RIDE COMFORT COMPARISON BETWEEN SUSPENSION MODES: INPUT TOWARDS DESIGNING DIFFERENCE THRESHOLD EXPERIMENTS DURING DRIVING

Cor-Jacques Kat[a]* (cor-jacques.kat@up.ac.za)
Kylian Praet[b]
Miguel Dhaens[b]
Schalk Els[a]

[a]Vehicle Dynamics Group, Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria, South Africa
[b]Tenneco Automotive Europe – Monroe® METC, Sint-Truiden, Limburg, Belgium
*Corresponding author

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Abstract

Ride comfort is an important topic for on- and off-road suspension design. Difference thresholds of whole-body vibration is important to determine perceptibility of changes in a vehicle's dynamics. Difference thresholds can be used to guide ride comfort improvements. Difference thresholds have been estimated for vertical and multi-axial seat vibration in laboratory settings. In order to determine the applicability of these laboratory difference thresholds and/or to estimate difference thresholds during driving, it is required that changes can be made in the vehicle's vibration that is transmitted to the occupants i.e. the stimulus. Ride comfort is quantified by the weighted vertical seat pad vibration and compared between four suspension modes of a vehicle over three roads from ten repeat runs. Significant differences in the median weighted vertical seat pad vibration were found between Mode 1 and the other three modes over Road 1 and Road 2. No significant differences were found over Road 3. The significant differences over Road 1 are in the range of the median relative difference threshold reported in literature. Over Road 2 the differences are below the reported 25th percentile relative difference thresholds. Some combinations of the suspension modes and roads result in ride comfort differences. The suspension mode and road combinations could be used to verify the applicability of available difference thresholds during driving.

Keywords: ride comfort, vehicle vibration, difference thresholds.

1. INTRODUCTION

The difference threshold for vehicle vibration on a seat is defined by Mansfield and Griffin (2000) as: "...the minimum change in the magnitude of the whole-body vibration required for the seat occupant to perceive the change in magnitude." The difference threshold is also referred to as the just noticeable difference. The relative difference threshold is obtained by taking the percentage of the Weber fraction which is the ratio between the just noticeable change in stimulus magnitude and the reference stimulus magnitude.

Knowledge of the difference threshold is useful in determining whether changes in a vehicle's vibration, for example due to different suspension characteristics, would be perceivable by vehicle occupants.

Studies have estimated difference thresholds for whole-body vibration for participants seated on a rigid surface exposed to vertical sinusoidal vibration (Morioka and Griffin, 2000, Matsumoto et al., 2002, Forta et al., 2009), for participants seated on a car seat exposed to vertical random vibration (Mansfield and Griffin, 2000, Pielemeier et al., 1997), and for participants in a vehicle on a 4-poster subjected to multi-axis random vibration (Gräbe et al., 2020). The studies using random vibration considered stimulus changes in magnitude resulting from changes over the entire spectrum. All these studies were conducted in laboratory conditions. The study with conditions closest to driving is that of Gräbe et al. (2020). Participants were seated in a vehicle that was excited on a 4-poster test rig in a semi-anechoic chamber, creating an environment with limited aural and visual inputs.

In order to determine the applicability of these laboratory difference thresholds, or to estimate difference thresholds during driving, it is required that changes can be made in the vehicle's vibration that is transmitted to the occupants i.e. the stimulus.

The aim of this paper is to determine the difference in ride comfort, as quantified by the vertical seat pad vibration between four suspension modes of a vehicle over three roads. Significant differences between modes are compared to difference thresholds in literature.

2. MATERIALS

The vehicle is fitted with a developmental Monroe Intelligent Suspension CVSA2/Kinetic® suspension system that can be set to different modes. Four different modes were defined for this study. The CVSA2/Kinetic® system was deactivated in one mode and activated in different development settings for the other three modes. Acceleration was measured on the driver seat surface in the vertical direction below the ischial tuberosities of the driver using a seat pad accelerometer (356B40, PCB Piezotronics). Data was sampled at 10 kHz using IPETRONIK (Mx-SENS2, IPETRONIK) with a 1250 Hz anti-aliasing filter. For ride comfort measurements, a lower sampling rate would be sufficient (e.g. sample rate of 400 Hz and anti-aliasing filter at 100Hz (Paddan and Griffin, 2002)). The selected sample rate was with respect to additional measures that were also recorded and used for other aspects. Details about the road profile and suspension modes are not provided as this information is proprietary.

3. METHOD

The vehicle was driven over three different roads in each of the four suspension modes. Ten repeat runs of each suspension mode over each road were completed. The cruise control of the vehicle was set to the desired speed for each road.

The effect of whole-body vibration on comfort was evaluated according to BS 6841 (1987) in order to compare to the relative DT difference thresholds obtained by Gräbe et al. (2020). They estimated difference thresholds using the BS6841 weighted vertical seat pad acceleration and the combined point ride value. No significant difference was found between the medians of the relative difference threshold of the two ride values. Therefore, the current study will consider the weighted vertical seat pad acceleration. The vertical seat vibration is measured by the seat pad accelerometer. The vertical seat acceleration is weighted in the frequency domain during post processing using the applicable weighting function and multiplication factor as defined in BS 6841 (1987). All frequency content below 0.5 Hz and above 80 Hz is discarded. This results in the vertical component ride values (CRVz). The crest factors for all suspension modes over Road 1 and 3 are below six. The crest factors for the suspension modes over road 2 range between 5.8 to 6.8. The root-mean-square (r.m.s.) is used to represent the magnitude of the acceleration since the crest factor is below six for most of the modes and roads. The severity of high peaks over Road 2 may be underestimated by using r.m.s. (BS 6841, 1987).

Statistical analyses, including hypothesis testing, were done with MATLAB® version 2020b (Mathworks, Natick, MA, USA). Because of the small sample size, non-parametric hypothesis tests were used. Friedman’s test and Dunn’s multiple comparison tests were used to determine if the vertical component ride value differ significantly between the four suspension modes.

The percentage relative difference in the median vertical component ride value between suspension modes are calculated using Eq. 1. The convention used with respect to the reference mode is that the mode with the lower mode number in a pair is chosen as the reference mode.

$$\textit{perc.rel.diff.} = (\text{mode-reference mode})/(\text{reference mode}) \times 100 \qquad (1)$$

4. RESULTS

The distributions of the vertical component ride value are shown in the box plots in Figure 1, Figure 2 and Figure 3 for Road 1, Road 2 and Road 3, respectively.

Friedman’s test did indicate a significant difference between at least two median vertical component ride values across the four suspension modes on Road 1 (p-value < 0.001) and Road 2 (p-value < 0.001). Friedman’s test did not indicate a significant difference between any of the median vertical component ride values across the four suspension modes on Road 3 (p-value = 0.266). Table 1 and Table 2 present the adjusted p-values (Bonferroni correction) for Dunn’s multiple comparison tests over Road 1 and Road 2, respectively.

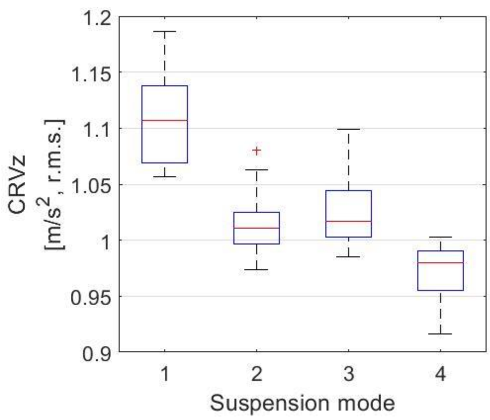

Figure 1. Box plots showing the distribution of the vertical component ride value (CRVz) over Road 1

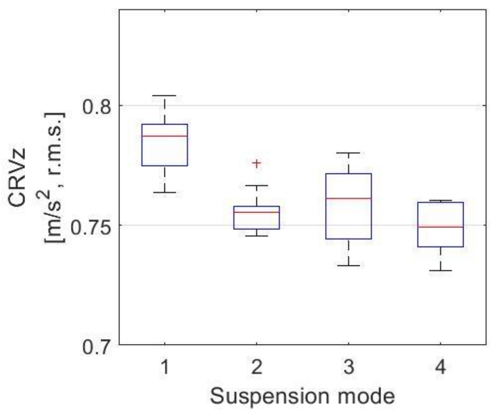

Figure 2. Box plots showing the distribution of the vertical component ride value (CRVz) over Road 2

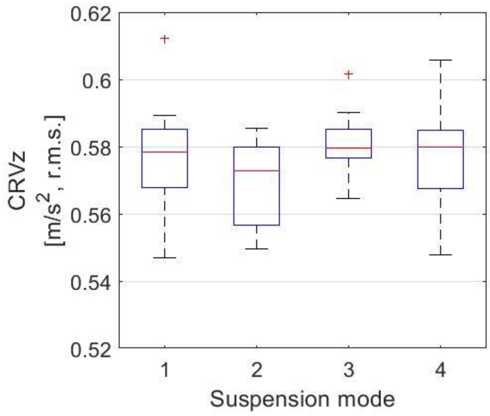

Figure 3. Box plots showing the distribution of the vertical component ride value (CRVz) over Road 3

Significant differences were found over Road 1 between suspension Mode 1 and Mode 2 (p-value = 0.006) and between Mode 1 and Mode 4 (p-value = 0.000). Between Mode 1 and Mode 3 a marginally significant difference was found (p-value = 0.056). Over Road 2, significant differences were found between suspension Mode 1 and the other 3 modes (Mode 1 vs Mode 2, p-value = 0.019; Mode 1 vs Mode 3, p-value = 0.034; Mode 1 vs Mode 4, p-value = 0.000).

The percentage relative difference in the median component ride values between Mode 1 and the other three modes over Road 1 are -8.7%, -8.1% and -11.5%. Over Road 2, the percentage relative difference between Mode 1 and the other three modes are -4.0%, -3.3% and -4.8%, respectively.

Table 1. Adjusted p-values (Bonferroni correction) for Dunn's multiple comparison tests over Road 1 (*p-value < 0.05: significant difference at 5% level)

	Mode 1	Mode 2	Mode 3	Mode 4
Mode 1	-	0.006*	0.056†	0.000*
Mode 2		-	1.000	1.000
Mode 3			-	0.341
Mode 4				-

Table 2. Adjusted p-values (Bonferroni correction) for Dunn's multiple comparison tests over Road 2 (*p-value < 0.05: significant difference at 5% level)

	Mode 1	Mode 2	Mode 3	Mode 4
Mode 1	-	0.019*	0.034*	0.000*
Mode 2		-	1.000	0.500
Mode 3			-	0.341
Mode 4				-

5. DISCUSSION

Mansfield and Griffin (2000) estimated difference thresholds for 10 males seated on an automobile seat exposed to vertical vibration recorded in a vehicle. Four reference stimuli were considered i.e. tarmac stimuli at weighted magnitudes of 0.2, 0.4 and 0.8 m/s2, r.m.s. and a paved stimulus with a weighted magnitude of 0.4 m/s2, r.m.s. Over the four stimuli, the median relative difference thresholds range between 11.8 % and 14.1 %. They exposed participants to seated whole-body vibration in the vertical direction only. Gräbe et al. (2020) estimated difference thresholds for 10 males seated in a vehicle subjected to multi-axis vibration resulting from the vehicles response to two road profiles on a 4-poster test rig. Over the two roads, considering the vertical component ride value, the median relative difference thresholds were 8.58 % and 10.99 %. Both Mansfield and Griffin (2000) and Gräbe et al. (2020) determined relative difference thresholds using the same psychophysical method and level of detection probability (i.e. 79.4 %).

Considering the suspension pairs which were found to have significant differences over Road 1, the percentage relative differences in median vertical component ride value are in the range of the median relative difference thresholds reported in Mansfield and Griffin (2000) and Gräbe et al. (2020). This means that 50% of occupants would be able to correctly identify the suspension mode with the larger vibration magnitude 79.4% of the time. Over Road 2, significant differences were found between Mode 1 and the other three. These relative differences are however below the median relative difference thresholds reported in Mansfield and Griffin (2000) and Gräbe et al. (2020). The relative differences are not only below the median relative difference thresholds but also below the 25th percentile reported. This would imply that only a few occupants may be able to identify the suspension mode with the larger vibration magnitude. No significant differences were found in the vertical component ride values between the suspension modes on road 3. The percentage relative differences were close to zero, well below the median relative difference thresholds. This would imply that almost none of the occupants will be able to identify the suspension mode with the larger vibration magnitude.

No formal subjective evaluation was conducted during this study but the driver and passenger (being two of the authors) did make some observations. Both the driver and passenger were able to perceive changes between suspension modes and identify the suspension mode with the larger vibration magnitude over all three roads. Over Road 1 and 2 differences in suspension modes were most noticeable, with differences noticeable on Road 3 but more difficult to identify between some of the modes.

The subjective observations seem to agree with the objective findings over Road 1 and 2. However, over Road 3 it seems that there is a disagreement. Further investigation is needed into the applicability of the available difference thresholds to real world driving situations.

6. CONCLUSIONS

The combination of the suspension modes and roads result in ride comfort differences, as quantified by the BS681 weighted vertical seat pad vibration, that is in the range and below the available difference thresholds in literature. The suspension mode and road combinations could be used to verify the applicability of available difference thresholds during driving.

7. NOMENCLATURE

CRVz Vertical component ride value [m/s2, r.m.s]

8. ACKNOWLEDGEMENTS

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