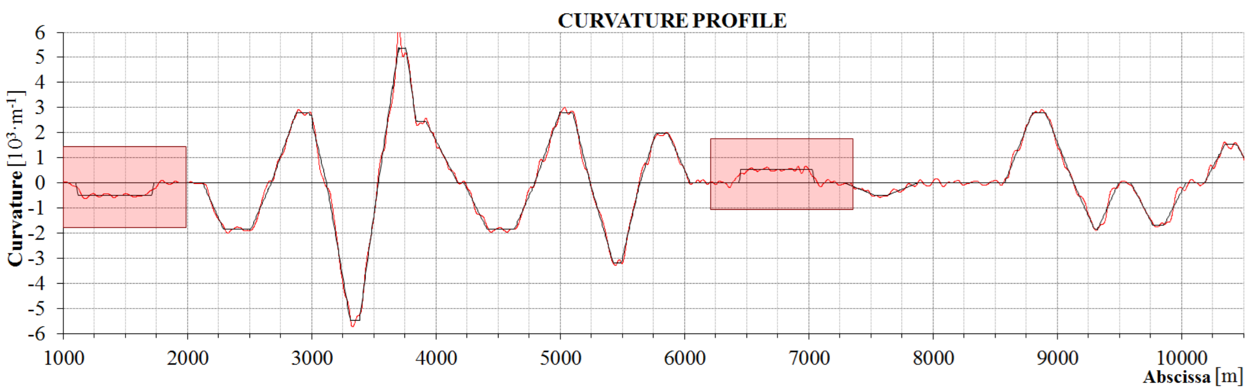

Figure 13 Spontaneous curvature in absence of clothoid

From the analysis of transition curves spontaneously followed by drivers, it is possible to observe a decrease of transition length with decreasing of curvature radius value. The limited numerousness of analyzed radius values does not allow to correlate them to the transition lengths through a significant regression process. The future step of research will be aimed to increase the number of data for this kind of study. The less sensitivity of curvature value than speed and transversal position does not permit further conclusion about other parts of layouts.

CONCLUSIONS

The research described in this paper represents a first study on the efficiency and the effectiveness of *SDS*, after its construction and development. The obtained data provided some very encouraging results about the realism achieved in the final configuration of *SDS*. The achieved results are very positive because they also provided various ideas to improve realism of audio-visual representation (as correction of skyline height and reduction of engine power of the virtual car).

The qualitative correlation between monitored speed trends and those theoretically calculated, according to the Italian standards, expresses the soundness of drivers' responses. The concordance of speed profiles ($\overline{S}$, S_{85} and *ISD*) is particularly appreciable on clothoids and small radius curves, because of ISD construction rules that impose a speed limitation on tangents and on large radius curve. The large quantitative differences between three profiles, particularly important on peak values, depend on the absence of an absolute validation process. Furthermore, the study of variance shows a correlation between the maximum value of recorded speed and speed variance of drivers. In road sections traveled at high speeds, the value of variance is greater to underline the low influence of geometric constraint on drivers' speeds. For example, correspondingly to abscissa 5945m of *Layout B*, the speed value is 195.2km/h and standard deviation is 35.5km/h, while correspondingly to abscissa 1563m the speed value is 112.6km/h and standard deviation is 20.1km/h. This tendency appears much attenuated in speed variance trend normalized on maximum speed value of each driver. It means that normalization on maximum speed value reduces the differences between performances of different drivers and makes more comparable their speed values. A speed normalization process would allow a direct comparison of trends, although it leads to misleading conclusions.

It is expected that, after an absolute validation process of *SDS*, a quantitative correlation between data obtained by simulator and those observed in real tests will be achieved. This fact allows to reach reliable evaluations even about the prediction of users' behaviors in real road contexts.

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APPENDIX

Table 1 Geometric characterization of layouts

Layout A			
n.	**Type**	**Extension**	**Parameter**
1	T	250.00m	---
2	C	257.89m	A=700.00m
3	A	95.00m	R=1900.00m
4	C	257.89m	A=700.00m
5	T	250.00m	---
6	A	610.00m	R=2000.00m
7	T	400.00m	---
8	C	170.38m	A=305.00m
9	A	218.40m	R=546.00m
10	C	164.84m	A=300.00m
11	C	200.64m	A=265.00m
12	A	105.00m	R=350.00m
13	C	138.29m	A=220.00m
14	C	190.00m	A=190.00m
15	A	76.00m	R=190.00m
16	C	152.11m	A=170.00m
17	C	160.56m	A=170.00m
18	A	63.00m	R=180.00m
19	C	78.22m	A=160.00m
20	A	80.00m	R=400.00m
21	C	256.00m	A=320.00m
22	T	50.00m	---
23	C	187.89m	A=320.00m
24	A	218.00m	R=545.00m
25	C	165.14m	A=300.00m
26	C	200.64m	A=265.00m
27	A	105.00m	R=350.00m
28	C	138.29m	A=220.00m
29	C	187.58m	A=245.00m
30	A	64.00m	R=320.00m
31	C	151.25m	A=220.00m
32	C	125.00m	A=250.00m
33	A	100.00m	R=500.00m
34	C	180.00m	A=300.00m
35	T	400.00m	---
36	A	589.00m	R=1900.00m
37	T	250.00m	---
38	C	245.00m	A=700.00m
39	A	100.00m	R=2000.00m
40	C	245.00m	A=700.00m
41	T	700.00m	---
42	C	224.00m	A=280.00m
43	A	105.00m	R=350.00m
44	C	224.00m	A=280.00m
45	C	169.14m	A=305.00m
46	A	27.50m	R=550.00m
47	C	166.93m	A=303.00m
48	T	100.00m	---
49	C	176.04m	A=325.00m
50	A	90.00m	R=600.00m
51	C	176.04m	A=325.00m
52	T	150.00m	---
53	C	162.50m	A=325.00m
54	A	97.50m	R=650.00m
55	C	162.50m	A=325.00m
56	T	400.00m	---

Layout B			
n.	**Type**	**Extension**	**Parameter**
1	T	400.00m	---
2	C	251.19m	A=370.00m
3	A	218.00m	R=545.00m
4	C	101.92m	A=300.00m
5	A	168.50m	R=337.00m
6	C	108.25m	A=191.00m
7	C	127.12m	A=150.00m
8	A	53.10m	R=177.00m
9	C	127.12m	A=150.00m
10	C	108.25m	A=191.00m
11	A	134.80m	R=337.00m
12	C	192.95m	A=255.00m
13	C	159.68m	A=295.00m
14	A	109.00m	R=545.00m
15	C	176.33m	A=310.00m
16	T	400.00m	---
17	C	292.57m	A=320.00m
18	A	140.00m	R=350.00m
19	C	292.57m	A=320.00m
20	C	187.89m	A=320.00m
21	A	27.25m	R=545.00m
22	C	224.77m	A=350.00m
23	T	400.00m	---
24	C	166.67m	A=500.00m
25	A	150.00m	R=1500.00m
26	C	166.67m	A=500.00m
27	T	300.00m	---
28	A	495.00m	R=1500.00m
29	T	250.00m	---
30	C	172.41m	A=500.00m
31	A	116.00m	R=1450.00m
32	C	172.41m	A=500.00m
33	T	300.00m	---
34	A	464.00m	R=1450.00m
35	T	300.00m	---
36	C	290.91m	A=400.00m
37	A	27.50m	R=550.00m
38	C	174.73m	A=310.00m
39	C	178.57m	A=250.00m
40	A	70.00m	R=350.00m
41	C	178.57m	A=250.00m
42	T	100.00m	---
43	C	174.73m	A=310.00m
44	A	110.00m	R=550.00m
45	C	163.64m	A=300.00m
46	T	500.00m	---
47	C	300.31m	A=310.00m
48	A	160.00m	R=320.00m
49	C	290.70m	A=305.00m
50	T	150.00m	---
51	C	168.46m	A=303.00m
52	A	109.00m	R=545.00m
53	C	168.46m	A=303.00m
54	T	350.00m	---
55	C	265.79m	A=305.00m
56	A	140.00m	R=350.00m
57	C	274.57m	A=310.00m
58	T	500.00m	---

Layout C			
n.	**Type**	**Extension**	**Parameter**
1	T	250.00m	---
2	C	186.18m	A=320.00m
3	A	82.50m	R=550.00m
4	C	186.18m	A=320.00m
5	C	186.18m	A=320.00m
6	A	27.50m	R=550.00m
7	C	222.73m	A=350.00m
8	T	250.00m	---
9	C	251.19m	A=370.00m
10	A	218.00m	R=545.00m
11	C	34.86m	A=300.00m
12	A	225.00m	R=450.00m
13	C	206.72m	A=305.00m
14	C	220.00m	A=220.00m
15	A	66.00m	R=220.00m
16	C	181.82m	A=200.00m
17	C	174.22m	A=280.00m
18	A	135.00m	R=450.00m
19	C	117.56m	A=230.00m
20	C	173.02m	A=175.00m
21	A	61.95m	R=177.00m
22	C	110.73m	A=140.00m
23	C	110.25m	A=210.00m
24	A	160.00m	R=400.00m
25	C	256.00m	A=320.00m
26	T	400.00m	---
27	C	290.91m	A=400.00m
28	A	275.00m	R=550.00m
29	C	169.14m	A=305.00m
30	C	213.56m	A=310.00m
31	A	90.00m	R=450.00m
32	C	206.72m	A=305.00m
33	C	275.00m	A=275.00m
34	A	82.50m	R=275.00m
35	C	209.45m	A=240.00m
36	C	176.40m	A=210.00m
37	A	112.50m	R=250.00m
38	C	250.00m	A=250.00m
39	C	225.00m	A=300.00m
40	A	80.00m	R=400.00m
41	C	225.00m	A=300.00m
42	T	600.00m	---
43	C	265.79m	A=305.00m
44	A	140.00m	R=350.00m
45	C	208.29m	A=270.00m
46	C	166.12m	A=305.00m
47	A	39.20m	R=560.00m
48	C	171.61m	A=310.00m
49	T	300.00m	---
50	A	500.00m	R=500.00m
51	T	250.00m	---
52	A	490.00m	R=490.00m
53	T	400.00m	---
54	C	192.20m	A=310.00m
55	A	125.00m	R=500.00m
56	C	192.20m	A=310.00m
57	C	196.12m	A=310.00m
58	A	122.50m	R=490.00m
59	C	196.12m	A=310.00m
60	T	400.00m	---

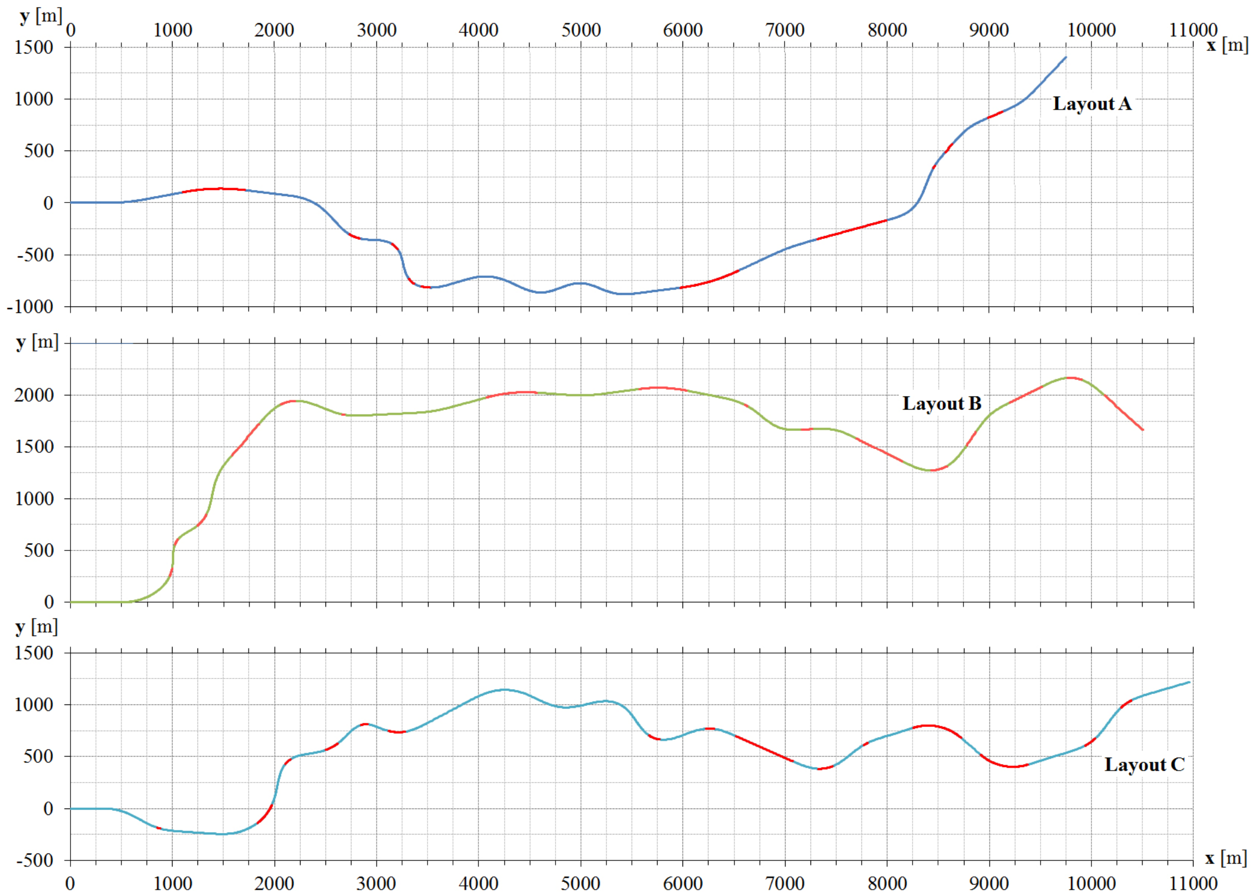

Figure 14 Horizontal representation of layouts: in red elements with design faults