



## A NEW APPROACH TO ASSESS THE INFLUENCE OF ROAD ROUGHNESS ON DRIVER SPEED BEHAVIOR BASED ON DRIVING SIMULATOR TESTS

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**Abstract.** Vehicle speed is one of main parameters describing driver behavior and it is of paramount importance as it affects the travel safety level. Speed is, in turn, affected by several factors among which in-vehicle vibration may play a significant role. Most of speed reducing traffic calming countermeasures adopted nowadays rely on vertical vibration level perceived by drivers that is based on the dynamic interaction between the vehicle and the road roughness. On the other hand, this latter has to be carefully monitored and controlled as it is a key parameter in pavement managements systems since it influences riding comfort, pavement damage and Vehicle Operating Costs. There is therefore the need to analyse the trade-off between safety requirements and maintenance issues related to road roughness level. In this connection, experimental studies aimed at evaluating the potential of using road roughness in mitigating drivers' speed in a controlled environment may provide added value in dealing with this issue. In this paper a new research methodology making use of a dynamic driver simulator operating at the TEST Laboratory in Naples is presented in order to investigate the relationship between the driver speed behavior on one hand, and the road roughness level, road alignment and environment, vehicle characteristics on the other. Following an initial calibration phase, preliminary results seem fairly promising since they comply with the published data derived from scientific literature.

**Keywords:** driver speed behavior, driving simulator, road roughness.

### 1. Introduction

Vehicle speed is one of main parameters describing driver behavior (Bifulco *et al.* 2015; Iodice, Senatore 2015) and it is of paramount importance as it affects the travel safety level (Pariota *et al.* 2016; Sołowczuk 2011). There is a major concern among researchers on speed mitigating countermeasures (Montella *et al.* 2012, 2015) and recently some interesting studies based on driver simulator systems have been presented (Galante *et al.* 2010; Montella *et al.* 2010). This technology appears to have the potential to investigate complex relationships between parameters affecting safety such as those related to friction (Baldoni *et al.* 2011; D'Apuzzo *et al.* 2012) or to road environment perception (Montella *et al.* 2010, 2011).

However, it has to be acknowledged that drivers' speed is affected by several factors among which in-vehicle vibration may play a significant role. Most of speed reducing traffic calming countermeasures adopted nowadays rely on vertical vibration level perceived by drivers

that is based on the dynamic interaction between the vehicle and the road roughness. On the other hand this latter has to be carefully monitored and controlled as it is a key parameter in pavement managements systems since it influence riding comfort, pavement damage (D'Apuzzo *et al.* 2004, 2012) and Vehicle Operating Costs (Bennett, Greenwood 2001; Chandra 2004). In urban environment road roughness may also have an adverse effect since it increases ground vibration level induced by road traffic, similarly to what it may be observed for railway traffic (D'Apuzzo *et al.* 2008).

In detail, when a vehicle is traveling onto an irregular surface, as a results of the dynamic interaction, dynamic vertical forces are transmitted on pavement and in-vehicle vibrations are generated. Several studies have highlighted that dynamic vertical forces greatly reduce pavement service life as they may accelerate degradation of pavements (Abagnale *et al.* 2014; D'Apuzzo *et al.* 2004, 2012). On the other hand, vibrations transmitted to the vehicle are

related to the riding comfort perceived by the driver and to the vehicle operating costs such as fuel consumption, maintenance and repair costs (Bennett, Greenwood 2001; Chandra 2004).

Ride quality is therefore related to in-vehicle vibration that, in turn, is dependent on the level of road roughness, on the speed chosen by the driver and on the inertial and mechanical characteristics of the vehicles. As a matter of fact, some authors (Bennett, Greenwood 2001; Chandra 2004) have underlined that, under certain road roughness conditions, drivers may be induced to vary their speed in order to reach an acceptable in-vehicle vibration level according to their subjective exposure threshold and to the mechanical characteristic of the vehicle.

There is therefore the need to detect the trade-off between safety requirements and maintenance issues related to road roughness level. In this connection, experimental studies aimed at evaluating the potential of using road roughness in mitigating drivers' speed in a controlled environment may provide added value in dealing with this issue.

In this paper, a further contribution on this issue is presented. In detail, relationship between driver speed and road roughness level has been investigated by means of the VERA Dynamic Driving Simulator (DDS) currently operating at the TEST (Technology Environment Safety Transport) Laboratory in Naples. The DDS employs a real car fixed on a 6 degrees of freedom (d.o.f.) motion platform and it is able to reproduce most of the accelerations the occupants feel, in particular those arising from turning and braking maneuvers and from dynamic interaction with pavement surface singular irregularities such as trenches, potholes, road humps, etc. A team of researchers from University of Naples "Federico II", Second University of Naples, University of Cassino and Southern Lazio and the Oktal Company has improved the system allowing the implementation of a module simulating vehicle vibrations induced by distributed irregularities.

In this paper the development and the implementation of the vibration simulation module and the results from preliminary experimental calibration procedures are conveniently reported. According to the first calibration approach, the real vertical acceleration level of the motion platform has been compared to that provided by the vibration simulation module evaluating the dynamic interaction between the vehicle and the road roughness. A second calibration phase has been carried out by means of driving sessions performed by expert users of DDS. At the end of the paper, results from a preliminary experimental investigation aimed at studying the effects of the vehicle vibrations on driver behavior due to vibration induced by road roughness is briefly presented.

## 2. Past experiences in riding comfort and driver behavior

It is well known that road pavement surface is not a perfect flat but includes irregularities that can be singular or distributed (Fernando, Rawool 2005). Typical examples of

pavement surface singular irregularities are trenches, local depressions and potholes. Within an urban environment, manholes and traffic calming devices can also be regarded as singular road profile defects. Distributed irregularities are always present in every pavement surface. They can be ascribed to the unavoidable defects in the road construction process (Iodice, Senatore 2013) and to the progressive degradation of the materials and of the structural capacity of pavements.

Vehicles moving onto the road surface are dynamically excited by the variations of the elevations of road profile and, as a result of this, vibrations are transmitted by vehicle body to car occupants. The discomfort drivers feel because of these vibrations is one of the key factors in the speed perception and choice. Indeed, it is a common experience that drivers select different speeds in relation to the vibration level they feel because of the dynamic interaction with road pavement profile (Bennett, Greenwood 2001; Chandra 2004).

Pioneering work on this subject has been carried out by Karan *et al.* (1976) where speed measurements and traffic counts were made on 72 sites covering a wide range of roughness values but with homogeneous geometric characteristics (level and tangent sections). Several regression models have been proposed relating mean speed with measured roughness level (expressed in terms of *Riding Comfort Index, RCI*), volume to capacity ratio and site speed limits. Comparison with the another previously developed prediction model is also presented.

A huge amount of data on this issue has been subsequently collected by World Bank within the development of the Highway Design and Maintenance Standards (HDM) model. Extensive experimental campaigns have been carried out in Kenya, Brazil, Caribbean and India, yielding several relationship between vehicle speed and roughness level (expressed in terms of *International Roughness Index, IRI*) for paved and unpaved road. An overall relationship has been subsequently proposed linking vehicle speed with roughness level and with the maximum value of the Average Rectified Velocity, namely *ARV<sub>max</sub>*, that it is claimed to better describe the perceived driving comfort level.

Within the release of the new framework of HDM models, an extensive critical review of vehicle speed vs. roughness relationships has been presented, highlighting major drawbacks of previous works on this subject. However, the final model proposed is still that released in the previous HDM version but it is suggested the use of an updated value of *ARV<sub>max</sub>* derived from an Australian calibration study (Bennett, Greenwood 2001)

More recently, a research carried out in India has focused on the influence of road roughness on capacity of two-lane roads (Chandra 2004). Speed measurements and traffic counts were made in three two-lane highways sections with an overall length of 56 km. Road profile data have been collected by means of a British Towed fifth wheel bump integrator. Relationship between free flow speed and road roughness, expressed in terms of *Unevenness Index, UI*, have been proposed for light and heavy vehicles.

Summarizing the research carried out on this subject, it has to be underlined that the main weak point of most of experimental investigations is that driver behavior, and specifically vehicle speed, is affected by a huge amount of factors and therefore it appears extremely difficult to select a set of experimental sites that can allow to highlight the contribution of road roughness on vehicle speed. Speed prediction derived from empirical models may be biased.

In this connection, the use of a DDS may offer an economic, feasible and effective solution, since it allows to develop repeated and “tailored” driving scenarios where different speed constraints can be easily and conveniently “switched off”.

As far as the use of DDS in riding comfort research is concerned, it is worth to be mentioned the recent experiences developed with the Kitami Institute of Technology Dynamic Driving Simulator (KITDDS) reported in (Kawamura *et al.* 2008). In these works, in order to investigate relationship between road roughness and driving comfort, several test subjects performed a ride with the KITDDS where an artificial vibration derived from a vehicle model traveling onto an measured road profile with different roughness level is inputted. However, under the riding simulation mode, the test subjects were not free to interact with the driving simulator and therefore were not able to modify their speed in order to reach an acceptable in-vehicle vibration level. As previously stated, the DDS described in the followings has been recently improved in order to simulate vehicle vibrations induced by traveling onto a pavement surface with distributed irregularities.

### 3. The VERA driving simulator

As previously highlighted, the riding comfort arising from vibration generated by traveling onto irregular pavement surfaces represents one of the key factors in the speed perception and choice. In conventional static driving simulators where these vibrations are not provided it seems to

drive on “silk” and this induces driver to select speed values that may be fairly higher than those actuated in the real environment (Kemeny, Panerai 2003). To overcome these limitations a dynamic driving simulator can be employed.

The VERA (Virtual Environment for Road sAfeTy; Montella *et al.* 2011) dynamic-driving simulator with a hexapod motion platform is operating at the TEST (Technology Environment Safety Transport) Laboratory (Fig. 1). The simulator is located in the Engine Institute of the C.N.R. (National Research Council) facilities in Naples, inside a 115 m<sup>2</sup> simulation room; a supervision room and a briefing room are also present.

Three flat screens (dimension: 3×4 m) are fixed at the simulation room floor in order to surround the motion platform. The visual scene is projected to a high-resolution three channel 180°×50 forward field of view with rear and side mirror views replaced by 6.5” LCD monitors.

The visual system allows a resolution of 1400×1050 pixels for each channel and a refresh rate of 60 Hz. A half Citroën C2 vehicle body with realistic operation of controls and instrumentation (Fig. 1) is connected to the motion platform. The audio system can reproduce various sounds that can normally be heard while driving, including the rolling, engine and exhaust noise produced by the driving vehicle as well as the surrounding sound field from other vehicles.

Feedback is provided by a force feedback system on the steering and a 6 d.o.f. electric motion platform. The torque feedback at the steering wheel is provided via a motor fixed at the end of the steering column. The motion system consists of a hexapod with six electric actuators, able to reproduce most of the accelerations that real car occupants feel, in particular those arising from turning and braking maneuvers, from tyre behavior in on-center handling manoeuvres (Baldoni *et al.* 2011) and from dynamic interaction between vehicle and pavement surface singular irregularities like trenches, potholes, curbs etc. A team of researchers from University of Naples “Federico II”, Second University of Naples, University of Cassino and the Oktal Company has improved the system allowing simulation of vibrations induced by distributed irregularities. Table 1 shows the kinematic operation limits of the motion system.

The VERA driving simulator is running on a SCANer©II framework which is a set of distributed, multi-platform application software allowing the user to build set up / assemble and implement a vehicle simulation. Galante *et al.* (2010) performed a validation of the VERA driving



Fig. 1. The VERA driving simulator

Table 1. Kinematic limits of the motion system

Translation	Position, mm	Speed, mm/s	Acc., g	Rotation	Position, °	Speed, °/s	Acc., °/s <sup>2</sup>
Longitudinal	-491/+432	718	±1.39	Pitch	-24/+25	48	595
Lateral	±425	712	±1.20	Roll	±25	50	575
Vertical	-247/+248	484	±0.59	Yaw	±43	82	1100

simulator for speed data, comparing real-world and driving simulator speed. The vibration simulation module that has been ad hoc developed and implemented in the DSS can be split in three sub-modules: the road roughness generation sub-module, the dynamic interaction sub-module and the transfer acceleration sub-module.

The first sub-module splits, if needed, the test track in sections having different magnitude of road surface roughness. At this stage of system development, in every section, an artificial road profile is generated for each wheel of the front axle from an arbitrary Power Spectral Density (PSD) function of the vertical elevation of road surface. As a matter of fact, according to the conventional mathematical modeling approach, road profile can be mainly described into two ways: deterministic and stochastic. In the former way, the discrete function describing the road profile is known whereas in the latter way the road profile is treated as a surface is employed.

If the PSD of a longitudinal road unevenness is known, it is possible to generate an artificial road profile by means of the following relationship between the spectral content and the PSD function of a road profile (D’Apuzzo *et al.* 2004):

$$y(x) = \sum_{i=0}^{n_{\max}} \sqrt{2\Delta n G_d(i\Delta n)} \cos(2\pi i\Delta n x + \varphi_i), \quad (1)$$

where  $y(x)$  – the elevation of longitudinal road profile at station  $x$ , m;  $n_{\max}$  – the maximum theoretical sampling spatial frequency, cycles/m;  $\Delta n$  – the discrete frequency band in the frequency domain, cycles/m;  $G_d$  – the value of the PSD function for the  $n_i = i \cdot \Delta n$  spatial frequency,  $m^3$ ;  $\varphi_i$  – a random phase angle following an uniform probabilistic distribution within the  $0 \div 2\pi$  range, radians.

Once the artificial profile has been generated, road elevation is therefore updated based on the instantaneous vehicle position on the pavement surface according to the speed chosen by the driver. For a specific vehicle speed, the same artificial road profiles generated for the front axle are conveniently shifted in the time domain for the rear axle according to a time lag that is dependent on the wheel base length and on the instantaneous vehicle speed itself.

It has to be underlined that, if the influence of roughness on driver behavior has to be investigated, it is necessary to provide profile data with steady statistical and spectral characteristics in order to reduce biased results and therefore the generation of an artificial profile by means of a PSD function appears to be the most effective solution. As a matter of fact, measured road surface profiles can hardly be considered as stationary and ergodic but they can be reduced to several stationary sections once that roughness singularities have been conveniently detected and removed (Rouillard *et al.* 2001).

However, further improvements are obviously expected in order to implement measured pavement profile data.

In the second sub-module, dynamic interaction between the vehicle and the road surface profile is evaluated in

order to calculate the accelerations of the vehicle induced by the road unevenness. The vehicle model (Fig. 2) is a discrete system with lumped masses connected by springs and non-linear dashpots that is conventionally used in mechanical engineering.

Vehicle dynamics is simulated by solving the non-linear differential equation set describing the vehicle motion by means of an explicit integration scheme.

The full car model adopted in the simulation has 7 degrees of freedom, namely: the vertical motion of the right front tire, X1, the motion of the left front tire, X2, the motion of the right rear tire, X3, the motion of the left rear tire, X4, the bounce motion of the vehicle body, X5, the pitch motion of the vehicle body, X6, and the roll motion of the vehicle body, X7, respectively. In detail, the rigid vehicle body is connected to the wheels through the suspension system that is modeled by means of linear springs in parallel with non-linear dashpots.

The frontal wheels and the rigid body are also connected through a torsion bar modeled by means of a spring and a dashpot in parallel, the same model layout has been adopted for the rear wheels. Vehicle wheels are connected to road surface profile through spring-dashpot systems accounting for tire vertical stiffness and damping.

The third sub-module acquires the acceleration signal provided by the previous one and adds it to the acceleration derived from the driving behavior in the driving simulator session.

The overall module was implemented in the VERA driving simulator. The software that was written in C++ reads data from the “Trydim” dynamic module of SCANeR©II using its API and calculates using the previously described methodology, the position of the cockpit center with respect to the road surface pavement. The software then transmits this data joined with those provided by the vibration simulation sub-module to the platform, allowing the representation of the platform response to different road roughness level.

It is worth to be observed that most of the studies on whole body vibration and exposure limits are usually carried out on subjects seating on vibrating chairs. The system developed may offer a more effective approach to this problem since it allows to evaluate in-vehicle whole body vibration on subjects that are contemporarily involved in a drive task.

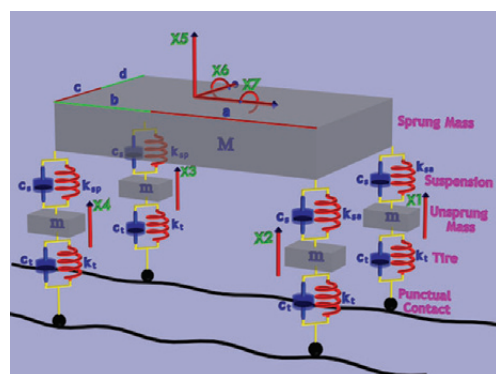


Fig. 2. The full car model

## 4. Description of the experimental investigation

### 4.1. Preliminary system calibration

The overall module set up was calibrated according to two main approaches.

According to the first calibration approach, the real vertical acceleration level of the motion platform has been compared to that provided by the vibration simulation module evaluating the dynamic interaction between the vehicle and the road roughness. A second calibration phase has been carried out by means of driving sessions performed by expert users of DDS, in order to have a global rating of the improved driving simulator.

In detail, the first calibration phase was carried out by driving automatically (driverless mode) the simulator on three 10 km long straight roads characterized by 2, 4 and 6 m/km IRI values respectively. During each session, the real vertical acceleration of the motion platform and the simulated one provided by the dynamic model sub-module were recorded. The acceleration of the platform was acquired by means of an inertial sensor mounted on the chassis near the center of the gravity of the vehicle body. In Fig. 3a comparison in the frequency domain between the platform and the simulated acceleration for an IRI value equal to 4 m/km is showed.

It is worth noticing that the two spectra appear to be comparable in the 0–9 Hz range, whereas the platform acceleration frequency content quickly drops to zero for higher frequencies. However the perception of vibrations should be rather close to that sensed in the real

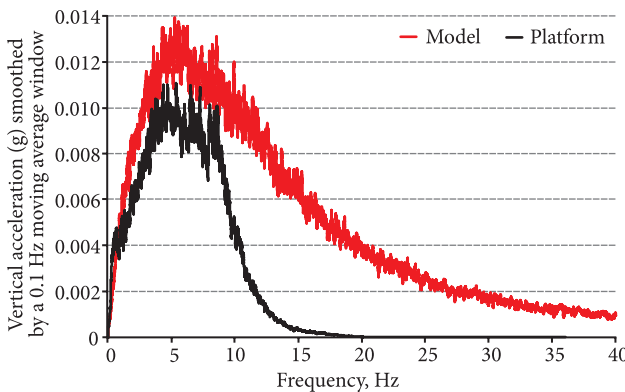


Fig. 3. Comparison of the spectrum of accelerations for IRI 4 m/km

Table 2. Results of the questionnaire on irregularities

Question	Answer
Realism of irregularities	Fair/Very good
Physical comfort of irregularities	Very good
Improving of speed perception	Yes
Driving with irregularities	Quite easy
Realism of passing between different surface profiles	Very good
Irregularities effects meet your expectation	Sufficiently/Yes

environment since, according to the mechanical properties of conventional seats and the mass of adult users, all of the accelerations spectral content higher than 10 Hz is characterized by a lower gain.

Following this phase, a further calibration test of the improved system has been carried out by means of six European experts – DDS drivers, not tied to the project, having at least 7-year experience in the field of driving simulation. The track was a 10 km long rural road. During the test, each expert driver, met only two types of road surface profiles (IRI 1.5 m/km and IRI 6 m/km). Each participant was asked to fill a questionnaire on his/her driving perception. Table 2 shows the results of the questionnaire.

The preliminary results obtained seem to indicate that the framework developed is able to effectively reproduce the accelerations the drivers sense in real environment.

### 4.2. Experimental trial

The aim of experimental investigation was to evaluate and to compare the effects of vibrations due to road surface profiles with different roughness on driver behavior. To this purpose, three road profiles have been generated by rectified smoothed PSD ISO functions (ISO 8608:1995. *Mechanical Vibration – Road Surface Profiles – Reporting of Measured Data*) according to the following IRI values: 2 m/km, 4 m/km and 6 m/km.

The subjects in the study were drawn from the student and staff population of the University of Study of Naples (Italy). Ten subjects (seven males and three females), ranging from 24 to 46 years old, were involved in the study. All participants had a valid driving license for at least five years and were considered as experienced drivers since they declared an everyday car usage. Four of the ten participants had drivers experience in off-road driving. Before the experiment they signed an informed consent form and they have no information on the real purpose of the experiment.

Every participant had a familiarization session (8–10 minutes) prior to the test. The aim was to discover the simulation environment in advance in order to reduce stress and simulator effects during the real test and to instruct them to control the simulated vehicle by using steer, pedals (brake and accelerator) and gear box. It also permitted to exclude participants suffering from motion sickness. This session was conducted in the similar conditions as the experimentation: presence of a co-pilot, similar simulated track. In the familiarization driving, no vibrations due to road roughness was rendered to the driving simulator cockpit.

Each participant drove the same virtual rural road network. The road network was about 20 km long with no posted speed limit. The whole road was divided into sections of equal length; at each section was randomly assigned a different road surface profile artificially generated by means of Eq (1) assuming a minimum and a maximum spatial frequency respectively equal to 0.0033 cycles/m i.e.

and 5 cycles/m i.e. a wavelength ranging from 0.2 m to 300 m (Figs 4 and 5) and corresponding to:

1. IRI 0 m/km: totally flat surface (no irregularities – experimental module inactive);
2. IRI 2 m/km: newly constructed pavement surface;
3. IRI 4 m/km: medium aged pavement surface (older pavements with surface imperfections);
4. IRI 6 m/km: poor pavement surface (maintained unpaved roads with frequent minor depression).

It has to be underlined that, although simulations with zero IRI surfaces may appear rather unrealistic since they do not reflect actual pavement conditions, they are highly significant as they provide immediate evidence for a “shifted” driver speed behavior between realistic driving conditions and conventional driving simulator scenarios where road roughness effects are usually neglected.

Gentle curves with radius ranging from 400 m to 600 m forced the driver to keep an active steering and speed control. Subsequent curves were separated by 1200 m long tangent sections. Virtual road platform had two 3.75 m wide lanes, one in each direction with standard lane marking, no road signs, and 0.5 m wide shoulders with superelevation in curves according geometric design standards. Along the right and the left side of the track road poles were set every 50 m. The surrounding virtual environment mimicked a rural road layout. No vehicle was expected in the same and in the opposite direction of the driver for the entire test.

Participants were instructed to drive as naturally as possible and to consider to be the owner of the vehicle. No speed restrictions were imposed.

### 5. Preliminary results

To evaluate the influence of the cockpit vibrations due to road irregularities on the behavior of the subjects driving the simulator, the following data were recorded: kilometric position of vehicle, longitudinal speed, brake pedal position and accelerator pedal position. The data analysis focused on speed-choice, reaction time and deceleration due to the road roughness level longitudinal variation. No subject lost vehicle control during the test.

### 5.1. Speed

A typical speed profile that depicts the effects of the different magnitude of the road irregularities is reported in Fig. 6. The highest speeds are reached in sections where road roughness has not been reproduced (Table 3). The

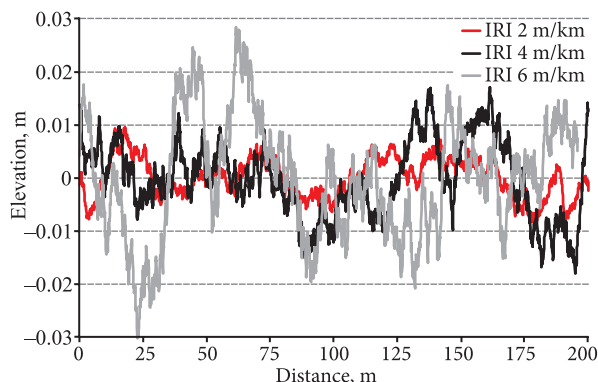


Fig. 4. Tested road profile for chosen IRI value

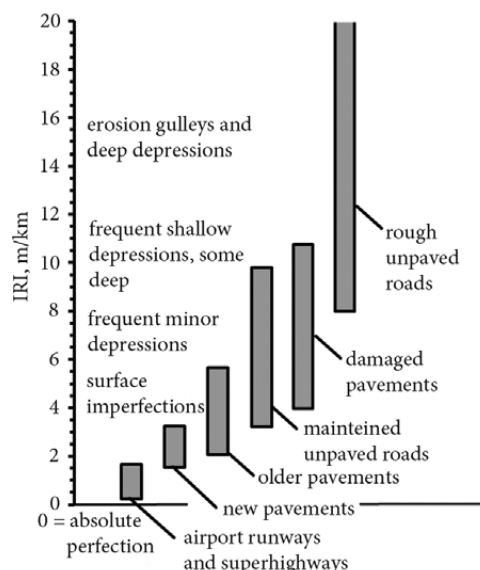


Fig. 5. IRI value and pavement condition

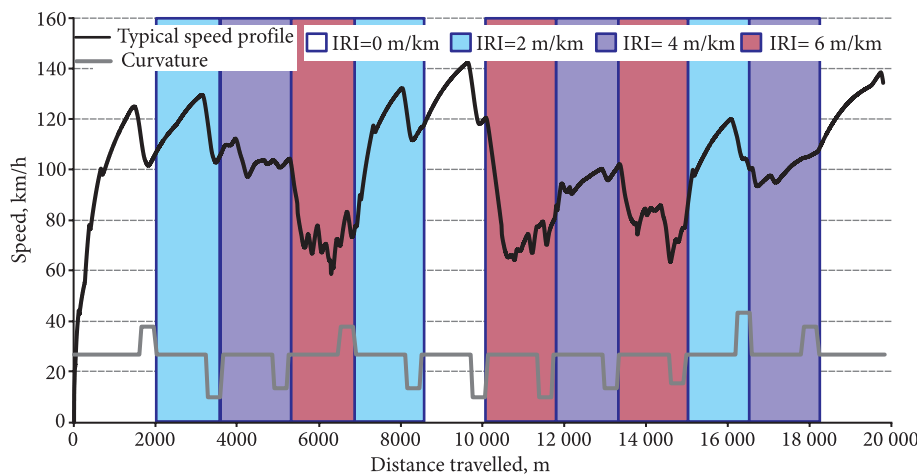


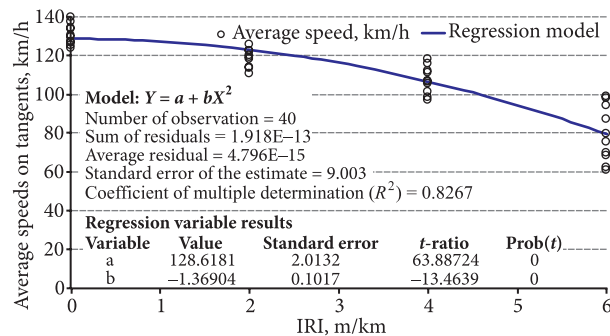
Fig. 6. Typical speed profile

subject dramatically reduces his speed in the section with higher values of IRI namely 4 m/km and 6 m/km. The change in the speed was not significant for lower IRI values. A clear dependence of the relative speed-choice on the downward and upward IRI value can be detected.

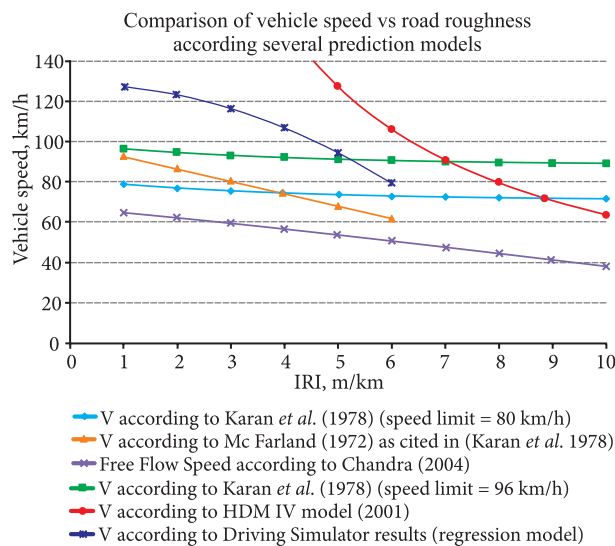
A regression model highlighting the relationship between preferred speed-choice in the tangent sections and the related IRI value is reported in the Fig. 7 with related statistics. The model seems to confirm the influence of the magnitude of the irregularities on the driver selected speed. Furthermore, the relationship between road roughness and speed has been analyzed using a repeated measures Analysis of Variance (ANOVA) with IRI level following the Mauchly's test for sphericity that yielded positive

**Table 3.** Speed on tangents as a function of IRI value

IRI, m/km	Speed on tangents Average value, km/h	Speed on tangents Standard Deviation, km/h
0	131.15	5.77
2	119.92	5.74
4	107.32	7.10
6	79.42	14.37



**Fig. 7.** Correlation between average speed and IRI value



**Fig. 8.** Comparison with different speed-roughness model derived from literature

results. The threshold for statistical significance was set at 0.05. Results from ANOVA indicated a reliable IRI level effect ( $F = 3.454E3, p < 0.0001$ ). Also the post hoc pairwise comparison showed significant speed difference as a function of IRI level.

As it can be easily observed from the Fig. 7, speed slightly decreases moving from IRI 0 m/km to IRI 2 m/km whereas significant variations (about 25 km/h) occurred passing from IRI 0 m/km to IRI 4 m/km and a large reduction (about 52 km/h) in speed is visible for a pavement with IRI 6 m/km. In Fig. 8 mean speed values derived from simulations as a function of road roughness level are compared with similar data derived by technical literature. Conversion of the several road roughness descriptors employed in the different sources to IRI have been made in order to express road unevenness on a common basis. It can be easily observed that DDS speed values appears to be fairly higher than those provided by empirical on-site investigation (Chandra 2004; Karan et al. 1976) whereas are lower than those proposed by latest HDM model. It has to be highlighted that this latter model is claimed by authors to correctly represent the unique roughness contribution on driver behavior within a more complex probabilistic speed prediction model taking into account speed constraints related to the road roughness, the desired speed, the driving power, the braking power and the road curvature by means of an harmonic mean; in other terms, the depicted relationship should describe the speed behavior when it is solely related to roughness (Bennett, Greenwood 2001) and it is not affected by any other external constraining factor; in this connection it can be regarded as a sort of theoretical or “ideal” maximum speed that cannot be reached in real driving conditions. It is therefore reasonable to assume that speed values predicted by previous empirical models and, to a lesser extent, by the DDS are always fairly biased by these constraints. As a matter of fact, in the model proposed by Karan et al. (1976) there is an explicit contribution of the speed limit; furthermore, it may be argued that traffic conditions could have affect somehow driver behavior, since speed measurements have been carried out when low (but not negligible) volume to capacity ratios were reached. In order to overcome these limitations, as suggested by several authors, before-and-after studies are planned to be implemented in the DDS in the future, by implementing realistic traffic conditions and speed limits.

**5.2. Reaction time and deceleration**

The reaction time (RT) examined within this study is the time between the beginning of a road section with higher IRI value and the moment the drivers begin to reduce the speed. From IRI 0 m/km to IRI 2 m/km, there was no reaction. From IRI 2 m/km to IRI 4 m/km, the average RT was 1.1 sec with an average deceleration of 3.2 m/s<sup>2</sup>. From IRI 4 m/km to IRI 6 m/km, the average RT was quite similar to the previous with an average deceleration of 4.5 m/s<sup>2</sup>. The change from IRI 0 m/km to IRI 6 m/km was remarkable: the average RT and deceleration were 0.9 s and 5.4 m/s<sup>2</sup> respectively.

## 6. Conclusions

In this paper a simulation module allowing the reproduction of the vibrations due to distributed irregularities in the TEST dynamic driving simulator has been described. The core of the model is represented by a non-linear full car model with seven degrees of freedom.

1. By comparing the acceleration data acquired from the motion platform and those provided by the simulation model, it has been demonstrated that a good agreement in the 0–9 Hz range can be obtained between the real and imposed acceleration level. This may be regarded as a rather good result since most of the driver seats usually attenuates frequencies higher than 10 Hz.

2. Furthermore, a group of European dynamic driving simulator experts, not tied to the project, drove the system and expressed a positive opinion with reference to both the improving of the speed perception and the realism of the irregularities.

3. Finally, preliminary results of an experimental campaign with few participants showed a real influence of the road roughness level on the behavior of the subjects which drove the simulator, especially in the speed-choice process.

4. Furthermore, a comparison with available speed-roughness models has been carried out.

5. Preliminary results seem to indicate that since speed-roughness models have been developed according to slightly different experimental conditions (as far as traffic and speed limit are concerned), data derived from dynamic driving simulations appear to be fairly consistent to those derived from technical literature. However, it has to be acknowledged that longitudinal roughness is only one of the vibration sources that is “sensed” by the driver therefore it is planned to develop a more accurate 3D road surface models in future research that will be carried out in order to confirm and extend the results obtained in this work.

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