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DYNAMIC BEHAVIOR ANALYSIS ON HANDLING AND COMFORT OF A PASSENGER CAR

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Abstract. *Automotive suspension systems are designed to allow the driver full control of the vehicle. These systems must ensure efficiently the vibration insulation of the car cabin, the tire grip on the road and the vehicle's stability while performing maneuvers. In this paper, an experimental investigation regarding the dynamic behavior of a typical passenger car is presented. The dynamic behavior analysis of the vehicle suspension aims at verifying the efforts and displacements of this system, in order to evaluate the steering response and passengers comfort. Typical ride and handling maneuvers were considered in the physical tests. The ride comfort study is presented emphasizing the required metric to quantify the vehicle comfort, according to ISO 2631. In this proposed evaluation the gains of typical transfer functions and the respective phases were built and displayed in Bode diagrams. The data collected were processed and analyzed in frequency domain using the LMS software Test.Lab and relevant aspects of the tests on the vehicle were evaluated. In general, the analyzed results in the frequency response indicate that the vehicle-A features show faster response, verified mainly due to lower phase angle when analyzing the roll angle. Comfortable vehicles tend to have lower lateral acceleration when response to Yaw, which was confirmed by low Ride Index, as it does with vehicle-B. The phase analysis had a significant influence on evaluation and Bode plots were very helpful. The procedures and results of this study will be applied to develop a multi-body model adapted to accurately simulate the vehicle's behavior. It enables to better balance the conflict between comfort and handling performance earlier in the development process.*

Keywords: *Vehicle Dynamics, NVH, Handling, Ride Comfort, Suspension System*

1. INTRODUCTION

Both handling and ride comfort are important aspects in the passenger car performance and usually result in a reliable suspension. Vehicle handling refers to the way the vehicle performs during turning maneuvers and ride to how the vehicle suspension responds to holes, bumps and other roadway irregularities. Vehicle's ride comfort is one of the most important factors affecting the purchase decision and customer satisfaction. The smoother the ride is, the less track irregularities the vehicle occupants feel. Mechanical requirements of the suspension system for directional control, cornering forces and ride comfort are continuously changing according to driving conditions, although many ride problems are peculiar to a specific road. Thus, the suspension system of a vehicle should perform efficiently the vibration insulation for the vehicle cabin, the tire grip on the road and the vehicle's stability during maneuvers (Gillespie, 1992).

Firstly, a good ride response from the vehicle requires soft suspensions that lead to better passenger comfort. However, if handling performance is the main target, the suspension needs to be stiffer, although decreasing passenger comfort. Therefore, the suspension characteristics have a great influence on noise, vibration and harshness (NVH), handling performance and vehicle's design.

The vehicle vibration is transmitted to passengers by the seat, the floor and the steering wheel during the vehicle driving process (ISO 2631-1, 1997). Several studies in the literature seek to characterize and find a standard for ride comfort evaluation; however, there is no fully defined standard for this type of evaluation. The international standard ISO 2631-1 provides a useful and well known criterion about ride comfort. This standard is applied in case of vibrations transmitted to human body in the frequency that ranges from 1 to 80 Hz and the use of weights allows to delineate this sensitivity.

In this paper, the dynamic behavior of a passenger car was investigated, as well as the ability to provide additional comfort, and to promote stability and drivability when performing maneuvers. Therefore, the study of vehicle dynamics was based on experimentally obtained data for ride and handling maneuvers, under stabilized speed condition. The vehicle ride study is presented emphasizing the required metric to quantify the comfort, according to the ISO 2631. In this case, the frequency-weighted mean square value of the acceleration was the proper norm for evaluating comfort.

This paper also considers the criteria that have been used to measure handling performance by focusing on the vehicle's steering wheel response, based on metrics describing the gains input from a given steering wheel angle (SWA). The majority of these metrics are related to Yaw rate and lateral acceleration of the vehicle.

The vehicle dynamics behavior can be more significantly characterized by considering the input and output relationships, and the ratio of these relationships represents a gain for the dynamic system (Gillespie, 1992).

In this proposed evaluation, the gain of four typical transfer functions and their respective phases are built and shown in Bode diagrams, as follows: 1- SWA as input and lateral acceleration as output; 2- SWA as input and Yaw rate as output; 3- Yaw as input and lateral acceleration as output; 4- SWA as input and roll angle as output. The data collected were processed and analyzed using different methodologies in the frequency domain using the LMS software Test.Lab v.14A.

2. METHODOLOGY

The tests were performed in two different vehicles of the B-segment, in order to compare the behavior of dynamic events. This vehicle class is defined by the European market car classification. The B-segment cars, also known as superminis in British market or subcompact cars in North America, are small, lightweight and designed to seat four passengers comfortably (Opland, 2007).

2.1 Comfort tests

The international standard ISO 2631, used as a guide on ride comfort analysis, can be applied to vertical excitation input, under the condition that the energy frequency band considered is comprised between 1 and 80 Hz.

Ride comfort tests can be of two types: transient and deterministic, such as obstacle passing; or uneven and random road such as city asphalt, cobblestone roads and highway. In the case of obstacle passing, where the basic evaluation method may underestimate the effects of vibration, the fourth power vibration dose value should also be determined (ISO 2631-1, 1997).

In this context, the dynamic behavior was observed during the passage of the vehicle through obstacles, travelling in a straight line, which generated an excitation pulse on the tire. In order to evaluate the ride comfort influence, the dynamic responses in the frequency domain are obtained, using as input a pulse on the tire, when the vehicle is travelling over the obstacle at 30 kph (8.33 m/s). The obstacles (0.012 x 0.012 m cross section) used in the tests are positioned along a paved section, as shown in Fig. 1.

Figure 1. Road obstacles acts as a vertical displacement input to the tires

2.2 Handling tests

The tests were carried out using three options of maneuvers for handling evaluation, known as On-Center, Swept Steer and Lane Change. The Lane Change procedure is to leave the vehicle at the required test speed in a straight line and then apply the steering wheel angle as soon as possible to a pre-set value. The longitudinal speed is kept stabilized and the steering wheel angle is changed.

In the Lane Change tests, a steering wheel angle rate from 400 to 700 deg/s (6.98 to 12.217 rad/s) is applied to achieve lateral acceleration between 0.3 and 0.6 g (2.94 to 5.88 m/s^2), within the linear range of the vehicles behavior, according with guidelines contained in the literature (Blundell and Harty, 2004). The maneuver is performed at 75 kph

(20.83 m/s), which resulted in a steering increment rate around 550 deg/s (9.599 rad/s). The Lane Change maneuver performed in this study is represented by single cycle sinusoidal steering input. Figure 2 shows the steering wheel angle over acquisition time.

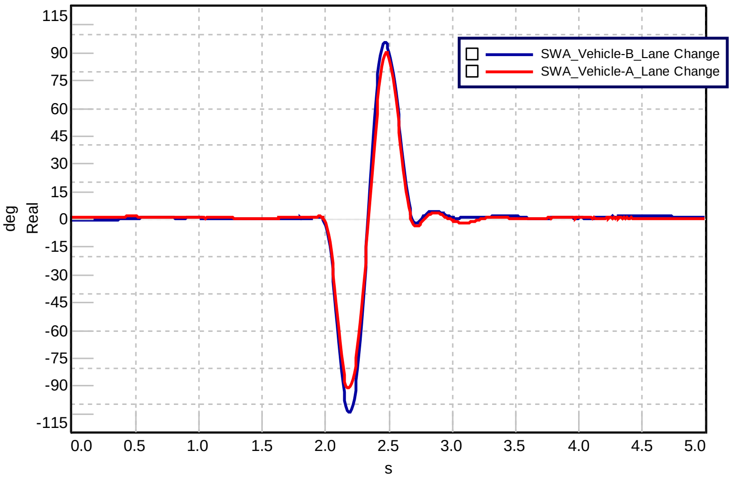

Figure 2. SWA over time in Lane Change Maneuver

On-center maneuver is conducted on the vehicle from an input of steering wheel angle with amplitude of about 30 deg (0.52 rad), under continuous sinusoidal steering input. This maneuver is an open-loop test method to determine the transient response behavior and steering performance for low lateral accelerations, about 0.2 g (1.96 m/s^2). The vehicle is driven at a constant speed of 75 kph (20.83 m/s).

Swept Steer test determines the steering performance at sufficient steady state to characterize the roll and lateral dynamics. This test is an open loop maneuver performed in order to evaluate turning performance at steady state. The steering wheel angle is linearly ramped up to a pre-set value. The standard steady state lateral acceleration level is 4 m/s^2, over a pulse width of 0.3 to 0.5 s. Under steer gradient and steering wheel torque is used to evaluate torque feedback and response.

To choose the right maneuver to be evaluated, a methodology already implemented (Fernandes et al., 2007) was used, in which the right maneuver for analysis should be one with the greatest ability to excite high frequencies of vehicle dynamics, to have a higher frequency range for Steering analysis. For this aim, one of the most useful representations is the Power Spectral Density (PSD) function.

By analyzing the mentioned maneuvers through the PSD of SWA, it is possible to verify that the Lane Change maneuver is the one that achieves higher excitation frequencies and, therefore, maintains a relatively constant and adequate level of excitation energy up to 1.5 Hz, as shown in Fig. 3. Based on these arguments, the Lane Change maneuver was selected for the investigation.

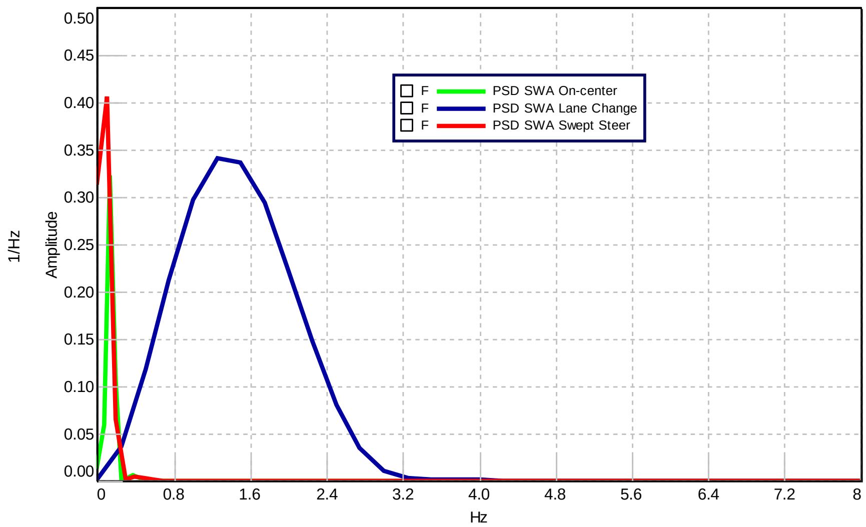

Figure 3. Power Spectrum Density of Steering Wheel Angle

3. RESULTS

This section presents and discusses the tests results obtained with the two vehicles evaluated. Before discussing any data, it is important to mention that the methodology to measure the vehicle behavior during maneuvers was essential to understand the subjective phenomena that occur during handling tests. The method also provides more insight into the relationship between comfort and handling performance.

3.1 Ride comfort

One of the evaluation criteria used by the ISO 2631 standard to compare the limits of whole body vibration signals is the acceleration levels measured in one-third octave band, treated as a root mean square (RMS). Figure 4 shows the basicentric axes of the human body in the seated position.

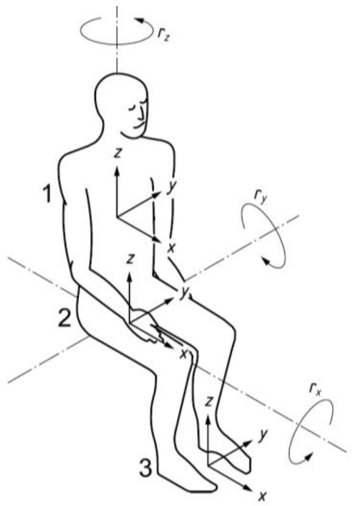

Figure 4. Basicentric axes of the human body in the seated position (ISO 2631-1, 1997):
1- Seat-back / 2- Seat-surface / 3- Feet

An important aspect used by the ISO 2631 to evaluate the ride comfort is the Ride Index creation process, which must be calculated to get a global level of analysis axes. For this, the standard requires the application of the following steps, as shows in Tab. 1.

Table 1. Schematic process to calculate the Ride Index (ISO 2631-1, 1997)

Acceleration Component	Frequency Weighting	Weighting for each axis	VDV Component	Ride Index
a_x	W_d	1.0	VDV_x	
a_y	W_d	1.0	VDV_y	$(\Sigma VDV)^{1/4}$
a_z	W_b	1.0	VDV_z	

The weighted RMS acceleration can be given by:

$$a_w = [\Sigma_i (W_i \cdot a_i)^2]^{1/2} \quad (1)$$

where a_w is the weighted acceleration, a_i is the RMS acceleration for each central frequency in one-third octave band and W_i the weighting factor for the corresponding frequency.

The factors are normalized to 1.0.

The fourth power vibration dose value (VDV) is handled for each basicentric axis, as shown in the Eq. (2):

$$VDV_{(x,\,y,\,z)} = \Sigma\, a_{w\;(x,\,y,\,z)}^{4} \tag{2}$$

Finally, the Ride Index (RI) is then computed by multiplying each basicentric axis of this serial by frequency-weighted values:

$$RI = [\Sigma\, VDV_{(x,\,y,\,z)}]^{1/4} \tag{3}$$

However, the ride comfort criterion should not be the magnitude, but the level of comfort. For this, the standard presents the Tab. 2.

Table 2. Vibration values that determine the comfort level (ISO 2631-1, 1997)

Less than 0.315 m/s²	not uncomfortable
0.315 m/s² to 0.63 m/s²	a little uncomfortable
0.5 m/s² to 1 m/s²	fairly uncomfortable
0.8 m/s² to 1.6 m/s²	uncomfortable
1.25 m/s² to 2.5 m/s²	very uncomfortable
Greater than 2 m/s²	extremely uncomfortable

In accordance with ISO 2631, values in Fig. 5, 6 and 7 show that the cars are in the range from comfortable to slightly uncomfortable, and in some axes to achieve fairly uncomfortable. The dotted lines correspond to the threshold of daily occupational vibration exposure, to different magnitudes and durations. It should be noted that the most sensitive frequency bands, in which the limit is lower, are 4 to 8 Hz for vibration in the z-axis and less than 2 Hz for vibration in the x and y-axis, and the tolerance to vibration decreases due to the increase in exposure time.

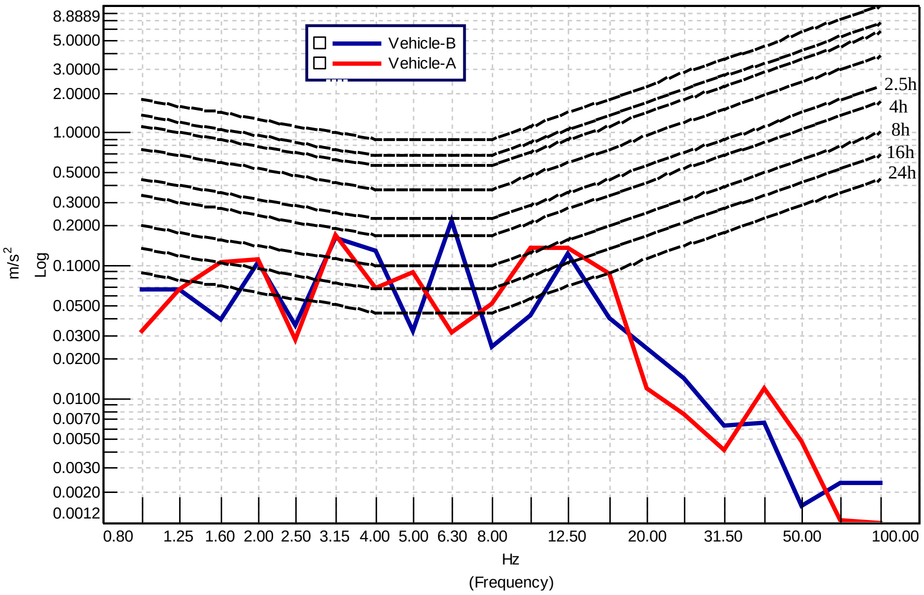

Figure 5. Comfort results for z-axis measured on the driver's seat

An important feature that can be observed in Fig. 5, 6 and 7, i.e., while the tolerance for vibration in the x and y-axis is lower than in the one along the z-axis at very low frequencies, the opposite occurs for higher frequencies.

In general, the results in experimental tests for the three directions showed that the vehicle-B was well adjusted to the relative standard comfort. In the Z direction, the vehicle-A exhibited a similar behavior as compared to vehicle-B, and the response in the critical range between 4 and 8 Hz was even better than the competitor. However, for the other directions the vehicle-A showed a certain level of discomfort.

According to Tab. 2, the vehicle-B received the best evaluation and can be considered a comfortable vehicle, which had a Ride Index of 0.246 m/s^2. However, the vehicle-A showed a high rate ride of 0.395 m/s^2, which tends to behave as a "little uncomfortable" vehicle.

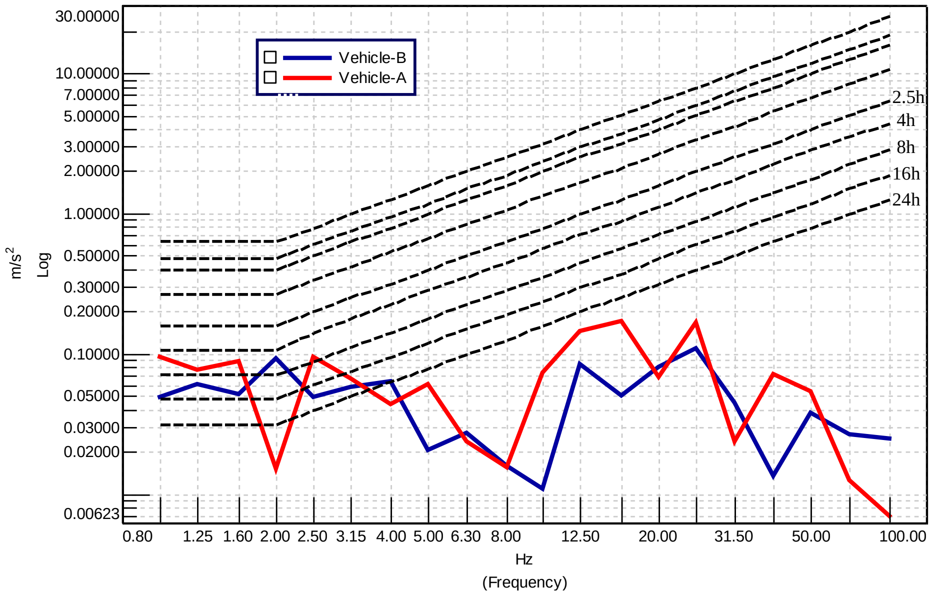

Figure 6. Comfort results for x-axis measured on the driver's seat

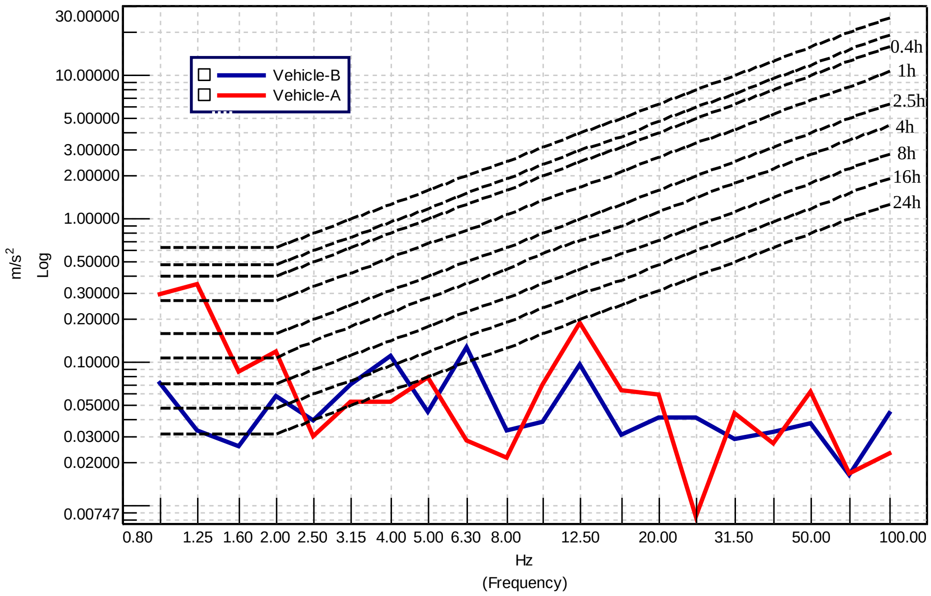

Figure 7. Comfort results for y-axis measured on the driver's seat

3.2 Handling performance

The analyzed metrics are presented using Bode diagram plots, as given by gain and phase functions over frequency. The Bode plot represents a function window divided into two parts. It shows two aspects of the same data. The upper part shows the amplitude and the lower part shows the phase of the same trace. A Bode plot helps to analyze how the output follows the input, showing the ratio of them and the excitation frequency and the phase between the two signals.

In order to obtain good coherence for the measured transfer function, the time signal was conditioned in four runs of equal size, to produce a signal with 10 seconds interval and resolution of 0.4 Hz. In addition, a Hanning window was applied to improve the results without data loss due to the windowing process. The signal overlap assumption was not required. Data blocks can overlap the preceding one to compensate the effects of applying a time window. These are equidistantly distributed over the whole signal, thus the amount of overlap depends on the signal length.

Observing the Fig. 8(a), which represents the SWA as input and lateral acceleration as output, the vehicle-A showed a slightly higher gain compared to the vehicle-B with a frequency of 1.8 Hz, tending to increase significantly above this value. Furthermore, the vehicle-A showed less phase lag than the vehicle-B.

In the evaluation results of SWA (Input) and Yaw (Output), Fig. 8(b), the vehicle-A showed a slight gain and smaller phase lag, showing that this vehicle has the characteristics of faster response when performing specified maneuvers.

When assessing the results of Yaw (Input) and lateral acceleration (Output), Fig. 8(c), a similar behavior to the one shown in Fig. 8(a) can be observed, both gain and phase of the vehicles. Comfortable vehicles tend to have lower lateral acceleration as a response to Yaw, which was confirmed by low Ride Index, as it does with vehicle-B. The analyzed results from the four transfer functions analyzed in the frequency response indicate that the vehicle-A features show faster response, as verified mainly due to lower phase angle when analyzing the roll angle, as shown in Fig. 8(d).

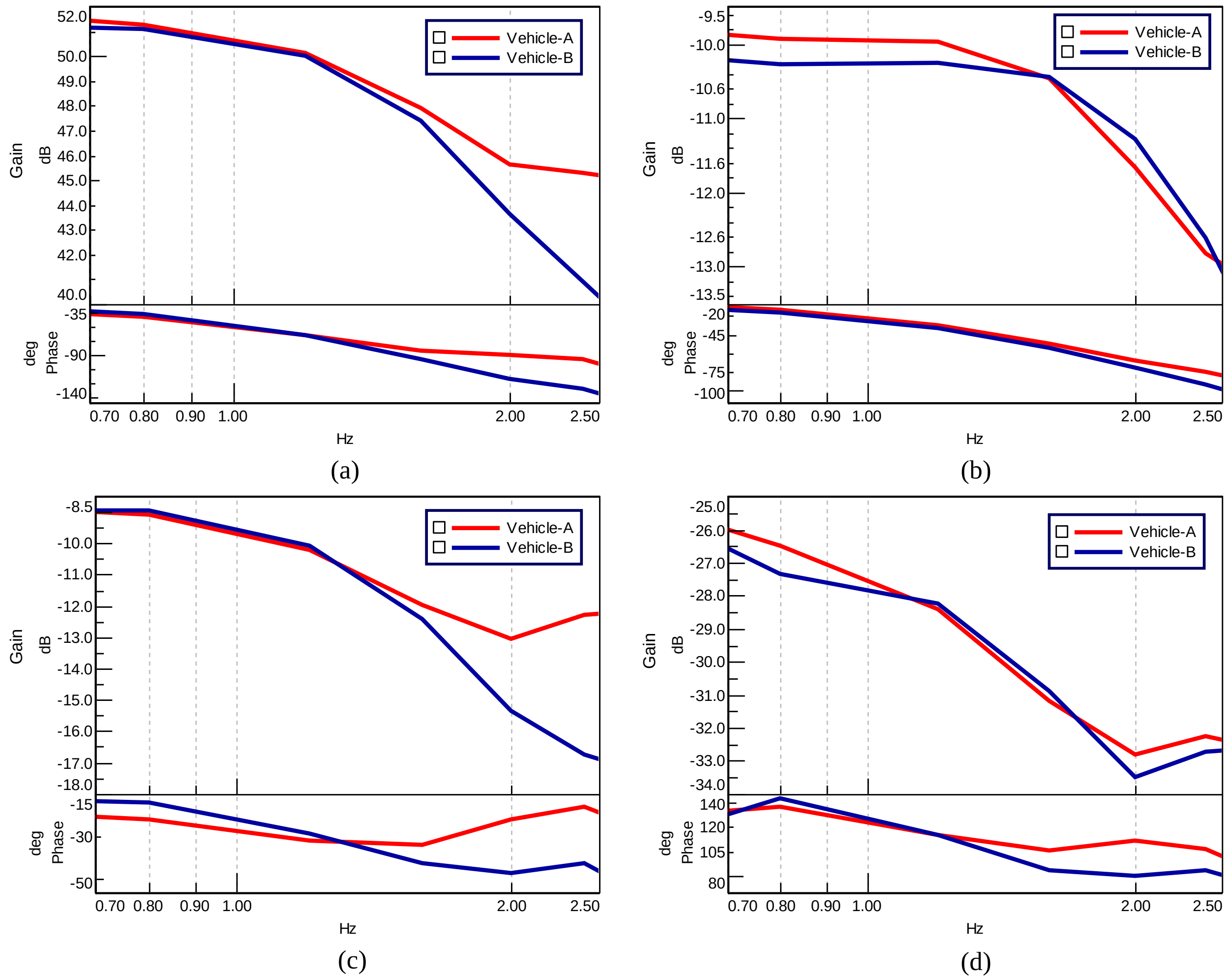

Figure 8 – (a) Lateral acceleration response to steering wheel angle; (b) Yaw rate response to steering wheel angle; (c) Lateral acceleration response to Yaw rate; (d) Roll angle response to steering wheel angle

4. CONCLUSIONS

The method proposed to analyze the dynamic behavior of two chosen passenger cars shows that the vehicle-A has an optimal behavior in steering response. However, this vehicle is on the limit of not complying with the ride comfort requirement.

According to ISO 2631-1 the results from experimental tests for the three directions show that the cars are in the range between “comfortable” and “little uncomfortable”, and for some axes they are prone to achieve “fairly uncomfortable”. It was observed that the vehicle-B was well adjusted to the relative comfort standard. The vehicle-B was considered a comfortable vehicle, which had a Ride Index of 0.246 m/s^2. However, the vehicle-A showed a high rate ride of 0.395 m/s^2, which tends to behave as a “little uncomfortable” vehicle.

In general terms, the analyzed results from the four transfer functions in the frequency response indicate that the vehicle-A features show faster response, as verified mainly due to lower phase angle when analyzing the roll angle. The vehicle-B has lower lateral acceleration when response to Yaw is considered, which has been confirmed by low Ride Index. Observing the frequency transfer function between the steering wheel angle (input) and lateral acceleration (output), the vehicle-A showed a slightly higher gain compared to the vehicle-B in a frequency of 1.8 Hz, which tends to increase considerably above this value. The phase analysis had a significant influence on evaluation and Bode plots were very helpful to understand the well-known phenomena that occur during handling tests.

The procedures and results of this study will be applied to develop a multi-body model adapted to accurately simulate the vehicle's behavior. The purpose of creating this model is to significantly reduce the experimental costs during vehicle development phase. It enables to balance comfort and handling performance during body design. It is expected that the virtual model may be reliable, thereby boosting the component's development that comply with the previously established criteria.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Blundell, M.; Harty, D., 2004. *Multibody Systems Approach to Vehicle Dynamics*. Oxford: Elsevier Science, Burlington, MA.

Fernandes, C., Passos, L., de Mello, K., and Peres, E., 2007. "A New Approach to Improve Steering Response Development Using Bode Diagrams". *SAE Technical Paper* 2007-01-2548, 2007, doi:10.4271/2007-01-2548.

Gillespie, T. D., 1992. *Fundamentals of Vehicles Dynamics*. SAE International, Warrendale, PA.

International Standards Organization, 1997. Mechanical vibration and shock, Evaluation of human exposure to whole-body vibration, Part 1: General requirements, ISO 2631-1, 1997(E).

Opland, L., 2007. *Pre-study on how to size classify passenger cars by inventorying the existing classification models.* Master's Thesis, Chalmers University of Technology, Göteborg, Sweden.

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