Influence of Sensor Position in Measuring Lateral Vibration Due to Vehicle Groove Wander

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The objective of the study presented in this paper was to determine the optimal sensor location to assess human discomfort during vehicle groove wander, a phenomenon whereby vehicle occupants experience uncomfortable lateral vibrations when driving over longitudinally grooved (or tined) Portland cement concrete pavement. Field testing was performed over a 4.8 km stretch of interstate highway using a vehicle known to experience vehicle groove wander. Lateral accelerations were measured during wander and nonwander driving at several sensor positions including the seat frame, seat cushion, seat back, and the passenger’s head. The most effective sensor location to capture vibrations due to vehicle wander proved to be the passenger’s head. The standard methods for evaluating human exposure to vehicle vibrations did not yield a reliable indication of the occurrence of wander or the discomfort it causes. [DOI: 10.1115/1.4007563]

Keywords: vehicle vibration, occupant/passenger vibration, groove wander, grooved/tined pavement

Introduction

When driving on longitudinally grooved (tined) Portland cement concrete pavement (PCC, Fig. 1), some motorists experience lateral instability or “jerking.” This phenomenon is referred to as vehicle groove wander (hereafter, wander). Wander is caused by an imbalance of lateral forces created when tire treads partially overhang a pavement groove [1]. A number of research studies have examined the cause of wander from a theoretical perspective [1–5]. However, little documented work has been performed to develop a suitable measurement system for wander, and wander has proven difficult to measure in the past [6]. Vibrations due to wander are low frequency, low amplitude, and are often obscured by high levels of extraneous vibrations (i.e., noise) due to the engine, tire rotation, road roughness, and wind. This note presents results from field testing to explore the influence of sensor position in measuring lateral vehicle and human vibration due to vehicle wander. Measurement positions included the seat frame, seat cushion, seat back, and passenger’s forehead. In addition, standard methods to evaluate human discomfort due to wandering are evaluated.

Human Exposure and Sensitivity to Vehicle Vibrations

Standard methods for evaluating human exposure to transportation induced vibration are provided by both the British Standards Institute in BS-6481 [7] and the International Standards Organization in ISO-2631 [8]. To the author’s knowledge, the Society of Automotive Engineers (SAE) does not currently have a separate standard, but refers to the ISO standard. To gauge passenger discomfort, ISO-2631 and BS-6481 specify the use of various acceleration measurements: vertical and horizontal acceleration at the seat back, seat rest, and vehicle floor. In order to quantify discomfort, ISO-2631 permits the use of the most severe single measurement or the weighted average of several measurements. Measurement locations are still limited to the above list. For all cases, vibration measurements are weighted as a function of frequency depending on the sensor location. There is not a wide consensus on which method is most appropriate, and the weighting factors themselves are the topic of ongoing research [9–11]. Citing results from several studies, Griffin [11] found that vibrations at the floor of a vehicle can be quite different from those at the seat and those experienced by vehicle occupants. Previous research has also shown that assigning levels of discomfort is an error prone process, with large variations existing between test subjects and due to posture changes in repeated tests with the same subject [12–14]. Finally, the standards themselves deal with human exposure to vibration in general. Their application to vehicle ride comfort can be limited due to the factors listed above and the manner in which frequency, direction, and duration of acceleration are weighted, particularly for low amplitude and low frequency events like wander [11].

Field Testing

Field measurements of vehicle and occupant vibration during wander and nonwander were carried out on a 4.8 km stretch of PCC pavement textured with longitudinal tining (Fig. 1). Vehicle and vehicle occupant vibrations were measured with analog ceramic piezoelectric accelerometers with sufficient sensitivity and range to capture the low amplitude wander vibrations in the ISO-2631 recommended range of 0.5–80 Hz. Lateral acceleration data (perpendicular to the travel direction) was collected from two accelerometers recommended range of 0.5–80 Hz. Lateral acceleration data (perpendicular to the travel direction) was collected from two accelerometers during each test pass; several accelerometer placements were tested. One accelerometer was fixed to the seat frame (Fig. 2(a)) and remained in place for all test runs. The location of a second accelerometer varied based on the results of the literature review. Locations

Fig. 1 (a) Tire tread on the Uniroyal Laredo van tire and (b) longitudinal tining of the PCC pavement. A 2000 GMC Safari cargo van was used for the study.

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included the seat back (Fig. 2(b)) and the seat cushion (Fig. 2(c)). These locations were chosen because of their specification in ISO-2631, because the seat assembly has low pass filter characteristics, and because vibrations enter the passenger’s body through the seat [12,15]. The other location tested was the passenger’s head (Fig. 2(d)). This placement was chosen because of the human body’s tendencies to amplify low frequency vibrations and attenuate high frequency vibrations. More than 30 individual vibration records (data sets) were collected over highway pavement with the van traveling at constant velocity. A hand held, push button trigger was used to record locations where wander was felt by the passenger. The trigger is an important component of the sensing system because there are several sources of acceleration that have characteristics similar to wander. The accelerometer data was collected with a 16-bit, data acquisition system (DAQ) employing anti-aliasing filtering. Complete details of the measurement system are provided in [6].

Results

Figure 3 presents raw (unfiltered) lateral acceleration time histories measured at the seat frame, seat cushion, seat back, and passenger’s head during vehicle travel when wander was not experienced (left plots) and when wander was experienced (right plots). The 4.5 s of data shown in each plot corresponds to 120 m of vehicle travel. This is a typical sample vibration record; all vibration records are presented in [6]. With the exception of the passenger’s head, there is little visually discernable difference between the raw vibration records during wander and nonwander behavior because the signal is dominated by higher frequency waveforms due to engine vibration, rotation of the tires, road roughness, etc. This higher frequency vibration is most prevalent in the seat frame (rigidly attached to the vehicle body) and is somewhat attenuated by the low pass characteristics of the seat cushion and the seat back [11]. To this end, only subtle differences are visually discernable between the wander and nonwander data sets. In the passenger head acceleration record, the higher frequency signals are significantly attenuated by the body. A frequency domain analysis presented elsewhere [6] shows increased passenger head acceleration amplitude in the 0.5–2 Hz range during wander. This is consistent with previous findings [16,17] demonstrating that lateral vibration is amplified by the torso in the 0.5–2 Hz range. Figure 3 shows clear visual differences between wander and nonwander behavior when acceleration is measured at the passenger’s head (e.g., see data from 1–2 s and from 2–4 s).

The vibration records were quantitatively assessed to explore the influence of sensor position on vehicle wander. Table 1 summarizes the average percent change in lateral root mean square (rms) acceleration from nonwander stretches to wander stretches for both raw acceleration and zero phase shift, low pass filtered acceleration (cutoff frequency \( \frac{1}{2} \)). Low pass filtering aids in interpreting the vibration data by removing the higher frequency energy not of interest here [6]. All available data was used to compute the statistics, i.e., data from 24 to 82 km of travel (\( n = 5–17 \) vibration records) depending on the sensor location.

![Fig. 2 Accelerometers placed on the (a) seat frame, (b) seat back, (c) seat cushion, and (d) passenger’s head](image)

![Fig. 3 Raw lateral acceleration data measured at the seat frame, seat cushion, seat back, and passenger’s head (from top to bottom) with data from nonwander behavior on the left and wander behavior on the right](image)
ISO Analysis. One objective of this study was to evaluate if ISO-2631 could be used to identify passenger discomfort due to wander. ISO-2631 analysis involves applying a very specific frequency weighting function (filter) and for transient vibrations, such as wander, computing a running rms acceleration value. Conceptually, the ISO-2631 approach is similar to the analysis presented above, the difference being in the filter kernels and limitations regarding sensor locations. According to ISO-2631, several vibration measurements (e.g., seat cushion and seat back in the vertical, lateral and longitudinal directions) may be combined to assess discomfort, or a single measurement location and orientation may be used to examine a specific phenomenon (e.g., seat back or seat cushion in the lateral direction only). In the case of wander, it is desirable to isolate the lateral direction.

Applying the ISO-specified filter kernel and using the seat cushion sensor, the analysis revealed an average acceleration increase of 4% from nonwander behavior to wander behavior. However, there is a significant amount of variation between the individual runs, i.e., $C_v = 487\%$ [6]. These results are in agreement with those presented earlier, showing that the seat cushion measurement is not as reliable as measuring acceleration on the passenger’s head. Further, according to the published recommendations for vibration in public transport environments (see ISO-2631), wander at its most severe would be classified as “not uncomfortable.” However, as indicated in the literature [11], comfort is very subjective and dependent on many environmental factors. As evidenced by the negative feedback from drivers received by Colorado Department of Transportation, and in contrast to the results of the ISO-2631 analysis, wander is perceived as uncomfortable to motorists.

Concluding Remarks

An experimental study was performed to determine the influence of accelerometer position on capturing the phenomenon of vehicle groove wander. Based on the data collected and presented herein, the most effective sensor location to capture vehicle wander proved to be the passenger’s head. This location takes advantage of the human body’s amplifying and filtering characteristics. The standard analysis procedures recommended in ISO-2631 did not reliably capture wander. Further, even though highway travelers have indicated that wander is uncomfortable, the ISO-2631 analysis results in a rating of “not uncomfortable.” This discrepancy is due to the undesirable seat cushion sensor location and environmental factors that are not taken into account by the ISO procedures.

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References


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### Table 1 Summary of average change in lateral rms acceleration from nonwander to wander behavior

<table>
<thead>
<tr>
<th>Sensor location</th>
<th>$n$</th>
<th>Average change (%)$^a$</th>
<th>$C_v$ (%)$^b$</th>
<th>Average change (%)$^a$</th>
<th>$C_v$ (%)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat frame</td>
<td>17</td>
<td>-13</td>
<td>44</td>
<td>36</td>
<td>66</td>
</tr>
<tr>
<td>Seat cushion</td>
<td>6</td>
<td>-11</td>
<td>26</td>
<td>132</td>
<td></td>
</tr>
<tr>
<td>Seat back</td>
<td>6</td>
<td>-12</td>
<td>97</td>
<td>23</td>
<td>75</td>
</tr>
<tr>
<td>Passenger’s head</td>
<td>5</td>
<td>31</td>
<td>48</td>
<td>38</td>
<td>43</td>
</tr>
</tbody>
</table>

$^a$Digitally low pass filtered with cutoff frequency of 5 Hz.

$^b$Coefficient of variation $C_v = \text{mean/standard deviation}$. 

$^c$Average change from areas where wander was not observed to areas where wander was observed, as indicated with the hand trigger.