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# A PROCEDURE FOR VALIDATING FIXED-BASE DRIVING SIMULATORS

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**Abstract.** This paper aims to define a standard procedure for validating a fixed-base driving simulator to be used for road safety studies and in the automotive field for development of new vehicle-subsystems. The driving simulator was developed at the University of Pisa (Italy) – Department of Mechanical, Nuclear and Production Engineering; it is characterized by a static cockpit and a single front projection channel, with vehicle and pedestrian traffic opportunely generated. The validation procedure consisted in a statistical comparison between data recorded by an instrumented vehicle on an urban path and those recorded by the driving simulator on the same path reproduced in virtual reality. A sample of 93 volunteers were submitted to both the drive tests during which several vehicle signals, such as speed data, acceleration, braking action, engine RPM and steering angle were continuously stored. Speed and acceleration data were subsequently analysed through conventional statistical methods (z-test); in order to evaluate differences between real and simulated driving, the statistical analysis was integrated by regression techniques. The analysis allowed to highlight the efficiency of the procedure in both the relative and absolute validation process as well as to evaluate potentials of the specific driving simulator. The procedure has general validity and can be used as a standard procedure for validation of fixed-base driving simulators.

**Keywords:** driving simulator, driving behaviour, traffic safety, human factors, vehicle operation.

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## Introduction

Over the past few years, the development of driving simulators and the increasing level of reliability in virtual environment studies have allowed a widespread use of simulation techniques in pure and applied research fields. Nowadays, simulators are fundamental devices used in the analysis of man-vehicle-infrastructure-environment system interactions. They are essentially based on a reproduction of the graphic scenario and a simulation of the vehicle dynamic. A new dynamic model of a vehicle moving in the specific context of urban areas has been proposed recently (Makaras *et al.* 2011). The use of a driving simulator, that is able to ensure good standards of realism, shows significant advantages compared to studies carried out in real scale. In fact it allows to carry out tests in safe conditions as well as to reproduce and to check both the test environment and the boundary conditions.

Moreover it facilitates data acquisition of variables hard to measure reliably. Specific literature highlights the efficiency shown by driving simulators for studies on the operative speed estimation (Bella 2008) and on the evaluation of user behaviours in particular environmental conditions – approach to road singularities, weather/climate, reduced sight distance, etc. (McAvoy *et al.* 2007). Furthermore, the use of driving simulators deals with the study of the reduced drive ability of users who are under the influence of alcohol or drugs or use of a mobile phone (Törnros, Bolling 2006). As a consequence the FHWA (Keith *et al.* 2005) has recommended the use of simulators in road infrastructure design. Simulators are also applied in ergonomic studies of the driver–vehicle interface (Mourant, Sadhu 2002), in road safety educational programs (Fisher *et al.* 2002), in rehabilitation (Hitosugi *et al.* 2011) and in professional trainings for competitions or special vehicle driving

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(Myers 1999). Moreover, these tools are used in the automotive field where they are involved in the development of new vehicle-subsystems: they are often coupled to the physical component closely observed in order to simulate its operation in real time, forming the 'hardware in the loop' (Yeo, Kim 2002). Driving simulators are widely spread and differently characterized depending on their utilization.

The most significant differences among simulators are represented by two constitutive parts of the equipment, the driving cockpit and the video channel system. In fact, there are simulators composed from a static cockpit and a single channel visual system represented by a single computer monitor (STISIM Drive, *http://www.stisimdrive.com*); and, on the other side, there are devices made from a mobile capsule cockpit and a video system with parabolic screens that allows a 360 degree vision field (NADS Simulator – The National Advanced Driving Simulator, *http://www.nads-sc.uiowa.edu*).

One of the most important aspects that have to be considered during a driving simulator development is the validation. This process deals with the verification of the capability of the simulator in reproducing a real behavioural environment (Mudd 1968) and in eliciting from the operator the same sort of response, physical and behavioural, that he would make in the real situation (Blaauw 1982). The reliability of a simulation system is linked to two essential factors: the perceptive validity (or absolute perceptivity), which is based on the comparison of users ability to perceive motion in real and simulated conditions, and the behavioural perceptivity (relative perceptivity) that allows to compare effects produced on the driving behaviour by variations of some environmental parameters (road, vehicle and traffic conditions) (Reymond, Kemeny 2000; Törnros 1998). The specific literature points out that the validation processes (Klee *et al.* 1999; Godley *et al.* 2002) are generally based on the utilization of standard statistical tests (e.g. $z$-test or $t$-paired) conventionally applied on the variables examined in the specific survey (e.g. speed, braking distance, lateral acceleration, etc.). This paper, introduces shortly the driving simulator developed at the University of Pisa (Italy) (Bartolozzi 2011; Bartolozzi *et al.* 2008); subsequently, a validation procedure was developed at the Department of Civil Engineering (University of Pisa, Italy), that is based on the analysis of both data recorded by an instrumented vehicle, driven in urban area (Losa *et al.* 2011), and data recorded by the driving simulator on the same path reproduced in virtual reality. The innovative aspect of the procedure is related to the great dimension of driver sample used in the test; in this case, according to the statistical analysis, the two series of data cannot be equal, but it is important to evaluate reliably the difference between them.

For this reason, the proposed procedure aims to integrate standard statistical tests with regression techniques in order to evaluate the ability of the system to reproduce real driver behaviour.

## 1. Statistical Analysis Methodology

The comparison between data related to field ($F$-index) and simulated ($S$-index) driving conditions can be carried out through the conventional statistic. In order to gain reliable results, the statistical test has to be applied on large samples depending on the variance and the specific level of reliability (Cohen 1988); large samples allow indeed shortening the interval of confidence, but they can determine rejection of the null hypothesis when the interval of confidence becomes too small. Nevertheless, the no-rejection of the null hypothesis doesn't allow drawing reliable conclusions on the simulator performance.

For these reasons it can be more reliable to gain the rejection of the null hypothesis and then to further quantify the difference between real and simulated environments, and to evaluate the influence that these differences produce on the survey results. This aspect brings about the use of regression techniques that enable the computation of the effective 'distance' between the real and simulated environments, pointing out systematic errors and system limitations. Furthermore, this research demonstrated that regression techniques work out problems related to relative validation: they allow quantifying the driving behavioural variability of the same driver in the same boundary conditions. This aspect brings about to consider regression techniques as a valuable tool for validation processes.

## 2. Description of the Experimental Program

The experimental program was planned with the specific aim of validating the absolute and the relative perceptivity; as far as the relative perceptivity is regarding, only the effects produced on the driving behaviour by variations of traffic volume were investigated.

The minimum sample size was determined according to the Cohen's theory for Student $t$-Tests, given the desired probability level, the anticipated effect size, and the desired statistical power level. The anticipated effect size $\chi^2$ was assumed equal to 0.5 and 0.7 respectively for the absolute and the relative perceptivity, considering that in the case of high traffic volumes the speed variance is significantly lower; the statistical power level and the $p$-value were set respectively equal to 90% and 5% for both the validations. By using these parameters, the minimum sample size is equal to 86 and 44 respectively for the absolute and the relative perceptivity. Based on these results, the experimental program consisted in driving tests carried out by a sample of 93 drivers for the absolute perceptivity and 47 drivers for the relative perceptivity.

The drivers were representative of a balanced male and female population aged between 18 and 35 years (i.e. in the age range most frequently involved in injury or death road accidents) (Traffic Safety Basic… 2010). Information on the driving history of the participants such as prior involvement in road accidents or violation of traffic rules was not recorded. The only prerequisite considered was possession of a valid European driving license. Subjects were selected among the residential population of Pisa, originating from different areas of Italy and having diversified social background and educational training. Tests were carried out in an urban area purpose-selected for the presence of complex contexts helpful in differentiating driver behaviour (Losa *et al.* 2011). The route is roughly 3.5 km long and is composed of one-way stretches, two-way stretches with a broad carriageway alternating with other stretches in which the road section is narrow; it contains two traffic light intersections, three roundabouts and three raised pedestrian crossings. The entire route was subdivided into 8 homogeneous sections. Each section started and ended either with traffic lights, a roundabout or a pedestrian crossing. Each of these beginning and ending points constitute locations where drivers should have adequate sight distance in order to avoid conflicts with other road users. Fig. 1 and Table 1 show the main geometrical characteristics of the carriageway and the roadside. As far as the absolute perceptivity is regarding, the tests were carried

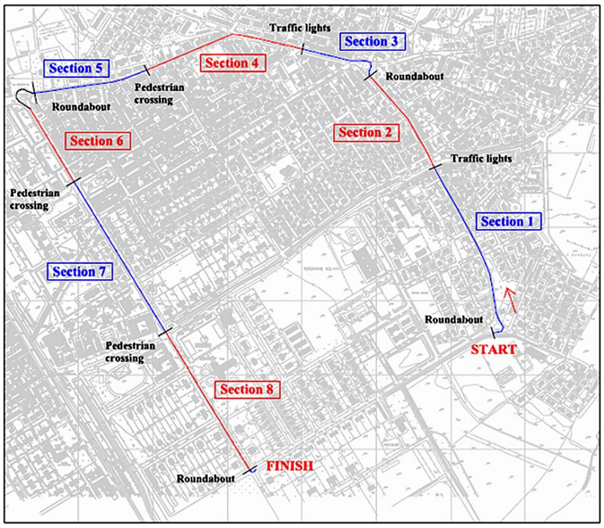


**Fig. 1.** Field driving route and geometrical characteristics

out during daylight off-peak periods (between 2:00 pm and 5:00 pm), whilst for the relative perceptivity, additional tests were performed during peak-hour periods (after 5:00 pm). As the drivers had never experienced the route before, a warm up lap was run for each subject before test recordings.

Tests were carried out in good visibility conditions and on a dry road surface free from any noticeable damage. The same procedure and conditions were adopted for tests in virtual reality.

In this case, the experimental procedure consisted in an initial driver training on the test path, few minutes long, in order to get the driver self-confident with the system.

## 3. Instrumented Vehicle

All real tests were carried out by using a *Fiat Grande Punto* car with a 90 HP and 1300 cm$^3$ capacity engine. Data on kinematic parameters were acquired from on-board sensors, available on the CAN (Controller Area Network) of the vehicle. The CAN bus is accessible from the OBD (On-Board Diagnostic) connector, which is available in cars of recent registration and, in accordance with the regulations, it is within easy reach of the driver (Losa *et al.* 2011). In the traditional approach, the vehicle is equipped with external sensors and with the related acquisition electronics (Piao 2010).

The acquisition system (Fig. 2) is composed of the following components:

- a laptop equipped with application software to decode CAN messages in real time and to display and record the data acquired;
- a CAN-USB interface to convert CAN signals – present on the OBD connector – into a format compatible with the laptop software;
- a GPS receiver to acquire the absolute position and speed data.

In the present application the OBD connector – normally used to provide self-diagnostic information for the on-board subsystems – is used as an access point

**Table 1.** Geometrical characteristics

| Homogeneous sections | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Length (m) | 500.00 | 320.00 | 234.00 | 440.00 | 325.00 | 325.00 | 475.00 | 430.00 |
| Roadway width (m) | 8.00÷4.75 | 8.00 | 8.00 | 7.40 | 7.00÷6.60 | 12.60 | 12.60 | 8.60÷7.60 |
| Number of lanes | 2÷1 | 2 | 2 | 2 | 2 | 3 | 3÷2 | 2 |
| Lane width (m) | 4.00÷2.75 | 4.00 | 4.00 | 3.70 | 3.50÷3.30 | 3.20 | 3.20÷4.80 | 4.30÷3.80 |
| Radius of curvature (m) | 0 | 0 | 0 | 180 | 500 | 0 | 0 | 0 |
| Posted speed limit (km/h) | 40 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| Slope (%) | 0/+1.00% | 0/+1.00% | 0.00 | –1.50% | 0.00 | 0.00 | 0.00 | 0.00 |
| Side parking width (m) | NA | NA | NA | NA | NA | NA | NA | 4.70÷5.00 |
| Sidewalk right width (m) | 1.10÷1.50 | 1.40 | 1.50 | 1.50÷2.00 | 2.10 | 3.50 | 3.00 | NA |
| Sidewalk left width (m) | 1.10÷1.50 | 1.10÷1.20 | 1.20÷1.40 | 1.40÷1.50 | 1.40 | 3.10 | 3.20 | NA |
| Bicycle path width (m) | NA | NA | NA | NA | NA | 1.50÷1.50 | 1.50÷1.50 | NA |

*Note*: NA – not available

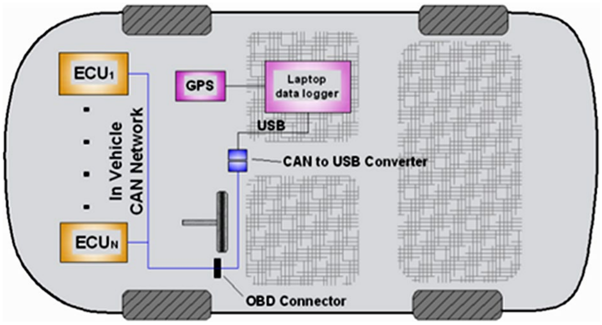


**Fig. 2.** Layout on-board instruments

to the CAN of the vehicle. The data on the state of the vehicle are transmitted over the CAN coded in a proprietary format chosen by the car manufacturer.

This system has proved to be simpler, faster and relatively cheaper than the external sensor system because it uses the on-board sensors normally available on cars of recent registration and doesn't require more complex external sensor systems that are more invasive and can modify natural driver behaviour. However, the precision and frequency sampling of data cannot be controlled, since such parameters are determined by the characteristics of the on-board sensors and by the transmission system of CAN messages containing the signals of interest. On the other hand, data recorded by the vehicle have an accuracy which is appropriate for monitoring driving behaviour and have the advantage of being consistent with the information presented to the driver by the on-board instrumentation.

It is therefore necessary to conduct a preliminary test phase, in which the signals of interest are validated, identified and decoded by determining the related scale factors. After this preliminary step conducted on the trial car, the acquisition system proved to be capable of continuously acquiring the following signals: instantaneous speed, distance, steering angle, position of the brake and accelerator pedals, pressure of the hydraulic braking system, number of engine Revolutions Per Minute (RPM) and throttle valve opening.

## 4. Driving Simulator

### 4.1. Architecture and Components

The system used in this work is a fixed-base driving simulator. This is based on a static instrumented cockpit and on a single channel front visual system, in which the driver's view is reproduced with a three-dimensional graphical scenario (Fig. 3a).

In a specific room there are the instrumented cockpit and the control desk, where an operator can follow and control all fundamental elements of the driving simulator, using specifically developed tools (Fig. 3b).

These elements are connected to each other as shown in Fig. 4, where the simulator architecture is represented. The driver interacts with the simulator by means of the typical inputs of an automatic transmission vehicle: the steering wheel, the throttle and brake pedals.

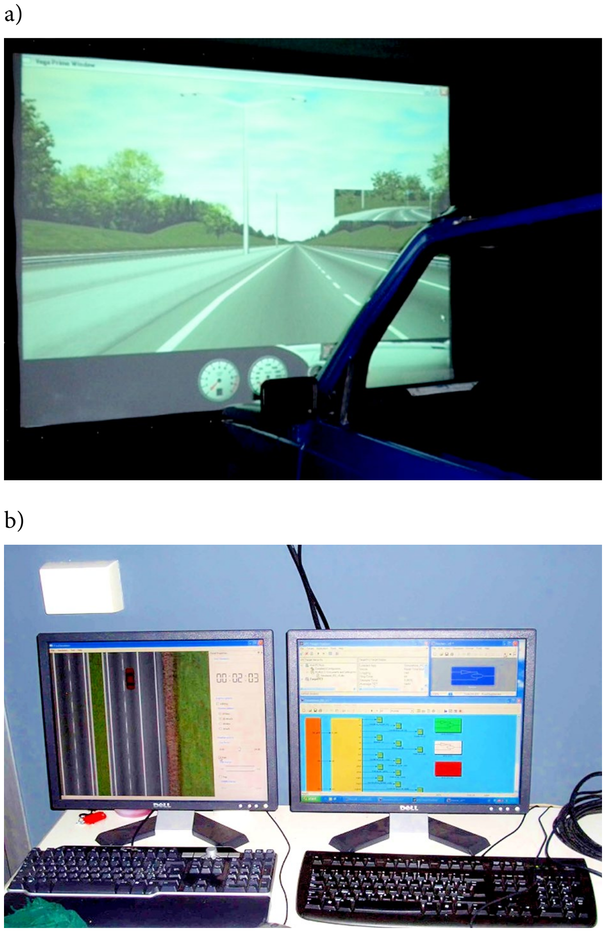

**Fig. 3.** Instrumented cockpit (a) and simulator control desk (b)

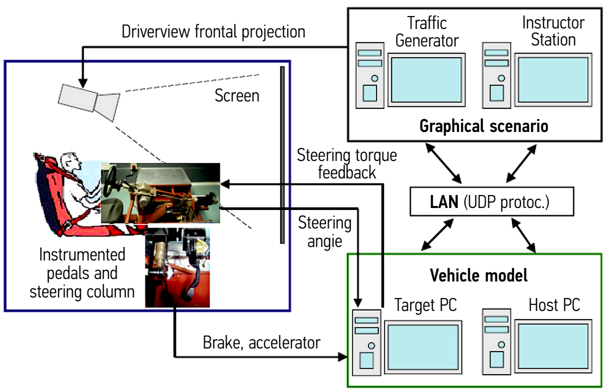


**Fig. 4.** Block Scheme of the driving simulator architecture

At the same time, the driver perceives the vehicle motion conditions by means of the front view, the engine noise and the active feedback on the steering wheel. All input elements are installed in a cockpit which reproduces the geometry layout of a real car, having a real car seat and also real car bodywork with front window. The pedals and the steering wheel are endowed with sensors which record the driver's inputs during the simulation.

The pedals have also passive feedbacks, whereas, on the steering column, a brushless electric motor applies the actual steering torque feedback computed by the vehicle model.

From the software point of view, the driving simulator is based on four personal computers connected by a local area network. Two computers are used for building and running the in house home-developed vehicle simulation model, whereas the other two run the software for the graphical scenario. In order to carry out real-time simulations, the vehicle model is compiled in C code and run by the dedicated Target PC. This computer communicates with the cockpit by means of a NI data acquisition board, recording the driver's inputs and sending the steering torque feedback signal to the electric motor. Moreover, it sends all model outputs to the other computers through the LAN. These signals, which include the driver's inputs (steering wheel angle and pedal positions), the vehicle motion conditions (speeds, accelerations, suspension strokes, etc.) and signals of all vehicle subsystems (engine speed, clutch status, tire forces, etc.) are stored for further analyses and, some of them, are used to update the graphical scenario. A specific *Matlab* toolbox (xPC Target), is used to manage and control the simulation in the Target PC from the Host PC. The Traffic Generator PC runs the main software of the graphical scenario, generating the driver's front view, which is projected on a screen. With the last computer, the Instructor Station PC, the operator at the control desk monitors the vehicle behaviour in the graphical scenario. It is also possible to change some environmental parameters, such as the weather (rain, fog, etc.) and the daylight.

### 4.2. Graphical Scenario

The graphical scenario reproduces a ring-shaped freeway path whose length is about 35 km. This route is connected to an urban area with an extension of about 1.40 $km^2$ modelled in order to reproduce the roads of Rosignano Marittimo (Livorno, Italy). In both the environments an autonomous traffic is managed by the graphical software. Some types of different cars run in the scenario following randomly generated paths at different speeds within the posted limits (130 km/h in the freeway and 50 km/h in the urban environment). The number of vehicles generated by the graphical software depends on the study carried out. In the urban environment, typical road elements such as roundabouts, traffic lights, pedestrian crossing and vertical and horizontal signals are represented. These were modelled with 3D graphical model software that faithfully reproduces the roads of Rosignano Marittimo, which on the scenario is based. The external elements of the environment (houses, trees, parked cars, etc.) were precisely positioned considering the real disposition through a DSM (Digital Surface Model). In the urban environment pedestrians were also included. They follow imposed paths crossing the roads where allowed. The driver's front view is projected on a 2.00×1.50 m flat screen. The visual angle of the driver is about 60 degrees and depends on the seat adjustment. On the screen, together with the road scenario, the car internal rear-view mirror and a virtual

a)

b)

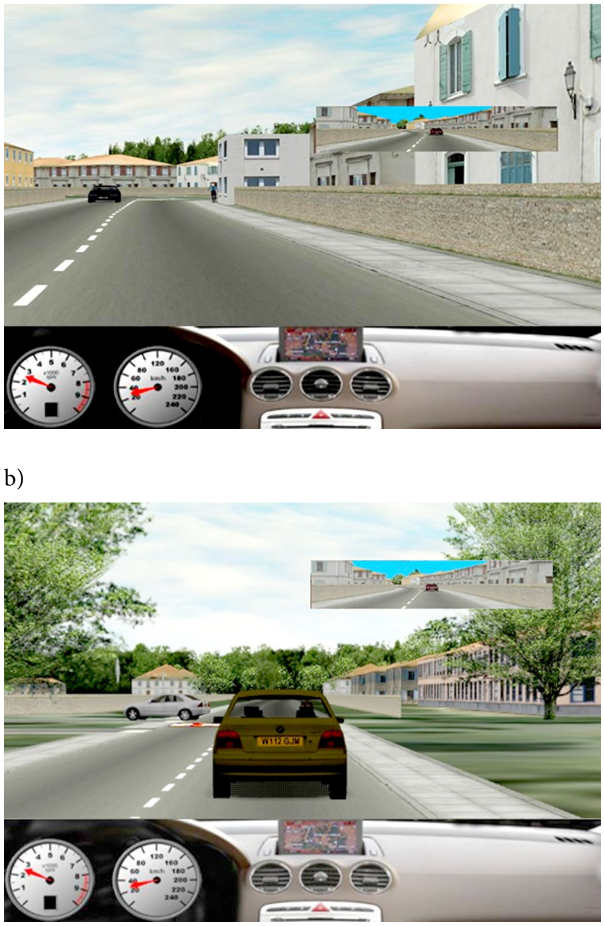

**Fig. 5.** Driver's front view in the urban environment

dashboard are also represented. The dashboard gives to the driver information about the car speed [km/h] and the engine speed [rpm] (Fig. 5). The image of the front view is refreshed with a frequency of 40÷50 Hz, which slightly changes depending on the effort of the graphical software.

### 4.3. Simulation Model

The vehicle model simulates the complete vehicle dynamic behaviour moving in the urban area and manages both the driver's input signals and the output signals sent to the other computers. The model was developed in *Matlab/Simulink* environment and it is completely parametric, thus allowing simulating several vehicle types (Bartolozzi *et al.* 2008). Currently two types of vehicles (a small and a medium-size European car) are implemented in the simulator: in this study, the medium-size car with features like the *Fiat Grande Punto* was chosen.

The vehicle model is made of several blocks representing different vehicle subsystems (braking systems, engine, tires, steering system, etc.). This model architecture allows developing each vehicle subsystem (block) independently, so that an easy upgrade of the model could be performed. More details about the simulation model are given in the research by Bartolozzi (2011).

During simulated drives, the model is run by using a solver with a fixed step size of 2.5 ms (solver frequency: 400 Hz). The fixed step, which is required for real-time applications, is about 7 times greater than the Task Execution Time (TET), i.e. the time required by the Target PC to solve a single time step, thus allowing the real-time simulation.

## 5. Test Results

Once the simulation laboratory was arranged, driving tests were carried out on the urban path, accurately reproduced in virtual reality (Fig. 6).

**Fig. 6.** Virtual reproduction of the urban path (top view)

The implemented vehicle model was a medium-size European car, which corresponds to the *Fiat Grande Punto* used for the tests in real environments.

The most suitable signals involved in the instrument validation and calibration are the steering angle and the longitudinal speed; the first signal was registered in the sections where the driver makes distinct and recognizable manoeuvres, the second signal was collected continuously on each homogeneous section, and data were used to calculate the average and the maximum values.

These signals are shown in Fig. 7, where they are plotted versus distance and overlaid to the correspondent real data. The first two plots (Figs 7a and 7b) are referred to a generic single driver, while the third one (Fig. 7c) represents the interpolation curve of the 85-th percentile and of the mean values of speed data recorded in the tests (93 drivers).

## 6. Data Analysis

### 6.1. Absolute Perceptivity of Speed Data

The statistical analysis of speed data (*z*-test) considers the instantaneous speed peak values in each homogeneous section.

This parameter results particularly suitable and reliable for the evaluation of the speed perception during the simulated test as well as to discriminate between the different driving behaviours.

Residuals between simulated and real speed data, for each homogeneous section, are distributed like a normal variable (Fig. 8).

In this application a Type I error, with probability $\alpha = 0.05$ can be allowed, whereby the normal standard value is $z_{1-\alpha/2} = z_{0.975} = 1.96$. This type of error, also known as an error of the first kind, is the wrong decision that is made when a test rejects a true null hypothesis

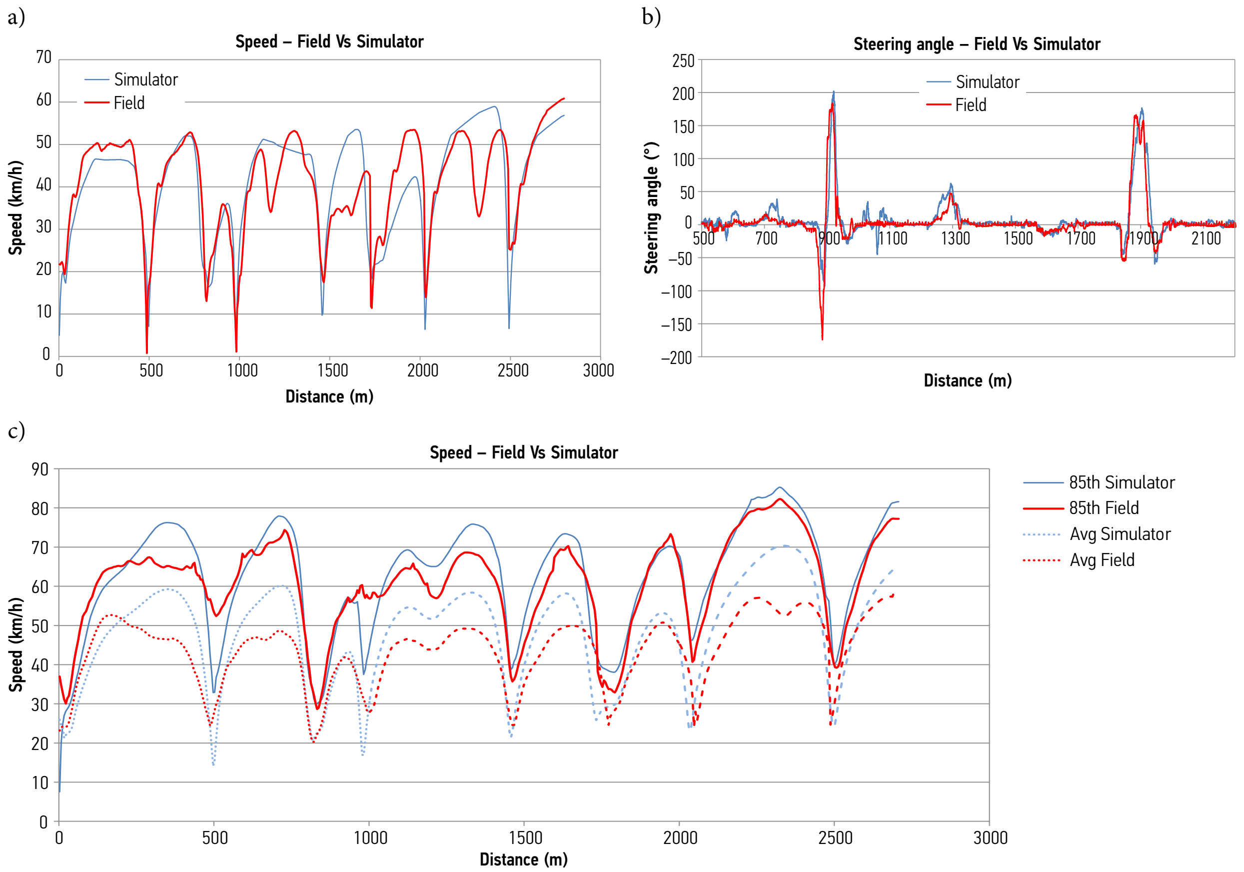


**Fig. 7.** comparison among field and simulated data: a – single driver speed; b – single driver steering angle; c – 85-th percentile and mean of speeds

($H_0$). A Type I error may be compared with a so called false positive in other test situations.

The critical value of the $z$-test $d_c$, for $\alpha = 0.05$, has been calculated for each homogeneous section and reported in Table 2, that contains also the average of residuals $d_i$ and the Confidence Interval ($C.I.$) for two probability values ($\alpha = 0.05$ and $\alpha = 0.01$).

Since the absolute value of the average of speed residuals $|d_i|$ is greater than the critical value $d_c$ on six of the eight homogeneous sections, the null hypothesis

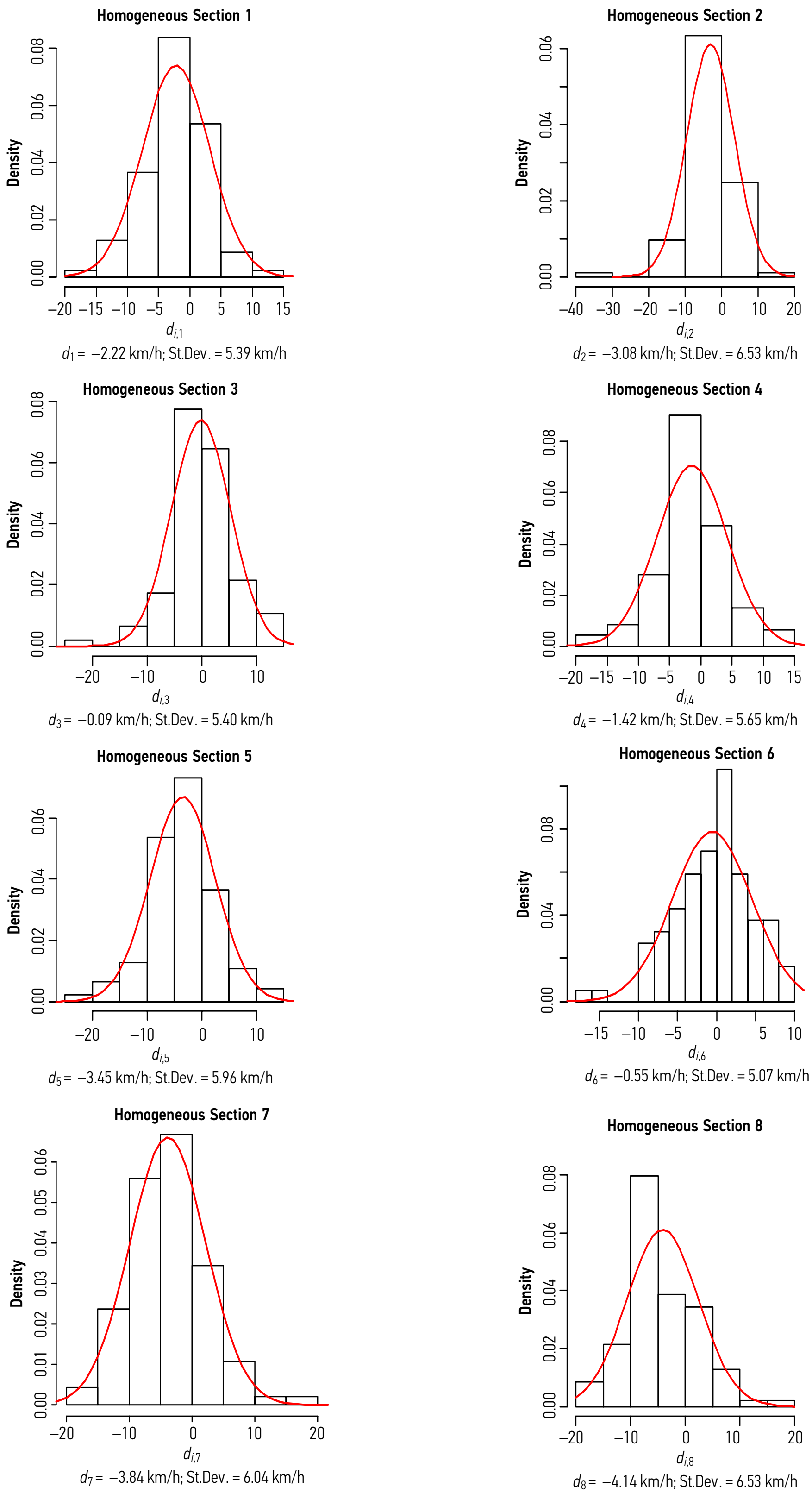


**Fig. 8.** Frequency density histogram of differences between simulated and real speed data

**Table 2.** Summary of results in all locations

| No of homogeneous sections | $H_0$, no-rejected / rejected (N/Y) | | $d_j$, average of speed residuals [km/h] | Standard deviation of speed residuals [km/h] | $d_c$, critical value ($\alpha$ = 0.05) | 95% *C.I.* [km/h] | 99% *C.I.* [km/h] | β, probability of Type II error (%) |
|---|---|---|---|---|---|---|---|---|
| | $\alpha$ = 0.05 | $\alpha$ = 0.01 | | | | | | |
| 1 | N | N | –2.22 | 5.39 | 1.10 | (–3.32; –1.13) | (–3.66; –0.78) | 35 |
| 2 | N | N | –3.08 | 6.53 | 1.33 | (–4.41; –1.75) | (–4.83; –1.33) | 38 |
| 3 | Y | Y | –0.09 | 5.40 | 1.11 | (–1.20; 1.00) | (–1.54; 1.35) | 35 |
| 4 | N | N | –1.42 | 5.65 | 1.15 | (–2.57; –0.27) | (–2.93; 0.09) | 35 |
| 5 | N | N | –3.45 | 5.96 | 1.22 | (–4.67; –2.24) | (–5.05; –1.86) | 36 |
| 6 | Y | Y | –0.55 | 5.07 | 0.95 | (–1.50; 0.48) | (–1.91; 0.80) | 33 |
| 7 | N | N | –3.84 | 6.04 | 1.23 | (–5.07; –2.61) | (–5.46; –2.23) | 36 |
| 8 | N | N | –4.14 | 6.53 | 1.33 | (–5.47; –2.82) | (–5.89; –2.40) | 38 |

$H_0$ is rejected on the majority of the considered sections.

The value of the Standard Normal Variable $z_\beta$ is calculated for the threshold value ($\Delta V$ = 1.80 km/h) defining the alternative hypothesis, to which corresponds the Type II error probability values β reported in Table 2, that range between 0.33 and 0.38, confirming the high probability to make a wrong decision when the test fails to reject a false null hypothesis. This type of error may be compared with a so-called false negative in other test situations.

Since this, the most suitable analysis tool which allows validating the driving simulator seems to be the regression technique. In fact, it brings about the use of techniques that enable the computation of the effective difference between the real and simulated conditions.

The regression analysis, carried out on the operative speed values (85-th percentile of speed distribution) recorded by the instrumented vehicle and by the driving simulator (Fig. 9), highlights the existence of a quite significant correlation among the values recorded with both the systems ($R^2$ = 0.62).

Actually, the linear regression curve plotted in Fig. 9 shows the simulator speed data are systematically lower than real data.

The overall error can be determined as the deviation from the equality line.

This error is about 2% inside the 30÷70 km/h speed range, with a peak of about 4% for higher speeds (~80 km/h).

This trend points out that:

- In the moderate speed range, the error is negligible and it is caused by the user different visual perception between real and simulated scenarios, since the simulator doesn't allow to see lateral objects adequately; this aspect, in addition to the steering feedback, the static cockpit and the compliance of regular trajectories, influences moderately the speed.
- In the range of higher speeds, the driving simulator underestimates the speed values due to the absence of dynamic actions, like vibrations and accelerations: the static cockpit, actually in use, allows the drivers to feel more self-confident and to keep a higher speed with respect to real conditions.

The values tend to be more compacted for lower speed values (about 40 km/h) whereas they tend to be more spread out for speed values around 80 km/h. The envelope of real speed dispersion data versus simulated speeds (15-th and 85-th percentile of distribution) shows a parabolic trend which tends to a minimum around 40 km/h (Fig. 10).

This fact highlights that for speed lower than 40 km/h there is a minimum dispersion between real and simulated conditions.

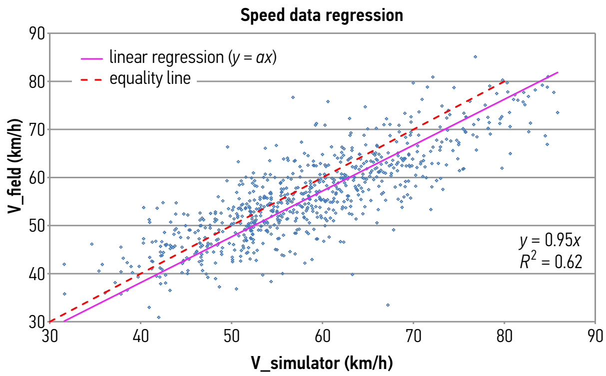


**Fig. 9.** Linear regression of speed data

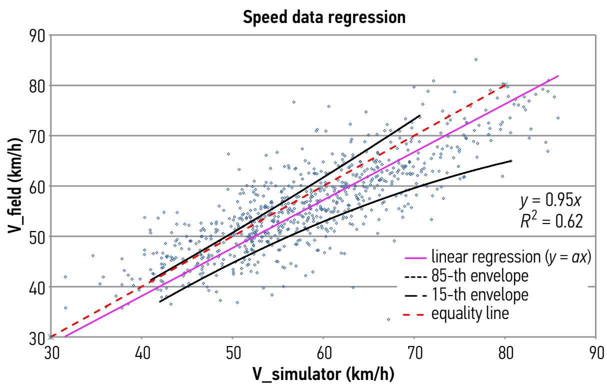


**Fig. 10.** Envelope of real speed dispersion data versus simulated speeds (15-th and 85-th percentile of distribution)

### 6.2. Relative Perceptivity of Speed Data

The relative perceptivity of the simulating system was carried out through driving tests in real and simulated environments, both characterized by different boundary conditions. These tests allow evaluating the differences in driving behaviours due to an increase of traffic volume and how these behaviours are reproduced with the simulator.

Traffic measurements were carried out in 2010. Recorded data allowed defining two different traffic conditions:

- low traffic (control site) characterized by a traffic flow of about 300 veh/h; in this case, the data recorded during the absolute validation tests, performed between 2:00 and 5:00 pm, were used (as shown in Fig. 11a with *v_field test1* and *v_sim test1*);
- high traffic (treatment site) whereby the flow was about 2500 veh/h; in this case the data were recorded during peak-hour period, after 5:00 pm (as shown in Fig. 11b with *v_field test2* and *v_sim test2*).

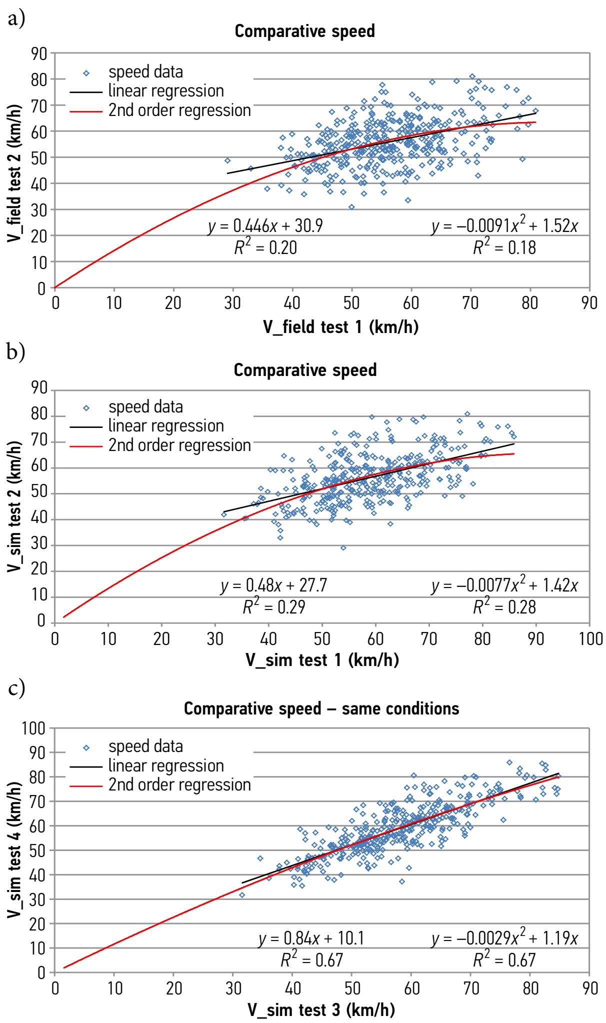


**Fig. 11.** Comparison in speed among two tests under different boundary conditions: a – with instrumented vehicle; b – with driving simulator; c – with driving simulator under same boundary conditions

The results pointed out that the different behaviors observed in simulated environment have the same trend and similar magnitude of the real ones. Figs 11a (real environment) and 11b (simulated environment) compare the two tests already mentioned.

In addition, two more prospections were carried out with driving simulator, both characterized by the same boundary conditions (low traffic – 300 veh/h).

The observed speed values (*v_sim test3* and *v_sim test4*), point out an homogeneous behaviour (Fig. 11c) that highlight the ability of the driving simulator in guaranteeing the test reproducibility. This aspect is a consequence strictly bonded to the high rate of experimental control that the simulator enables during the tests.

### 6.3. Steering Angle Value Validation

The realism of the steering angle simulation was checked through the same test. The validation process aims to understand if the steering wheel characteristics (e.g. damp, torque feedback, etc.) and the scenario perception determine reactions similar to those obtained in real conditions. The procedure for the validation is the same of the one just seen for speed data. Since the $z$-test provides the same conclusion just drawn for speed data (Table 3), values were straight analysed through the linear regression technique applied to the signal peak values corresponding to singular points of the path where the steering angle magnitude exceeds 90° (clearly defined manoeuvres).

The steering angle signal appeared noisy in some cases and these profiles were not analysed.

The analysis of the linear regression curve points out that the realism level gained by graphic performance of the video system produces driver reactions similar to those obtained in real environments (Fig. 12). The errors tend to be null and there is a strong correlation between instrumented vehicle data and simulated measurements.

The residual analysis farther highlights how much they are normally distributed.

## Conclusions

The validation procedure of the driving simulator already described allows drawing the following conclusions:

- The procedure has revealed to be efficient for the equipment validation.
- Even if the system is composed of a static cockpit and a single channel front video system, the error in simulated speeds is about 2% inside the 30÷70 km/h speed range, while it is about 4% for speeds higher than 80 km/h. These reduced errors determine an acceptable deviations from the ideal condition ($V^F=V^S$) whose threshold is fixed to 5 km/h by the research group and it is never overcome. These results point out the simulation system reliability in terms of absolute validation.
- Driving simulator allows evaluating driving behaviour variations due to different boundary conditions, determining the same kind of reactions, with the same trend and similar magnitude, registered in the field.

**Table 3.** Steering angle – summary of results in all locations

| No of homogeneous sections | $H_0$, no-rejected / rejected (N/Y) | | $d_j$, average of speed residuals [km/h] | Standard deviation ofspeed residuals [km/h] | $d_c$, critical value (α = 0.05) | 95% *C.I.* [km/h] | 99% *C.I.* [km/h] | β, probability of Type II error (%) |
|---|---|---|---|---|---|---|---|---|
| | α = 0.05 | α = 0.01 | | | | | | |
| 1 | N | N | –6.35 | 11.08 | 2.43 | (–8.77; –3.94) | (–9.53; –3.18) | 47 |
| 2 | N | N | 4.43 | 6.04 | 1.31 | (3.12; 5.75) | (2.70; 6.16) | 3 |
| 3 | Y | Y | 0.94 | 35.12 | 7.65 | (–6.71; 8.59) | (–9.13; 11.01) | 91 |
| 4 | N | Y | –2.67 | 11.74 | 2.56 | (–5.23; –0.11) | (–6.04; 0.69) | 52 |
| 5 | N | N | –5.68 | 5.52 | 1.20 | (–6.89; –4.48) | (–7.27; –4.10) | 2 |
| 6 | Y | Y | 1.01 | 7.72 | 1.68 | (–0.67; 2.69) | (–1.20; 3.22) | 17 |
| 7 | N | N | –6.02 | 8.69 | 1.89 | (–7.92; –4.13) | (–8.52; –3.53) | 26 |
| 8 | N | N | –5.66 | 8.77 | 1.91 | (–7.57; –3.75) | (–8.17; –3.15) | 27 |

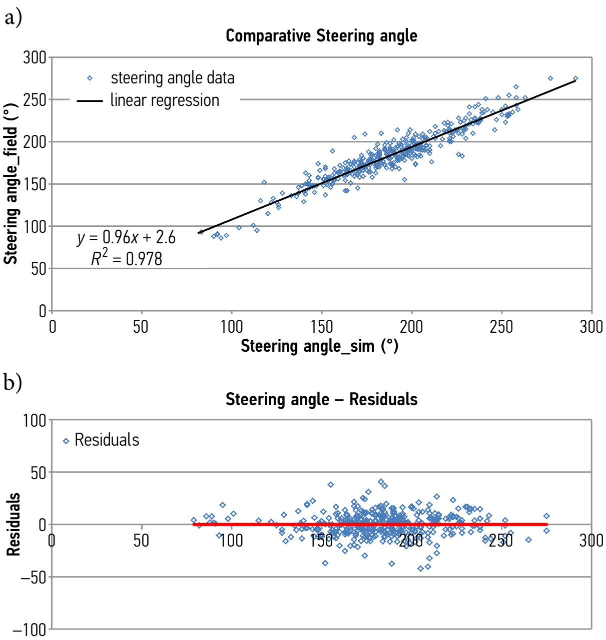


**Fig. 12.** Linear regression of steering angle data (a) trend of residuals (b)

– The pedals and torque feedback, coupled to the vehicle model, leads the drivers to feel realistic sensations: in fact, speed and steering angle data show a similar trend as the ones registered with instrumented vehicle, determining the same actions on the pedals and on the steering wheel, and the same manoeuvres already observed in real environment.
– The driving simulator guarantees reproducibility and repeatability of test conditions highlighting similar behaviours in similar traffic conditions.
– The graphic scenario reproduces real geometrical characteristics carefully gaining a frame rate equal to about 45÷50 Hz (the minimum frame rate is 25 Hz) that doesn't influence the driver operations.

The analysis allowed to conclude that the University of Pisa (Italy) driving simulator is capable of giving reliable driving sensations and can then is employed for road safety and on human factor studies both in urban areas and on roads with posted speed limit lower than or equal to 80 km/h.

In the next future, the research group will focus on the human factors and the relations between driving behaviour and psychological aspects; at the same time the researchers will analyse road safety in urban environment, paying special attention to the operative speed and the conflict zones between vehicles and weak users. Others studies will need a development of the simulator: i.e. the achievement of a dynamic platform that reproduces cockpit movement will allow more realistic drive perception and more detailed analysis of vehicle dynamic behaviour.

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