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## EVALUATION OF A SMARTPHONE EFFECTIVENESS AS AN INEXPENSIVE TOOL FOR VIBRATION ANALYSIS IN VEHICULAR COMFORT

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**Abstract:** *An important standard of a vehicle's quality is the comfort on its conduction. Vibrations transmitted to the driver, mainly caused by the road superficial irregularities, can disturb this comfort. Also, high magnitude vibrations may cause disease and health problems, especially Low Back Pain. In order to ensure the driver's health and comfort, Federal agencies enforce regulations to limit transmitted vibration. For vibration control, industrial instrumentation offers an effective way to perform these measurements. However they represent a huge cost that make not feasible for small companies and research laboratories. This paper intends to evaluate the smartphone's potential to perform such measurements, since it have on its structure gyrosopic sensors and accelerometers, sensors capable of executing this task. Furthermore, smartphones represent barely no costs comparatively, since it is a common good to the majority of the population. As a case study, a medium sedan is used as a test vehicle and it is mathematically modelled as a half-car with 5 Degrees of Freedom (DOF). For the numeric simulation, the driver is modelled with 4DOF. Smartphone measurements and numerical results are compared to prove its effectiveness.*

**Keywords:** *smartphone, comfort, health, vibration.*

### 1. INTRODUCTION

During the vehicle use it is noticeable the presence of vibrations, mainly caused by the road superficial irregularities. These vibrations are transmitted to the driver and can jeopardize his comfort. The comfort on the vehicle's conduction is one of the most important standards of vehicular design. Its design has to meet Federal regulations that limit the vibrations transmitted to the driver in order to ensure his comfort.

Whole-body vibration (WBV) is defined as vibration occurring when a greater part of the body weight is supported on a vibrating surface. WBV principally occurs in vehicles and wheeled working machines. In most cases, exposure to WBV occurs in a sitting position and the vibration is then primarily transmitted through the seat pan, but also through the back rest (Griffin, 1990). Human response to whole body vibration is very complex and nonlinear in nature. High magnitude of vibration formed may cause diseases and health problems, especially low back pain.

As an example (Hostens and Ramon, 2003) stated, "Agricultural machinery workers report performance problems usually associated with back pain and sitting discomfort. Low-frequency (2-20 Hz) cyclic motions like those caused by a vehicle's tires hitting the road can put the body into resonance." Also were reported the effects of the daily exposure over a number of years, "Long-term exposure can cause serious health problems, particularly with the spine like, disc displacement, degenerative spinal changes, lumbar scoliosis, intervertebral disc disease, degenerative disorders of the spine, herniated discs, disorders of the gastrointestinal system, and uro-genital systems" (Sayed *et al.*, 2012)

Typically, a frequency-weighted root mean square (RMS) of a vibration signal is determined and reported in order to quantify the vibration to which a worker would be exposed. RMS vibration magnitude is a good representation of

processes whose vibrations are continuous or intermittent rather than shock like. Whole-body vibrations, such as driving over a standard, well-maintained road are well described with an RMS value.

However, care must be taken when investigating shocks and processes with sudden changes in the acceleration, particularly when dealing with whole-body vibrations. For example, a vehicle driving across bumps in the road may easily cause shock-like vibrations. For such events, RMS measurements would not capture the essence of the problem. The intensity of a single shock, a few shocks or the sudden changes in acceleration may be beyond what the human body can accommodate, but if they are averaged out over a long period of time, their significance would be missed. Therefore, we have to look at the total energy in the event and the maximum vibration values reached during the operation. (Brüel&Kjær’s Human Vibration Analyzer Type 4447 - User Manual, 2009).

To better represent such vibration scenarios the Vibration Dose Value (VDV), which is a cumulative measure, is well suited to reflect the total exposure. It accumulates the vibration energy the worker would be exposed to, thereby putting more weight on peaks and/or sudden changes in the acceleration. Guidelines for calculating RMS and VDV values are given at ISO 2631-1:1997 (section 6.3.3) - Mechanical Vibration and Shock - Evaluation of Human Exposure to Whole-body Vibration.

To analyze the mechanical vibration in an automobile it is important to define a mechanical and mathematical model of the vehicle structural system. That way, the characteristic vibrational response can be obtained mathematically from the model. To model automotive systems, a model half-car with 5DOF (Gao *et al.*, 2007) was developed to analyze the control and stability. The ride comfort was analyzed in a full-car model with 10DOF (Hassaan and Mohammed, 2015).

Similarly, the response on the driver’s body can be analyzed with a mathematical model. A biodynamic model of the driver with 4DOF (Casas *et al.*, 2015) was utilized to evaluate the driver’s comfort.

The dynamic modelling of the vehicle and the driver, as well as the vibration transmitted to the driver are fundamental factors to this research. The main objective of this paper is to evaluate a smartphone as tool for vibration analysis, proving its capacity to acquire the needed vibration measurements to evaluate the driver’s comfort.

## 2. MATHEMATICAL MODEL

Instead of analyzing driver and car as a single mathematical model it will be done individually, using the seat response of the car’s model as input for the driver’s one.

### 2.1 Vehicle’s model

As a case study, a medium sedan is modelled as a half-car with 5DOF, as shown in Figure 1. The mass of driver and chair is  $m_p$  and  $m_c$  is the mass of automobile chassis. The mass of front and rear wheel are  $m_{fw}$  and  $m_{rw}$ , respectively. The stiffness coefficient and damping coefficient of the chair are  $k_p$  and  $c_p$ , respectively. The stiffness coefficient of front and rear suspensions are  $k_{fs}$  and  $k_{rs}$ , respectively. The stiffness coefficient of front and rear wheels are  $k_{fs}$  and  $k_{rs}$ , respectively. The road excitation forces at front and rear wheels  $q_f$  and  $q_r$ , respectively. The mass moment of inertia is  $J$ . The oscillatory responses of the driver and chair, automobile chassis, front wheel and rear wheel are  $Z_p$ ,  $Z_c$ ,  $Z_f$  and  $Z_r$ , respectively. The pitch movement response is  $\phi$ .

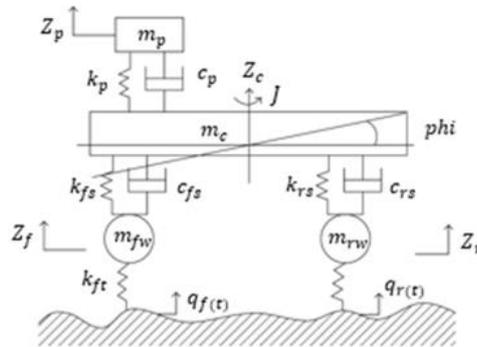


Figure 1. Half-car model 5DOF

The mathematical model that describes the car as the equation of the motion in the matrixial form is shown below:

$$[M]\{\ddot{Z}\} + [C]\{\dot{Z}\} + [K]\{Z\} = [F]\{Q\}, \quad (1)$$

where the mass matrix is given by

$$M = \begin{bmatrix} m_p & 0 & 0 & 0 & 0 \\ 0 & m_c & 0 & 0 & 0 \\ 0 & 0 & J & 0 & 0 \\ 0 & 0 & 0 & m_{fw} & 0 \\ 0 & 0 & 0 & 0 & m_{rw} \end{bmatrix}, \quad (2)$$

the damping matrix is

$$C = \begin{bmatrix} c_p & -c_p & c_p l_p & 0 & 0 \\ -c_p & c_p + c_{fs} + c_{rs} & -c_p l_p - c_{fs} l_f + c_{rs} l_r & -c_{fs} & -c_{rs} \\ c_p l_p & -c_p l_p - c_{fs} l_f + c_{rs} l_r & c_p l_p^2 + c_{fs} l_f^2 + c_{rs} l_r^2 & c_{fs} l_f & -c_{rs} l_r \\ 0 & -c_{fs} & c_{fs} l_f & c_{fs} & 0 \\ 0 & -c_{rs} & -c_{rs} l_r & 0 & c_{rs} \end{bmatrix}, \quad (3)$$

the stiffness matrix takes a similar of as the damping matrix:

$$K = \begin{bmatrix} k_p & -k_p & k_p l_p & 0 & 0 \\ -k_p & k_p + k_{fs} + k_{rs} & -k_p l_p - k_{fs} l_f + k_{rs} l_r & -k_{fs} & -k_{rs} \\ k_p l_p & -k_p l_p - k_{fs} l_f + k_{rs} l_r & k_p l_p^2 + k_{fs} l_f^2 + k_{rs} l_r^2 & k_{fs} l_f & -k_{rs} l_r \\ 0 & -k_{fs} & k_{fs} l_f & k_{fs} + k_{ft} & 0 \\ 0 & -k_{rs} & -k_{rs} l_r & 0 & k_{rs} + k_{rt} \end{bmatrix}, \quad (4)$$

$$\{Z\} = \{z_p \ z_c \ \varphi \ z_{fw} \ z_{rw}\}^T \text{ is the system response,} \quad (5)$$

$$F = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ k_{ft} & 0 \\ 0 & k_{rt} \end{bmatrix} \text{ is the force in the Equation 1, and} \quad (6)$$

$$\{Q\} = \{q_f \ q_r\}^T \text{ is the system input.} \quad (7)$$

## 2.2 Driver's model

As a simplification, the output of the car ( $z_p$ ) is utilized as the driver's model input ( $x_{se}$ ). The driver's body is model with 4DOF, as shown in Figure 2. The displacement input for the biomechanical model is  $x_{se}$  and  $x_{\#}$  is the analysed body part displacement. The analysed body part mass, stiffness coefficient and damping coefficient are  $m_{\#}$ ,  $k_{\#}$  and  $c_{\#}$ , respectively. The subscript numbers (#) 1, 2, 3 and 4 are the head, upper torso, lower torso and pelvic, respectively.

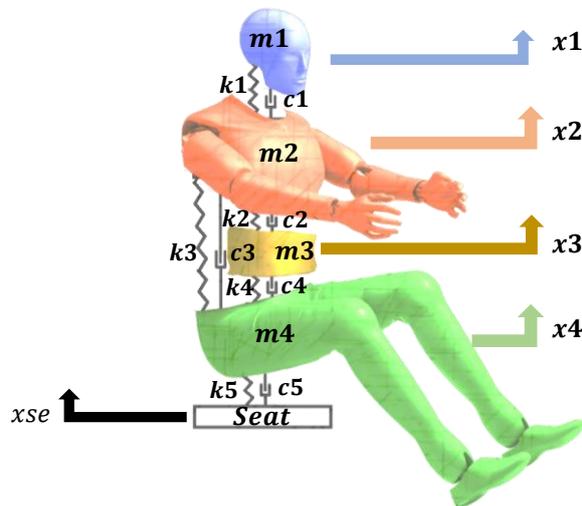


Figure 2. Driver's model with 4DOF

Analogously, the driver's mathematical model is also described by Equation 1. Where the system matrices, force, response and input, respectively, are given by:

$$M = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{bmatrix}, \quad (8)$$

$$C = \begin{bmatrix} c_1 & -c_1 & 0 & 0 \\ -c_1 & c_1 + c_2 + c_3 & -c_2 & -c_3 \\ 0 & -c_2 & c_2 + c_4 & -c_4 \\ 0 & -c_3 & -c_4 & c_3 + c_4 + c_5 \end{bmatrix}, \quad (9)$$

$$K = \begin{bmatrix} k_1 & -k_1 & 0 & 0 \\ -k_1 & k_1 + k_2 + k_3 & -k_2 & -k_3 \\ 0 & -k_2 & k_2 + k_4 & -k_4 \\ 0 & -k_3 & -k_4 & k_3 + k_4 + k_5 \end{bmatrix}, \quad (10)$$

$$\{X\} = \{x_1 \ x_2 \ x_3 \ x_4\}^T, \quad (11)$$

$$F = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ c_5 & k_5 \end{bmatrix}, \quad (12)$$

$$\{Q\} = \{\dot{x}_{se} \ x_{se}\}^T. \quad (13)$$

### 3. EXPERIMENTAL PROCEDURE

The experimental procedure is here divided into three sections, where the equipment, positioning and measurement were described.

#### 3.1 Equipment

For the experimental procedure, a Brüel&Kjær's Human Vibration Analyzer Type 4447 is utilized to comparison and validation for the results obtained with the smartphone. This instrument is a small analyzer that can be carried by the worker to assess his or her vibration exposure.

The smartphone chosen for the experiment is a Samsung Note 4 for its maximum acquisition rate, 200 Hz. This value is informed by the accelerometer's fabricant, Invensense, for the model built-in in this smartphone, ICM20610 Acceleration Sensor. After lab tests on a shaker, the results matched the informed acquisition rate. Also, the smartphone application that produced better results was Bosch's iNVH. Therefore, this app was chosen for the experiment, it provides the data in a csv file with four columns, the three-dimensional axis and time. Also, another app was used to monitor speed and route, Geo Tracker - GPS Tracker. Geo Tracker was chosen because it well represents rote taken over satellite image, displaying colors according to speed values. In this application, the green color represents the target speed and the color gradually changes to red when the speed is not respected. In addition, Octave was used for the post processing of the signals measured with the smartphone for generating analysis and indicators such as VDV.

#### 3.2 Positioning

For the first set of experiment, both smartphone and Human Vibration Analyzer are positioned on the driver's seat, as displayed on Figure 3. After, several measurements are to be acquired with the smartphone in the five positions shown in Figure 4.



Figure 3. Validation setup.



Figure 4. Smartphone positions. (a) seat; (b) pelvic; (c) lower torso; (d) upper torso; (e) head.

### 3.3 Measurement

For a representative study, a few from the most common situations of a car's urban use were chosen. They are: crossing a high bicycle (located on a stone paved street) lane at 15 km/h and driving in a standard stone paved street at 50 km/h. For each experiment case were used five samples.

## 4. RESULTS AND DISCUSSION

The mathematical model was simulated numerically per each case studied using Octave. Equation 1 were solved through Runge-Kutta Method for both models using ode package. The vehicle's model parameters and driver's parameters are shown in Table 1 and Table 2, respectively. The results of each case are expressed in the subtitles that follows.

Table 1 - Vehicle's model parameters

Mass		Stiffness coefficient		Damping coefficient	
$m_p$	35 (kg)	$k_p$	15000 (N/m)	$c_p$	300 (Ns/m)
$m_c$	569 (kg)	$k_{fs}$	1500 (N/m)	$c_{fs} = c_{rs}$	2500 (Ns/m)
$J$	1848 (kg.m <sup>2</sup> )	$k_{rs}$	1700 (N/m)		
$m_{fw} = m_{rw}$	52 (kg)	$k_{ft} = k_{rt}$	250000 (N/m)		

Table 2 - Driver's model parameters

Mass		Stiffness coefficient		Damping coefficient	
$m_1$	4.17 (kg)	$k_1$	166990 (N/m)	$c_1$	310 (Ns/m)
$m_2$	15 (kg)	$k_2$	10000 (N/m)	$c_2$	200 (Ns/m)
$m_3$	5.5 (kg)	$k_3$	144000 (N/m)	$c_3$	909.1 (Ns/m)
$m_4$	36 (kg)	$k_4$	20000 (N/m)	$c_1$	310 (Ns/m)
		$k_5$	49340 (N/m)	$c_5$	2475 (Ns/m)

### 4.1 Case 1

Case 1 is the condition of crossing a high bicycle lane at 15 km/h. Figure 5 is a picture of the high bicycle lane where the tests were made. The signal input used in Octave for this case was modelled with a trapezoidal shape (wider base

length 4m, shorter base length 2.5m and height 0.2m). After the numerical simulation, the displacements results were expressed on the graphic on Figure 6. In the bottom, the response of the car is represented. And by the wheels responses, that closely represents the road profile, it is apparent that the high bicycle lane is located on a stone paved street. In the top of Figure 6, the driver's response is represented. It is evident that driver's body responds uniformly. Therefore, the following analysis for this case will be done only regarding the head response because it is the most dependent value of the model.

The numerical response obtained for the head and the experimental data acquired by the smartphone on the head position are compared on Figure 7. Analyzing the graphic in Figure 7, it is evident the resemblance between the signals, especially in the exact time that the car is crossing the high bicycle lane. This graphic proves that the mathematical model represents the car utilized in the experiments.



Figure 5. High bicycle lane.

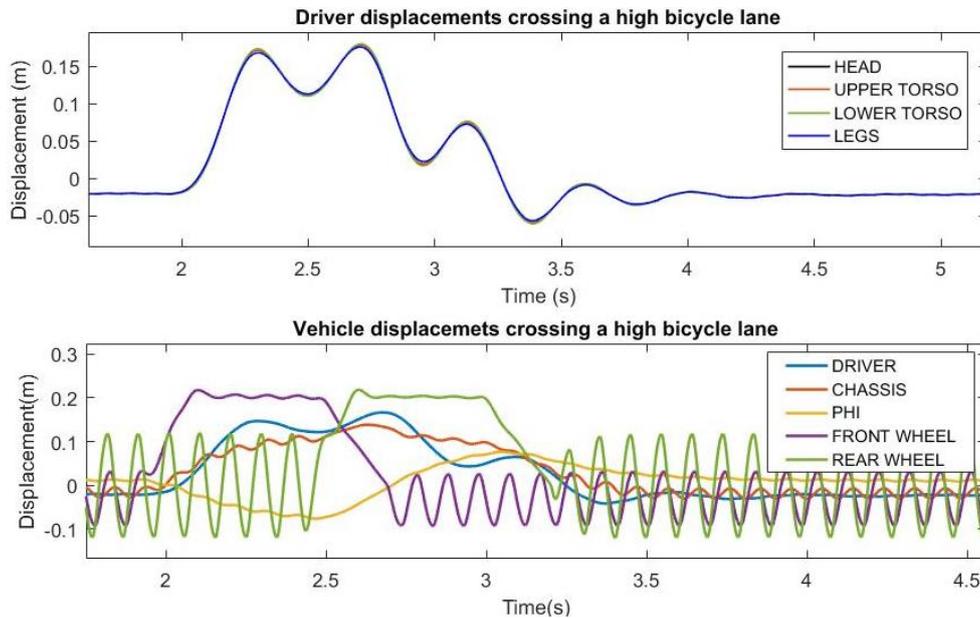


Figure 6. Displacements results of crossing the high bicycle lane numerical and experimental results.

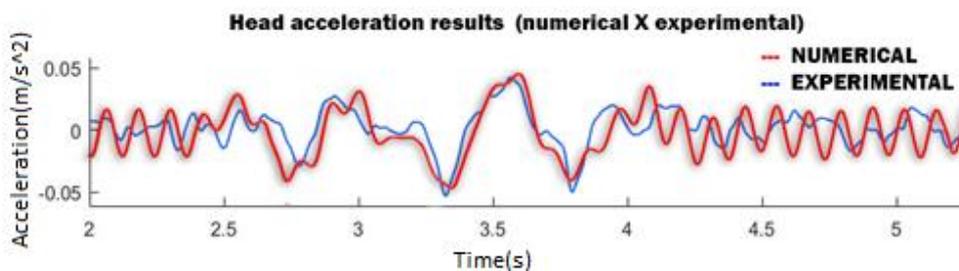


Figure 7. High bicycle lane numerical and experimental results.

## 4.2 Case 2

Case 2 is the condition of driving in a standard stone paved street at 50 km/h. The street where the experiment was performed is represented on Figure 8. Based on the data on this image, it was possible to select the target speed part (green) for further processing of the smartphone's accelerometer signal. The pertinent analysis for this experiment set is VDV. This measurement was performed with the Human Vibration Analyzer and the smartphone. VDV values measured are displayed on Table 3.



Figure 8. Stone paved street on Geo Tracker, located at UFSM campus in Santa Maria, RS, Brazil.

Table 3 - VDV values for paved street exposure

Human Vibration Analyzer	Smartphone
2,739	2,3329
3,057	2,5754
3,685	2,9279
3,407	2,7515
3,443	2,7875

In Table 3, it is visible the difference between VDV values from different sources. This divergence it's due either from a difference between the accelerometers cut points, or an inconsistency between the Human Vibration Analyser processing and the combine iNVH processing and Octave post processing of the measurements acquired with the smartphone. After realizing a pattern in the deviations of the smartphone's data, where they are always a little smaller, it is proposed a correction factor. This number is obtained by dividing de VDV from the Human Vibration Analyzer by the VDV from the smartphone for each measurement and taking the mean of those quotients. The corrected smartphone's VDV is calculated by multiplying the original value by the correction factor (1,218609). The Human Vibration Analyzer's VDV and the corrected smartphone's VDV are compared on the graphic on Figure 9, where they differ in less than 5% on their values.

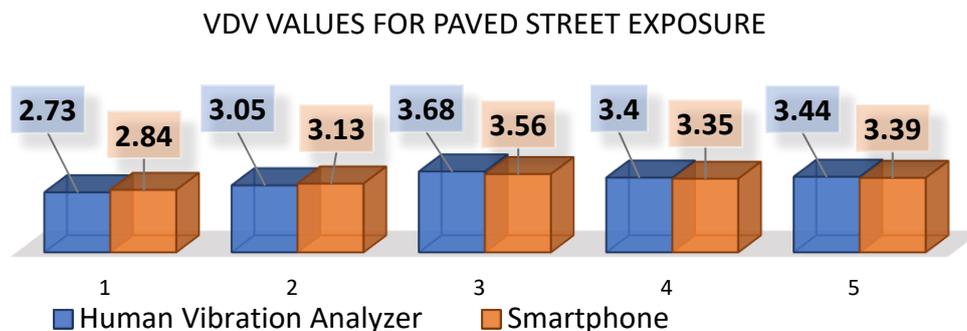


Figure 9. Comparison between VDV values Human Vibration Analyzer vs Smartphone.

## 5. ACKNOWLEDGEMENTS

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## 6. CONCLUSIONS

Concluding, the smartphone has formidable capacity for vibration acquisition and analysis. In addition, the smartphone is well capable of evaluating the driver's comfort. On the experiments performed on this paper, the smartphone achieve the same results of the Human Vibration Analyzer with 95% of accuracy for the two cases considered.

Another important conclusion is the fact that the four different body vibration measurements done in this paper are dispensable, and the measurement of the seat's vibration, similarly to the seat pad of the Human Vibration Analyzer, is fully capable of evaluating the driver's comfort for every scenario studied on this paper.

The above results are preliminary. This is an ongoing research and more cases are being studied including asphalt roads and off-road tests for RMS and VDV analysis, respectively.

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