Vibrational comfort on board the vehicle: influence of speed bumps and comparison between different categories of vehicle

Vincenzo Barone, Domenico Walter Edvige Mongelli and Antonio Tassitani

***Abstract*—**This paper shows the results of a study conducted on five different categories of vehicles in a specific test site. The aim was to investigate how the effect of the test site discontinuity determines variations of comfort related to the increase in speed and to the different class of vehicles. Measurements were obtained by combining data relating to vibrations in the three reference axes, detected through a vibration dosimeter (VIB-008), and geolocation data (latitude and longitude) identified by the GPS inside a smartphone. After the survey campaign it was determined a formulation that allows to define a Comfort Index CI depending on velocity and vehicle class. This study showed that the presence of speed bumps, in the test site investigated, appears to be unconfortable even at speeds well below those required by the Highway Code.

***Keywords*—**vibrational comfort, speed bump, comfort index.

I. State of Art

VIBRATIONS provoke different responses and sensations as a function of environmental conditions and user's physical state. Human responses to vibrations can be foreseen if they are measured and estimated in relation to the frequencies that have most influence on body reactions to stress; this requires knowledge of different parameters (eg. frequency, orthogonal axes direction, duration, etc.) as to define values representative of the true gravity of exposure [1].

Several methodologies have been introduced using differences of acceleration, of acoustic pressure and combinations of these [2], [3], [4], [5], [6], [7], [8], [9] through the use of smartphones or precision instruments, to detect abnormalities of road infrastructures. These methodologies, although using the same variables, do not identify values of comfort on board the vehicle, but allow to identify discontinuities of the road paving. As described [10] a body is considered "in vibration" if it describes an oscillating movement with respect to a specific reference system.

The level of vibration is determined by the square root of the instantaneous vibration corresponding to the time history measured on the whole body. The amount determined, represented in logarithmic scale, is defined as equivalent acceleration (a_{eq}), whose value can be made dimensionless by means of the ratio between equivalent acceleration (a_{eq}) and a reference value of 10^{-6} m/s^2. Other studies [11] propose a methodology to measure the comfort on public transport vehicles using an index called *Comfort Measuring System* CMS. The CMS system is comprised of three parts:

- Measurements obtained through the detection of smartphones' sensors;
- Database provided by operators of the transport system;
- Algorithm for the determination of results, using measurements from smartphones and from the database.

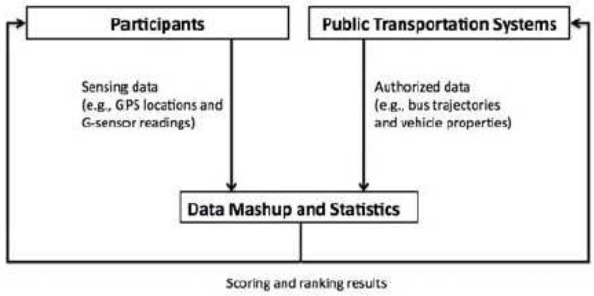

Fig. 1 The architecture of the CMS system [11]

According to ISO [12] acceptable values of vibration for the evaluation of comfort depend on many factors and specific analysis that are addressed. The same ISO [12] defines values to determine levels of comfort on public transport vehicles.

Values, however, depend on different variables, including the type of activity that passenger plays during the trip (reading, eating, writing, etc.) and other factors related to the environmental conditions inside the vehicles. In particular, the ISO 2631 defines specific classes of comfort/discomfort:

- Less than 0.315 m/s^2 – not uncomfortable;
- 0.315 m/s^2 to 0.63 m/s^2 – a little uncomfortable;
- 0.5 m/s^2 to 1 m/s^2 – fairly uncomfortable;
- 0.8 m/s^2 to 1.6 m/s^2 – uncomfortable;
- 1.25 m/s^2 to 2.5 m/s^2 – very uncomfortable;
- greater than 2 m/s^2 – extremely uncomfortable.

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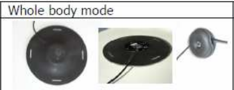
II. INSTRUMENTATION

The instrumentation used in this work, to identify the comfort on board, is as follows:

- **Smartphone Samsung Galaxy S4 I9505**: to geolocalize information;
- **Vibration Dosimeter VIB 008**: to detect, according to the European Directive [13], the Band limit frequency-weighted RMS acceleration in m/s² (a) and the Frequency-weighted RMS acceleration,*Wd*, *Wk*, *Wh* filter, in m/s² (a_w), over the x, y, z axis, etc. The main features are shown in Figure 2. The analysis of data recorded by the VIB 008 has been realized with the software dB Master Ver.5.5, supplied by the manufacturer. This software allows to analyze and export data collected and stored by the instrument.

	Whole body mode	Hand arm mode
		
Linearity domain	70 dB	70 dB
Dynamic range	0.04-120 m/s²	0.5-3000 m/s²
Frequency weightings	Wd, Wk, 1/1, 1/3	Wh, 1/1, 1/3
Broad-band weighting	0.4 - 3700Hz	
Display resolution	0.01	0.01
Recorded magnitudes	Band-pass acceleration Weighted acceleration Band-pass and weighted peak and peak-to-peak acceleration Peak factor Equivalent acceleration Daily exposure Mobile RMS vibration MTVV Vibration dose VDV Seat efficiency SEAT (option)	Band-pass acceleration Weighted acceleration Band-pass and weighted peak and peak-to-peak acceleration Equivalent acceleration Daily exposure
Configuration	Transducers Units m/s², g Integration time Reference duration Time constant	Transducers Units m/s², g Integration time Reference duration
Alarm, overload counting	Yes	Yes
Calculated magnitudes	Av, aeq, A(8), A(8)v, VDV, Fc, MTVV SEAT(option) Measurement time, calculation time	Av, A(8) Measurement time
Integration time	From 1s to 60s by steps of 1s	From 1s to 60s by steps of 1s
Spectrum (option)		
Octave	1 Hz - 2kHz	1Hz - 2kHz
1/3 octave	0.8Hz- 2.5kHz	0.8Hz- 2.5kHz
Signal mode (option)		
Sampling frequency	256-8192Hz	256-8192Hz
Pre-trigger	Depends on the calibration frequency From 0 s to 16 s	Depends on the calibration frequency From 0 s to 16 s
Maximum duration	-	-
Post-trigger	-	-

Operating temperature: -10°C / + 50°C (0-95% RH)

Fig. 2 Technical characteristics of VIB 008 Vibration Dosimeter (User Manual VIB 008 – 01dB)

III. 4. METHODOLOGY

The vehicles used to determine comfort on board are:

- **Alfa Romeo Giulietta** 2.0 140 CV (sport sedan);
- **Land Rover Freelander** 2.2 160 CV (SUV);
- **Opel Zafira Tourer** 2.0 160 CV (minivan);
- **Ford Fiesta** 1.4 96 CV (compact car);
- **Opel Insignia** 2.0 160 CV (sedan).

The vibration dosimeter was positioned, with appropriate orientation (Figure 3), on the driving seat (Figure 4), in order to determine vibrations suffered by the spine while driving and caused by the presence of potholes, speed bumps or other road abnormalities.

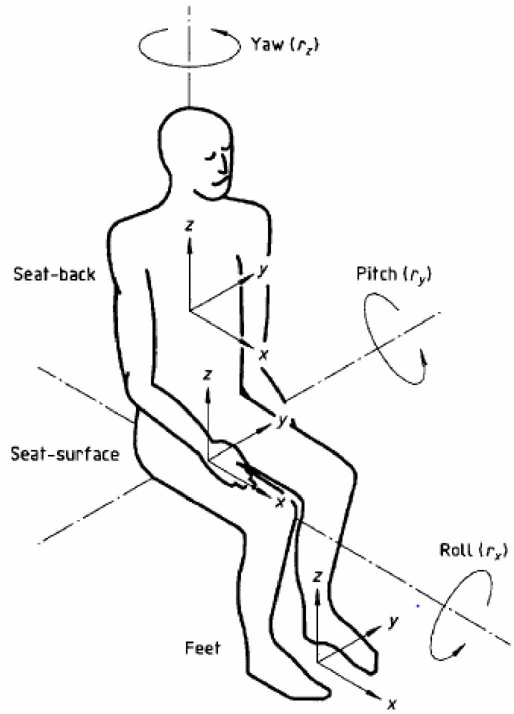


Fig. 3 Accelerations suffered from a body by sitting

Fig. 4 Positioning accelerometer VIB on the seat

Parameters used to determine comfort on board are: the a_w (frequency-weighted RMS acceleration (*Wd*, *Wk*, *Wh* filters) in m/s², along the three axis x, y, z), determined by the mathematical formulation (1) and the a_v, Overall whole-body vibration acceleration, determined by the mathematical formulation (2):

$$a_w = \left[\frac{1}{T}\cdot\int_0^T a_w^2(t)dt\right]^{0.5} \qquad (1)$$

where:

- $a_w\ (t)$: is the weighted acceleration (translational or rotational) as a function of time (time history), in metres per second squared (m/s^2);
- T: measurement duration, in second.

$$a_v = \left[(k_x\cdot a_{wx})^2 + (k_y\cdot a_{wy})^2 + (kz\cdot a_{wz})^2\right]^{0.5} \qquad (2)$$

where:

- a_{wx}, a_{wy} and a_{wz} are the weighted r.m.s. accelerations with respect to the orthogonal axes x, y, z, respectively;
- k_x, k_y, k_z are multiplying factors with respect to the orthogonal axes x, y, z, respectively. The multiplying factors value are: k_x=1.4, k_y=1.4 and k_z=1.

The use of these parameters has allowed to create a link between the traveling speed and the same parameter a_v, resulting in a *Comfort Index* (CI). This index is a function, as shown by the equation (3), of type of vehicle and speed.

$$CI(a_v) = a_v(T_{y0};T_{yv};v) = T_{y0}\cdot\exp(T_{yv}\cdot v_m) \qquad (3)$$

where:

- a_v are Overall whole-body vibration acceleration;
- T_{y0} is a overall whole-body vibration acceleration for $v=0$ and for a type of vehicles, T_{yv} is a overall whole-body vibration acceleration for $v\neq 0$ and for a type of vehicles;
- v_m is the average speed of the vehicle.

Once identified the value of CI, some reference thresholds were chosen to determine the vibrational comfort degree inside the vehicle:

- if CI less than 0.315 m/s^2: not uncomfortable;
- if CI = 0.315 m/s^2 – 0.565 m/s^2: a little uncomfortable;
- if CI = 0.565 m/s^2 – 0.9 m/s^2: fairly uncomfortable;
- if CI = 0.9 m/s^2 – 1.425 m/s^2: uncomfortable;
- if CI = 1.425 m/s^2 – 2.25 m/s^2: very uncomfortable;
- if CI greater than 2.25 m/s^2: extremely uncomfortable.

IV. Experiments and Results

Instrumental analysis were carried out along a stretch of road, in excellent condition and with a length of about 5.0 Km, with a not homogeneous road paving because of the presence of stone artificial bumps.

The test site is located in the City of Rende (Cosenza) along the Viale Principe (Figure 5).

Fig. 5 Test site

Five different categories of vehicles were used for the instrumental analysis, for each of which 15 measurements were made, in order to have a significant statistical relevance.

Data collected by the instrument, in any survey, were exported through the software Maestro 5.5 dB (Figure 6).

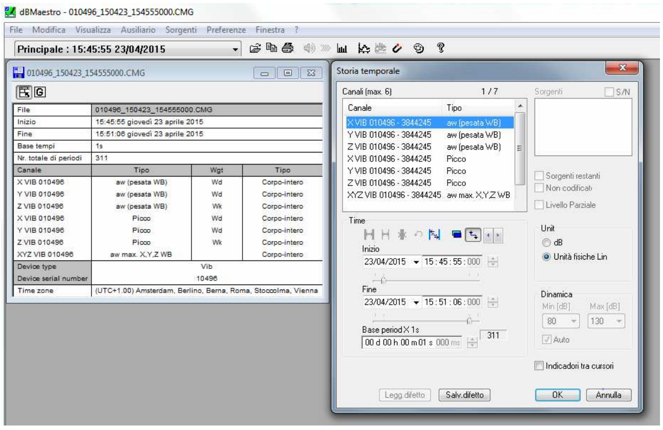


Fig. 6 dBMaestro Screenshot for exporting data

For each class of vehicle and for each measurements, the value of a_v was determined. Then the model was calibrated by means of an exponential regression, described by the equation (3), determining coefficients of dependent variables for each vehicle class useful to determine CI (Table 1).

Tab. 1 Determination of coefficients of CI for vehicle class

Type of vehicle	$\mathbf{T_{y0}}$	$\mathbf{T_{yv}}$
SUV	0.0638	0.0585
Sport sedan	0.0688	0.0589
Sedan	0.0588	0.0628
Compact car	0.0611	0.0643
Minivan	0.0694	0.0595

For each of the five categories of vehicle, it is determined the graph linking the traveling speed and the comfort index CI.

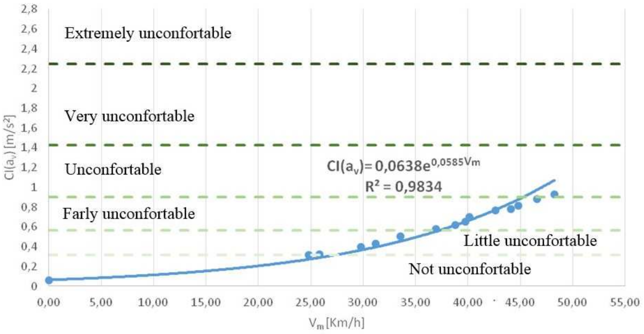


Fig. 7 CI Trend for Land Rover Freelander

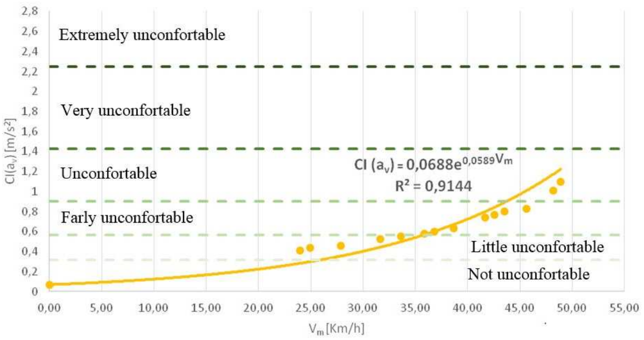


Fig. 8 CI Trend for Alfa Romeo Giulietta

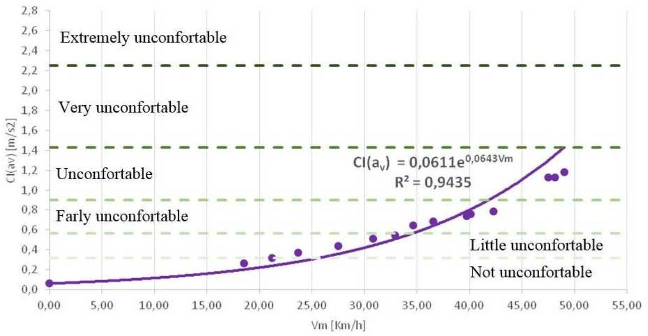


Fig. 9 CI Trend for Ford Fiesta

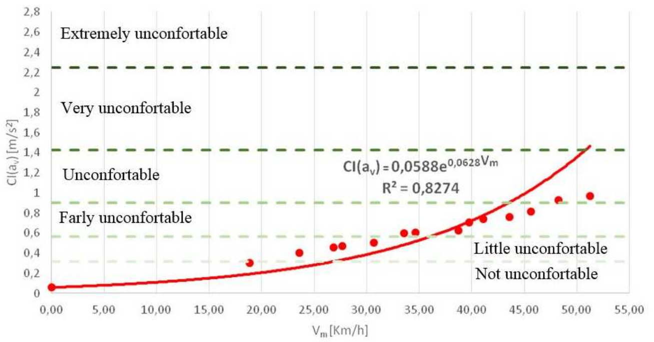


Fig. 10 CI Trend for Opel Insignia

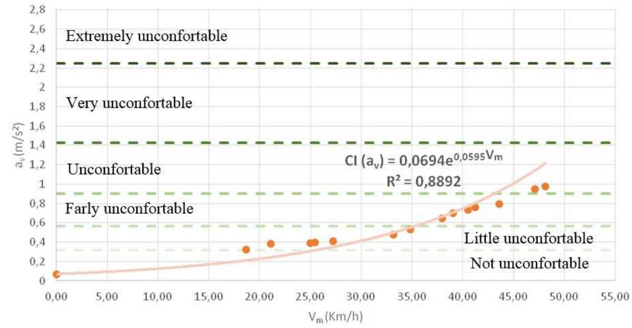


Fig. 11 CI Trend for Opel Zafira Tourer

Figures 7, 8, 9, 10, 11 show the trend of Comfort Index varying the traveling speed and the type of car. As can be seen from the value of R^2, for each type of car, the reliability of the exponential curve, which approximates the value of data obtained in the 15 measurements, is extremely high.

In order to have a more complete and clear view of differences between the various vehicles, it is shown a graph summarizing the CI trend for each type.

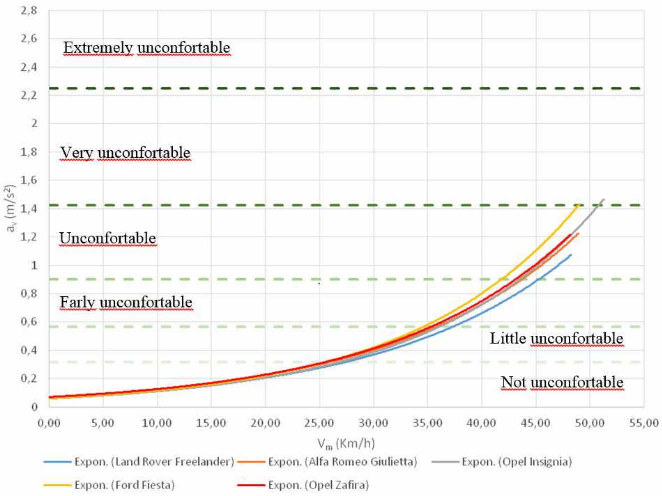


Fig. 12 General CI Trend

The figure 12, shows the CI Trend at different speed for all types of vehicle, highlighting some differences between the same types of vehicle. In fact, at low speeds the most comfortable vehicle is the sedan (Opel Insignia), however at high speeds the most comfortable vehicle is the SUV (Land Rover Freelander).

V. Conclusions

The user interprets the quality of road track through perceptions, often subjective, resulting in one of the possible variables of route selection.

The definition of Comfort Index CI allows to identify a measure of quality of the road track and can be a parameter for choosing the path. This study has identified an evaluation criterion of Comfort Index (CI) specific for vehicle class and travel speed. Some reference thresholds and six classes of vibrational comfort were also identified.

Starting from the analysis carried out on the test site, it was estimated that for speeds over 37 km/h, for each vehicle class, the road track results *"Farly Uncomfortable"*; also for speeds over 45 km /h the road track results "*Uncomfortable"*.

Therefore, while driving at speeds far below the maximum limit allowed by the Highway Code, in reference to all the five vehicle classes the road track results "*Uncomfortable"*.

Therefore, even if traveling at speeds well below the maximum limit allowed by the Highway Code, for all the five vehicle classes the track turns uncomfortable.

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REFERENCES

[1] M. J. Griffin, "Discomfort from feeling vehicle vibration", *Vehicle System Dynamics*, 45(7-8), 2007, pp. 679-698.

[2] D.C. Festa, D.W.E. Mongelli, V. Astarita, P. Giorgi, "First results of a new methodology for the identification of road surface anomalies", *In Service Operations and Logistics, and Informatics (SOLI), 2013 IEEE International Conference on*, 2013, pp. 192-197.

[3] V. Astarita, D.C. Festa, D.W.E. Mongelli, A. Tassitani, "New methodology for the identification of road surface anomalies", *In Service Operations and Logistics, and Informatics (SOLI), 2014 IEEE International Conference on*, IEEE, 2014, pp. 149-154.

[4] V. Barone, D.W.E. Mongelli, A. Tassitani, "Definition and validation of a methodology to identify the road surface anomalies on the streets by measuring the noise and vibration" *International Journal of Mathematical Models and Methods in Applied Sciences*, 9, pp. 677-682, 2015.

[5] S. d'Elia, F. Crocco, D. Mongelli, "An integrated prediction model to define the level of noise in urban areas", *4th WSEAS International Conference on Urban Planning Transportation UPT2011*, Corfu Island, Greece, 2011, 399-404.

[6] V. Barone, F. Crocco, D. Mongelli, "A mathematical model for traffic noise prediction in an urban area", *4th WSEAS International Conferense on Urban Planning and Transportation UPT2011*", Corfu Island, Greece, 2011, pp. 405-410.

[7] D.W.E. Mongelli, "An integrated prediction model for traffic noise in an urban area" *In Service Operations and Logistics, and Informatics (SOLI), 2013 IEEE International Conference on*, 2013, pp. 198-204.

[8] A. Aloe, V. Barone, F. Crocco, D. Mongelli, "Mathematical modelling of road traffic noise in urban centers", *7th WSEAS International Conference on Energy & Environment (EE '12)*, Kos Island, Greece, ,2012, pp. 228-233.

[9] A. Aloe, V. Barone, F. Crocco, D. Mongelli, "Traffic noise forecasting tools: A mathematical model", *7th WSEAS International Conference on Energy & Environment (EE '12)*, Kos Island, Greece, ,2012, pp. 2334-239.

[10] M. C. Gameiro da Silva, "Measurements of comfort in vehicles", *Measurement science & technology*, 13(6), 2002, pp. 801-820.

[11] C.Y. Lin, L.J. Chen, Y.Y. Chen, W.C. Lee, "A comfort measuring system for public transportation systems using participatory phone sensing", *ACM PhoneSense*, 2010.

[12] ISO 2631 1997 Evaluation of the Human Exposure to Whole-Body Vibration (Geneva: International Standard Organization).

[13] Directive 2002/44/EC of the European Parliament and of the Council of 25 June 2002 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration) (sixteenth individual Directive within the meaning of Article 16 (1) of Directive 89/391/EEC), Official Journal of the European Communities L 177 n. 13, 6.7.2002.

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