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CRITERIA FOR CORRELATING THE STEERING WHEEL'S VIBRATION (ENGINE IDLE) WITH THE SAE COMFORT SCALE: HANDS POSITION 2/10 AND MODERATE GRIP FORCE

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***Abstract:** Steering wheel vibration has been investigated on various aspects, given the importance of this factor on the acoustic and vibration comfort observed on a vehicle. However, there is no much study about such aspects when the vehicle is at idle condition. Considering the increasing number of vehicles on big cities, more and more drivers face traffic jams and are exposed to such situation. So, this study aims to establishing a testing methodology for comparing the vehicles steering wheel vibration with the subjective sensation based on the SAE scale. Several parameters have influence on the drivers´ perception of the steering wheel vibration. One can mention for example, hands position, grip force, driver seat position, vibration direction, subjective perception, beating effects, among others. The first two aspects are analyzed in this article to help the establishment of a methodology for testing such the steering wheel vibration with the engine idle.*

***Keywords:** Steering Wheel, Vibration, Engine Idle, SAE Comfort Scale, Hand Position, Grip Force*

1. INTRODUCTION

Several studies have been conducted to assess the subjective perception of the steering wheel vibration, under various conditions of stimuli. This is because customers, in general, are increasingly demanding to the degree of comfort. Within this context, vibration from the steering wheel may influence in the decision to choose a particular vehicle or brand. In this study special attention was given to the engine working condition to a minimum with the vehicle stationary. That is because the traffic in urban centers are increasingly intense and drivers are required to remain more time with the hands on the wheel in this condition, therefore, requiring more comfort in this aspect.

However, questions arise as to the acceptable level of vibration from the subjective point of view. Given the importance of this subject, there is a need to impose steering wheel vibration limits in early stage of vehicle development, according to an acceptable level range from the client's subjective point of view.

Focusing at this need, this work seeks to correlate the steering wheel vibrations levels measured experimentally to the subjective response based on the SAE scale, largely used for subjective evaluation at the automotive industries, in order to establish a function describing acceptable values from the subjective point of view. It is intended also to verify which parameter is the best for using at the experimental measurements. Based on these results, goals will be defined that can be applied to different categories of vehicles.

Since there are many variables involved in the vibration of steering wheel, a methodology for measuring the steering wheel vibration levels needs to be defined in order to correlate these levels with the subjective factors based on the SAE scale. In this study, only the hands position and the grip force at the steering wheel will be discussed. The methodology proposed in this work was based on studies related to human subjective response to this stimulus. In order to achieve this goal, some steps were performed, to know:

- Study of the steering wheel vibration behaviour and its mechanisms of generation and transmission of vibration to the wheel;
- Importance of studying the steering wheel vibration in the proposed condition;
- Investigation on factors that influence the perception of steering wheel vibration, although here, only the hands' position and gripping force will be considered

2. STEERING SYSTEM

Currently, the steering wheel has not only the primary function of providing the control of the vehicle's direction, but also has a secondary role of providing the driver a better access to control the vehicle's accessories, serving as support for such controls. Among these accessories are horns, radio control systems, mobile phones interfaces, air condition system, in addition to commands for changing gears when the vehicle is equipped with robotic gear box, as illustrated in Figure 1. These accessories cause the driver to stay longer periods with the hands on the wheel, even when the vehicle is stopped in a traffic jam or at the traffic light.

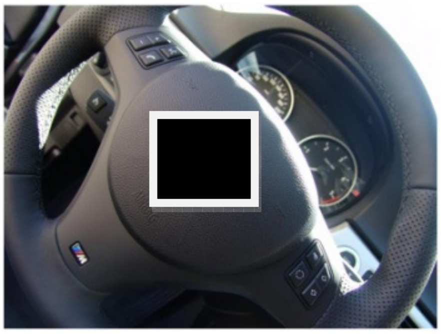

Figure 1**.** Control accessories shipped in the wheel of a luxury vehicle

The steering system of a vehicle, which can be hydraulic or mechanical, is composed basically by the steering wheel (a), steering column (b) and steering box (c), as illustrated in Figure 2. Some vehicles are equipped with electric power steering.

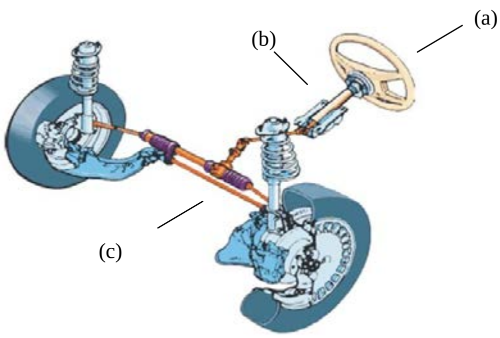

Figure 2. Vehicular steering system (a) wheel, (b) the steering column and (c) steering box

The vibration that arrives at the flywheel is transmitted through the vehicle body and steering column. The motor assembly and irregularities of the pavements are considered the main sources of vibration excitation. Regarding the vibration transmitted by the floor, the frequency and levels of wheel vibration are directly related to the type of floor and speed at which the vehicle is driven. The biggest discomfort for the driver is found on floors with large irregularities when compared to the condition when the vehicle is stopped with engine idling. However, the first type of excitation will not be addressed in this work since the goal here is the latter.

The engine is the main source of excitation of the steering wheel at the engine idling condition. The frequency of vibration generated by this source varies with the rotation of the engine. In the case of a four-stroke, four-cylinder engine (Figure 3), the excitation occurs at the 2nd, 4th and 6th engine operating orders, being the 2nd order the main contribution, which corresponds to the frequency of the engine explosion . The engine works usually at a rotation range next to 800 to 900 rpm at idle, which corresponds to an excitation frequency range around 27 to 30 Hz in 2nd order. However, intermediate orders also have influence on the flywheel vibration due to irregular idling operation.

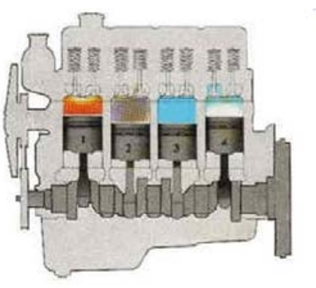

Figure 3. Operating cycles of combustion engine four-stroke and four-cylinder

Another factor that contributes to an increase flywheel vibration is when some device requiring engine power fires, as for example the air conditioning compressor, causing further vibration power from this source. Adjustments at the injection/power system are made by the central electronics for compensating the engine rotation when the a/c compressor is started, but that has little effect on vibration reduction.

The electric fan assembly (Figure 4) when fired has also great influence on generation of flywheel vibration. Being a system that rotates at high speed, small unbalances at the electro paddlewheel contributes significantly to increase the vibration of the flywheel.

The above mentioned factors make the flywheel vibration response to be a multi type periodic deterministic sine.

Figure 4. Eletrofan of the engine cooling system

Steering wheel vibration levels increase even more when the natural frequencies of either the body shell or of the steering column match the excitation frequency of these sources. Steering wheel natural frequency values ranges between 25 and 40 Hz (Figure 5), close to the excitation frequency range of the engine to a minimum in second order. According to this, it is recommended that the frequency of the flywheel to be above 35 Hz, so to escape the lower 2nd order excitation frequency.

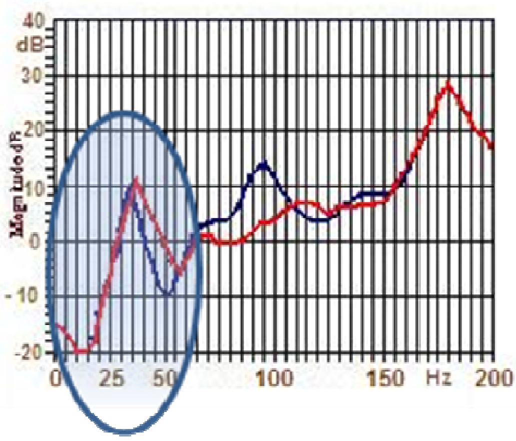

Figure 5. Typical FRF measured in the steering wheel of a driving tour vehicle

3. IMPORTANCE OF STUDYING THE STEERING WHEEL VIBRATION AT IDLE CONDITION

The drivers subjective perceived response regarding the flywheel vibration intensity at 28 typically used driving conditions was investigated by (Giacomin & Gananasekaran, 2005), based on the information collected through a questionnaire applied to 350 drivers. The intensity for each condition was quantified by means of the Borg CR10 scale method as shown in Table 1.

Their study shows low perceived flywheel vibration intensity at engine idle condition in relation to other conditions (Figure 6**)**. Although such research may serve as reference for the analysis of the importance of flywheel vibration at various conditions of use, it does not portray with fidelity the conditions of use in Brazil, in terms of streets and roads floors, vehicle types, fuels, etc. Another factor that emphasizes the importance of vibration at idle condition, from the point of view of the automotive industry is that, in this condition, clients associate the vibration discomfort perceived on the steering wheel to the actual vehicle quality. However, when the excitation is from an external source, even in higher levels, the client associates the discomfort to the external factors, such as the condition of the road.

ISSN 2176-5480

Table 1. Subjective assessment Borg CR10 scale (source: (Giacomin & Gananasekaran, 2005))

0	Nothing at all	"No P"
0.3		
0.5	Extremely weak	Just Noticeable
1	Very weak	
1.5		
2	Weak	Light
2.5		
3	Moderate	
4		
5	Strong	Heavy
6		
7	Very strong	
8		
9		
10	**Extremely strong**	**"Max P"**
11		
≈		
•	Absolute maximum	Highest Possible

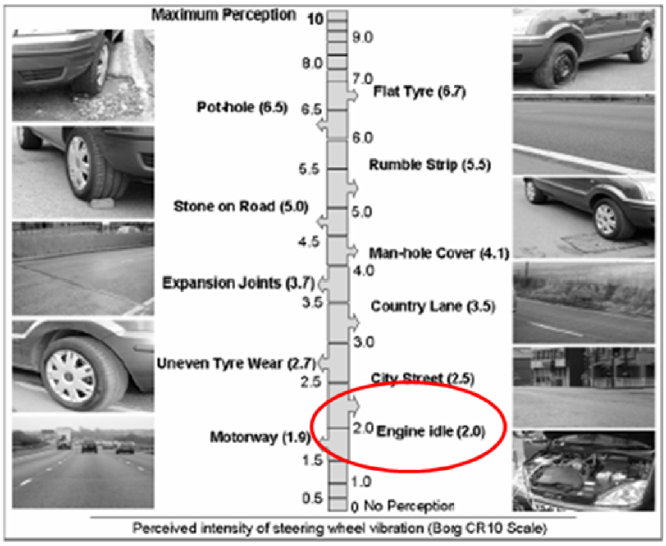

Figure 6. Proposal of subjective assessment scale to quantify the perceived vibration intensity at the steering wheel in various conditions of use of vehicle (source: (Giacomin & Gananasekaran, 2005)).

4. SOME FACTORS AFFECTING THE PERCEPTION OF STEERING WHEEL VIBRATION

There are several factors that can directly influence the perception of steering wheel vibration, linked to the frequency and levels of vibration, as it can be seem in Figure 8. Human factors also influence the subjective perception, as each individual responds differently to the same stimulus (Griffin, 1996). Some of them can be controlled by the drivers and others not. Although there are many factors, the investigation here will focus only at the drivers' hands position and grip force.

To assess the influence of these parameters in the comfort perception, a literature review was performed, targeting at the levels and frequencies of vibration of the engine operating condition proposed in this study (idle). For this, it was hypothesized that this frequency is around 30 Hz, based on the studies of the transmission sources described in Section 3. The vibration level was set at 0.7 rms, based on a survey correlating noise and vibration of the steering wheel in idle condition in 24 vehicles, conducted by (Ajovalasit & Giacomin, 2008), as shown in Figure 8.

ISSN 2176-5480

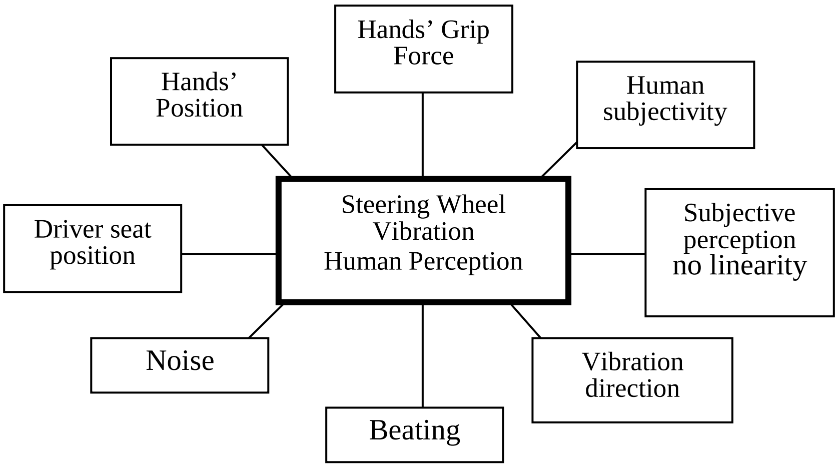

Figure 7. Factors influencing on the subjective perception of vibration of flywheel

In Figure 8 and from now on, all dotted lines are introduced by the authors (at the frequency and vibration levels that occur when the vehicle is stationary with the engine running at a minimum) to aid the analysis of the influence of the parameters on the vibration perception.

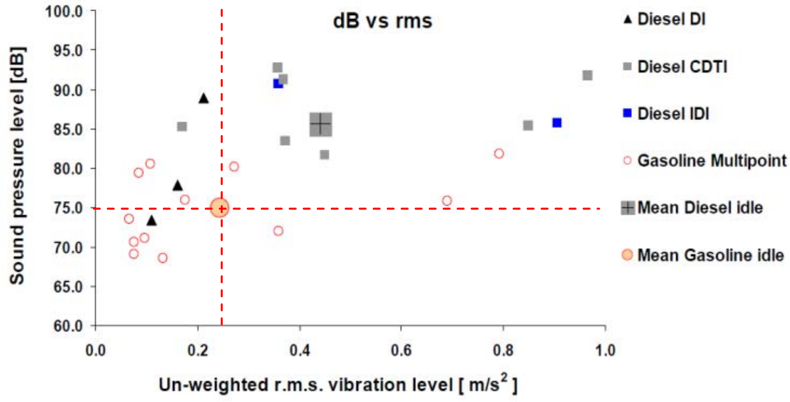

Figure 8. Analysis of sound pressure as a function of steering wheel vibration measured on 24 cars in idle condition (source:(Ajovalasit & Giacomin, 2008))

4.1 Influence of hands' position on the wheel

The influence of the hands' position on the wheel was evaluated by (Morioka & Griffin, 2009) through a vibration test in the vertical direction using the apparatus illustrated in Figure 9.

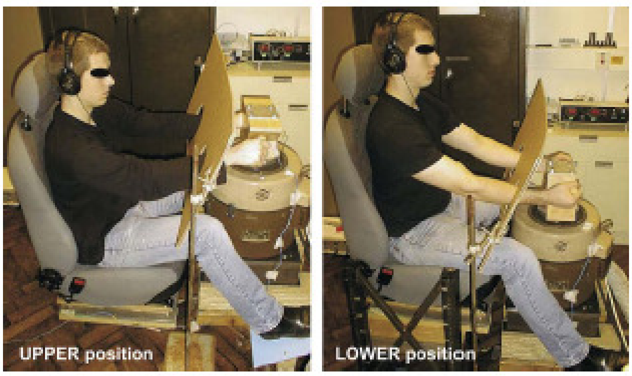

Figure 9. Apparatus used in the evaluation for the two hand positions (top and bottom).

Perception boundary curves from the two positions and comfort equivalent curves using psychophysical parameters were established. The results show low effect of the hands' position at the frequency and amplitude of interest indicated by the red dotted line.

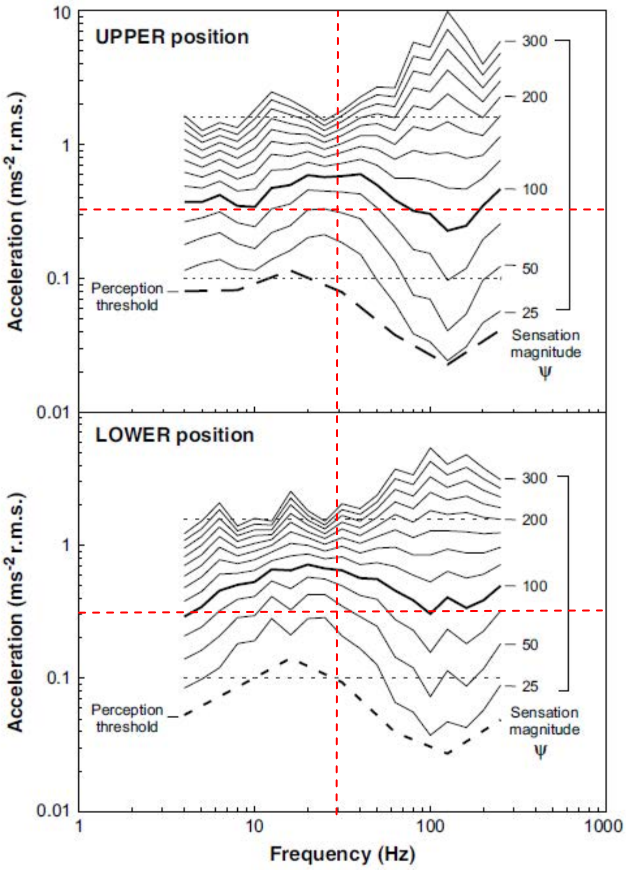

Figure 10. Equivalent comfort contours for each of the two hand positions (source: (Morioka & Griffin, 2009))

(Giacomin & Gananasekaran, 2005) investigated the usual hands' position on the flywheel. From the 350 volunteers' answers, 75% said they use both hands on the flywheel. From those, the majority holds the steering wheel at 2 and 10 position, as shown in Figure 11 and Figure 12.

Figure 11. Positioning statement holding both hands on the wheel (source: (Giacomin & Gananasekaran, 2005))

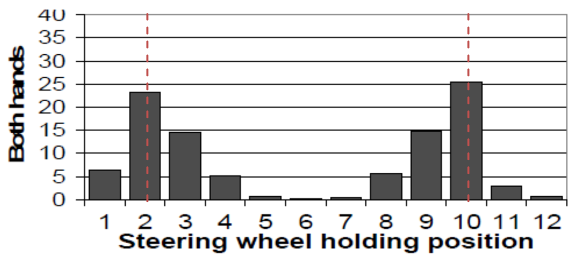

Figure 12. Percentage of drivers holding the wheel in each of the 12 positions shown in Figure 11 when holding with both hands (source: (Giacomin & Gananasekaran, 2005))

ISSN 2176-5480

4.2 Hands' grip force

The effect of the hands' grip force on the wheel was evaluated in the study by (Morioka & Griffin, 2009). In their experiment equivalent comfort curves using psychophysical parameters in terms of minimal, moderate and strong grip were raised. The results show the same effect caused in terms of minimal and light grip of the hands in the frequency and amplitude associated with the steering wheel vibration.

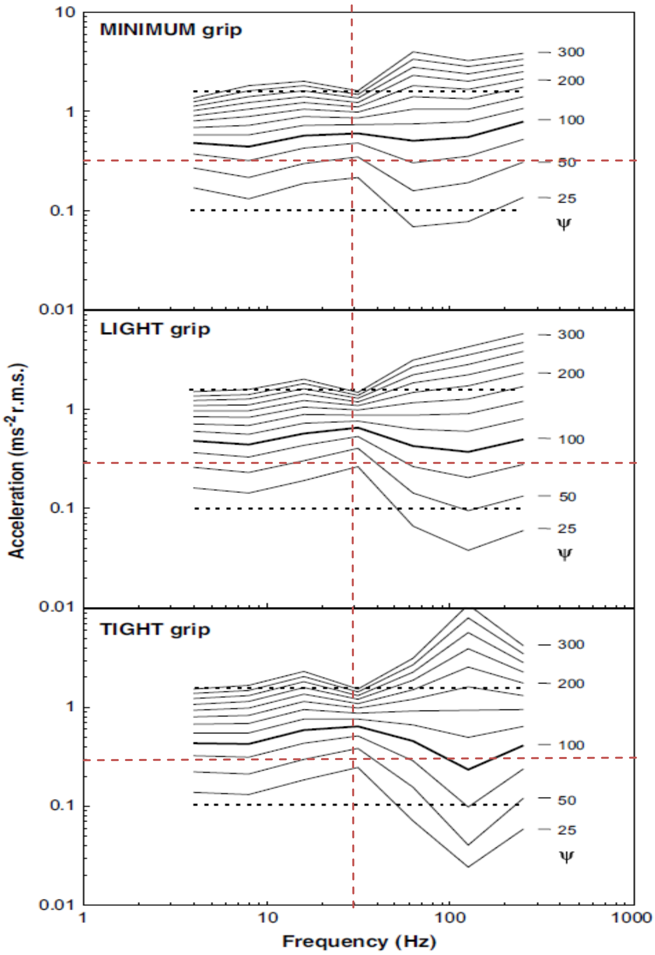

Figure 13. Equivalent comfort contours amplitudes for each of the three hands' grip force (source: (Morioka & Griffin, 2009)

On the same study by (Giacomin & Gananasekaran, 2005), they investigated the usual hands' force on the flywheel. For the subjects who use two hands on the flywheel, an average value of 3.76 points on the CR10 scale (Table 1) was obtained, which represents moderate hand grip.

5. TESTING METHODOLOGY

Experimental tests were performed on a sample of eleven vehicles of different categories and brands. The measurement for the characterization of steering wheel vibration was with the engine at idle condition, vehicle stopped, simulating the same condition when the driver waits at the red traffic lights. The operating temperature of the engine was stabilized at the normal operating condition of the engine.

5.1 Experimental Measurement

The measurements were made with both the a/c compressor ON and OFF in vehicles that have such device. The experimental apparatus used was a Mobile LMS Spectral Analyzer and a triaxial piezoelectric accelerometer PCB type for measurement of steering wheel acceleration levels in three perpendicular directions (X, Y and Z), as shown in Figure 14.

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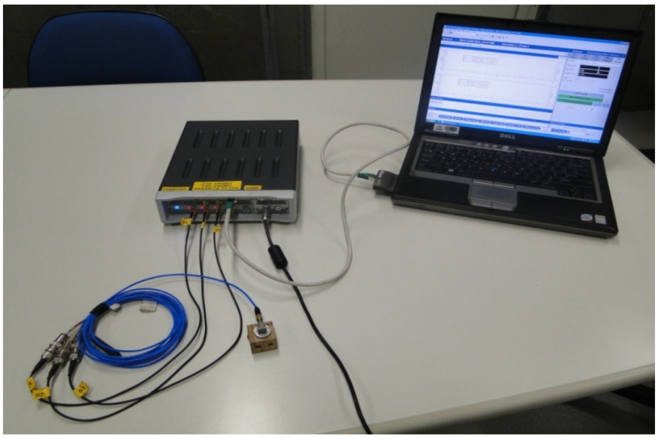

Figure 14. Experimental apparatus used for the tests performed

The accelerometer was positioned on the right side hoop as a 03:00 clock position, which normally supports the driver's right hand. This procedure is in accordance with both FIAT internal standards, as well as ABNT and European standards. The vibration direction during the study is shown in Figure 15 and the hand's position in Figure 16.

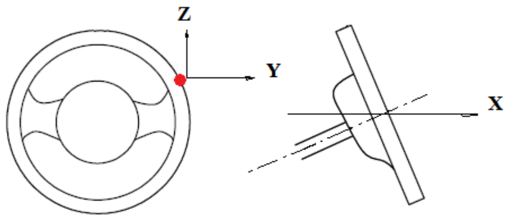

Figure 15. Direction of vibration during the study

Figure 16. Hand position during the subjective evaluation

5.2 Subjective Evaluation

The subjective parameter used for correlation with the experimental data was determined by the SAE standard scale, widely used in the automotive industry, as shown in Table 2. The feeling of comfort in this scale is translated into grades ranging from 1 to 10 varying from very poor to excellent respectively.

Table 2. SAE scale

<table>
<tr><th>SENSATION</th><th>REACTION</th><th>COSTUMER</th><th colspan="3">SCALE</th></tr>
<tr><td rowspan="3">Intolerable</td><td rowspan="2">Rejects</td><td>All</td><td>Very deficient</td><td rowspan="4">Not Acceptable</td><td>1</td></tr>
<tr><td rowspan="3">Middle</td><td>Deficient</td><td>2</td></tr>
<tr><td rowspan="3">Speak Out</td><td>Poor</td><td>3</td></tr>
<tr><td rowspan="2">Uncomfortable</td><td>Medíocre</td><td>4</td></tr>
<tr><td rowspan="2">Critic</td><td>Acceptance limit</td><td rowspan="6">Acceptable</td><td>5</td></tr>
<tr><td>Light nuisance</td><td rowspan="3">Accepted</td><td>Acceptable</td><td>6</td></tr>
<tr><td rowspan="2">Little discomfort</td><td rowspan="4">Expert</td><td>Appropriate</td><td>7</td></tr>
<tr><td>Good</td><td>8</td></tr>
<tr><td>No discomfort</td><td rowspan="2">None</td><td>Very good</td><td>9</td></tr>
<tr><td>No sensation</td><td>Excellent</td><td>10</td></tr>
</table>

A group of fourteen subjects were used for the subjective evaluation, being 12 males and 2 females. The evaluation was performed in the same vehicles and under the same conditions of experimental evidence

Subjects were instructed to position the two hands at 3:00 position and to apply moderate grip, based on the studies of the factors that influence the perception of vibration of flywheel (section 4). The subjective perception of vibration for each vehicle/condition was evaluated based on the SAE scale shown in Table 2.

ISSN 2176-5480

6. RESULTS AND DISCUSSIONS

Figure 17 shows the vehicles experimental spectral analysis obtained in X, Y, and Z directions indicating the predominant frequency around 30 Hz with average amplitude around 0.8 m/s². Such results confirm the values hypothesized in the search for the definition of the testing methodology (section 2).

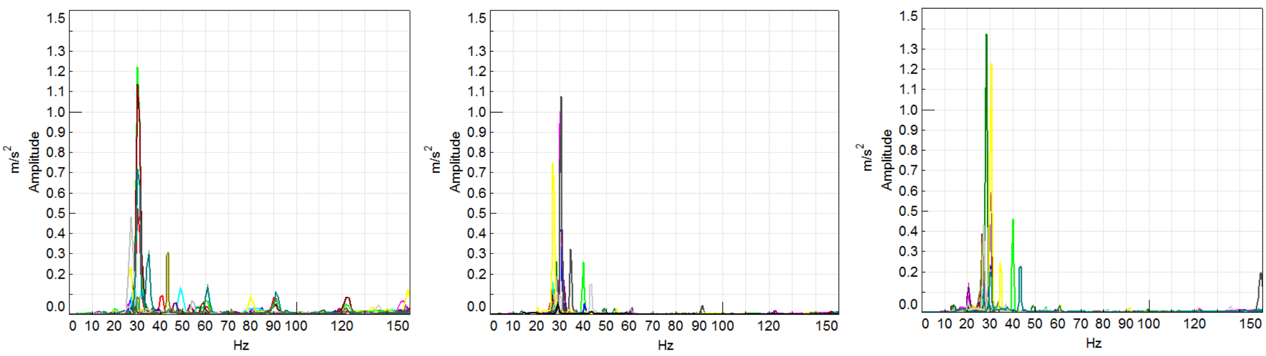

Figure 17. X, Y and Z direction vibration spectral analysis

The correlation between the flywheel vibration levels in function of their SAE note is shown in Figure 18.

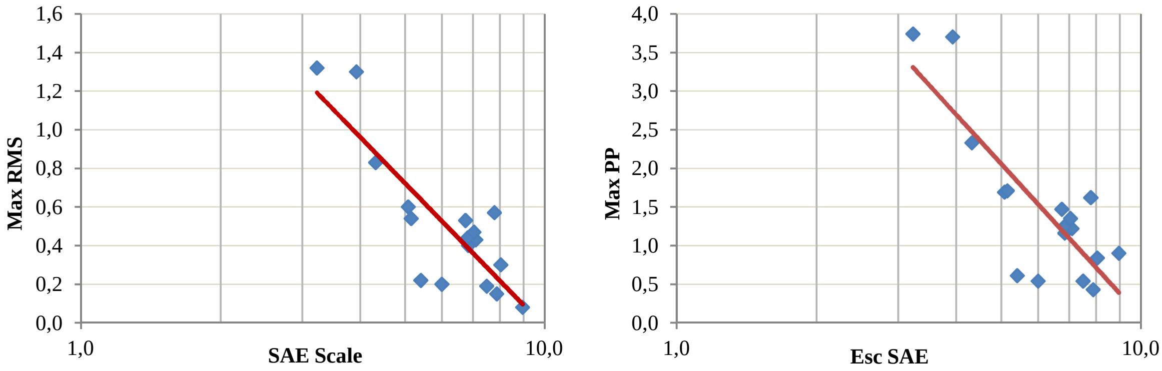

Figure 18. Correlation Max aRMS (left) and Max aPP (right) in (m/s^2) x subjective SAE scale

Figure 18 (left) shows the equivalent global vibration values curves OA using RMS as parameter. The maximum levels at the 3 directions were considered. Linear regression analysis of this figure suggests subjective equivalence defined by equation (1):

$$Max\ aRMS = -1{,}072 ln(SAEvalue) + 2{,}448 \quad (\mathrm{m/s^2}) \qquad (1)$$

The coefficient of determination (R^2) for this correlation was 0.71, indicating a fair correlation.

Figure 18 (right) also shows the equivalent global vibration values, however, now using peak-to-peak as parameter, again considering the maximum levels at the 3 directions. Linear regression analysis suggests the subjective equivalence defined now by equation (2):

$$Max\ aPP = -2{,}856 ln(SAEvalue) + 6{,}6534 \quad (\mathrm{m/s^2}) \qquad (2)$$

The coefficient of determination for this correlation was 0.67, equivalent to the one found with the RMS parameter. This coherence is justifiable since the average crest factor was around 1.4.

On the basis of this analysis, by using equations (1) and (2) and the SAE values at Table 2, it was possible to establish goals that reflect the perception of vibration of the subjective point of view in various levels of comfort, by using eqs. (1) and (2) and the SAE values at Table 2, as presented in Table 3.

Table 3. Comfort scale SAE for each parameter

SENSATION	Esc SAE	Max aRMS	Max aPP
Poor	≤ 4	≥ 0.96	≥ 2.694
Acceptance limit	5	0.72	2.06
Acceptable	6	0.53	1.54
Appropriate	7	0.36	1.1
Good	8	0.22	0.71
Very good	9	0.1	0.4
Excellent	10	0.02	0.08

As shown in Table 3, the value using Max aRMS considered excellent in the SAE scale is negative. Therefore, it should be considered a level equal 0 (zero), what makes impractical this approach. Therefore, the absolute value was considered.

7. CONCLUSION

This study defined some technical objectives for quantifying the subjective feeling of steering wheel vibration. Based on the survey it was possible to develop criteria for the evaluation of steering wheel vibration with engine idle in the most usual driver condition, that is hands at 2/10 position and moderate grip force. The experimental results were considered satisfactory for this criteria and a correlation between the SAE scale and the experimental levels was established.

The definition of criteria for the experimental evaluation was important in order to obtain a good correlation between objective and subjective data. Nevertheless, scatters were still significant due to the inter-subjectivity in the assessment. At first, only hands position and grip force were taken into consideration.

Among the factors evaluated, the analysis using the acceleration values peak-to-peak and RMS as parameter levels showed to be adequate, since the 3 directions were considered in the analysis. However, it is believe that the results may be improved even further by considering the weighting curves on the amplitude levels prior the assessment.

8. ACKNOWLEGMENT

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