# Driver estimation of steering wheel vibration intensity: laboratory-based tests

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## 1. Introduction

Frequency weightings have been proposed for transforming acceleration signals into perceived acceleration signals so as to assist the engineering evaluation of systems which are in physical contact with humans. These frequency weightings are analogous to the well-known decibel A, B and C curves [16] from the field of psychoacoustics. The weightings have been defined based on data from research studies which have measured the human subjective response to harmonic, to narrow-band periodic or to narrow-band random vibration.

Research regarding the human subjective response to hand-arm vibration includes translating plate studies [13] and translating handle studies [14]. The equal sensation curves from these studies have contributed to the definition of the $W_h$ frequency weighting which is currently used in both International Organisation for Standardization 5349-1 [12] and British Standards Institution 6842 [3]. $W_h$ is primarily intended for use in measuring and reporting hand-arm exposures for the purpose of quantifying possible health effects, but as the only standardised frequency weighting available it has often been used in the automotive industry for evaluating the perceived intensity of steering wheel vibration. The use of $W_h$ in the steering application raises some questions, however, particularly regarding its appropriateness in the case of the tangential acceleration caused by wheel rotation. This concern has lead to research in which the human subjective response to rotationally vibrating wheels was measured. This research has lead to a preliminary proposal [10] for a steering wheel frequency weighting, $W_s$, and to a partial confirmation of its accuracy [1].

The laboratory-based investigation described here was performed as part of a research programme aimed at quantifying the accuracy of the preliminary $W_s$ specification. The primary objective was to establish the level of correlation between direct subjective responses provided by test participants, and the estimates which can be achieved from the acceleration signals themselves by means of frequency weightings $W_h$ and $W_s$. The secondary objective was to compare the direct responses to memory-based estimates for stimuli belonging to the same general driving condition which had been gathered by means of a questionnaire in a previously reported study [9]. The scientific question of interest in this case was that of how close driver estimates of steering vibration intensity which are based on long-term memory might be with respect to the direct evaluation of stimuli of the same general class of driving condition.

## 2. Experimental Tests

### 2.1 Test Stimuli

Driving conditions were chosen based on three criteria. The first was that each should be broadly equivalent to one of those defined in the previously reported questionnaire study [9] so as to facilitate comparisons with the memory-based intensity estimates of the previous study. The second criteria was that the steering vibration should be mainly caused by the act of driving over a road surface. This was decided based on the results of the questionnaire study [9] which suggested that the respondents considered steering wheel vibration to be particularly useful towards the detection task of determining the road surface type. The third criteria was that the driving condition should be characterised in the questionnaire data by a statistical distribution of the subjective intensity responses which was Gaussian, as defined by a Kolmogorov-Smirnov test [6] performed at a 1% confidence level. Gaussianity was considered opportune in order to avoid test stimuli which might produce subjective responses characterised by bimodal or multimodal distributions. Such distributions would have complicated the analysis since it would suggest possible participant subgroupings based on factors such as age, gender or driving experience. The eight driving conditions listed in table 1 achieved all three criteria. Of these, five, namely pothole, rumble strip, stone on road, manhole cover and expansion joints can be classified as containing significant transient events, while the remaining three, namely country lane, city street and motorway can be classified as mildly non-stationary signals [8].

One tangential direction acceleration time history was associated with each of the eight driving conditions. It was chosen from an ensemble of available steering wheel acceleration time histories which had been measured in a mid-sized automobile. Each had been measured using an accelerometer which was mounted

| Road Surface | Speed [Km/h] | r.m.s [m/s²] | Kurtosis | Crest Factor |
|---|---|---|---|---|
| country lane | 80 | 1.88 | 1.30 | 5.08 |
| pothole | 60 | 1.34 | 4.46 | 4.31 |
| rumble strip | 60 | 2.02 | 3.64 | 4.32 |
| stone on road | 20 | 0.89 | 3.63 | 4.58 |
| manhole cover | 60 | 1.07 | 0.36 | 3.36 |
| city street | 50 | 1.10 | 0.76 | 3.80 |
| expansion joints | 16 | 0.71 | 8.09 | 5.02 |
| motorway | 96 | 0.10 | 3.83 | 4.75 |

Table 1) Global statistical properties of the eight acceleration stimuli used in the laboratory tests.

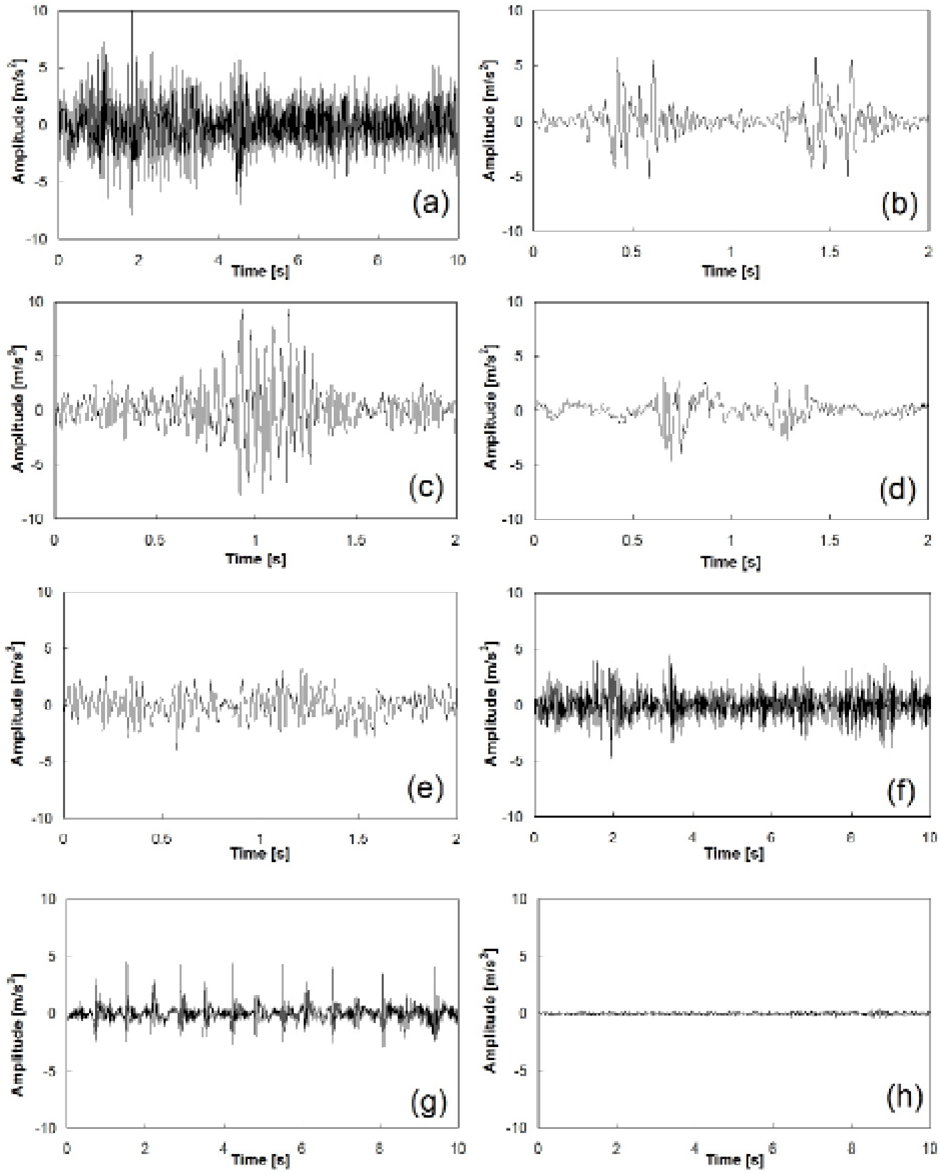


Figure 1) Steering wheel acceleration time histories used in the laboratory experiments: (a) country lane (vehicle speed 80 Km/h), (b) pothole (vehicle speed 60 Km/h), (c) rumble strip (vehicle speed 60 Km/h), (d) stone on road (vehicle speed 20 Km/h), (e) manhole cover (vehicle speed 60 Km/h), (f) city street (vehicle speed 50 Km/h), (g) expansion joints (vehicle speed 16 Km/h) and (h) motorway (vehicle speed 96 Km/h).

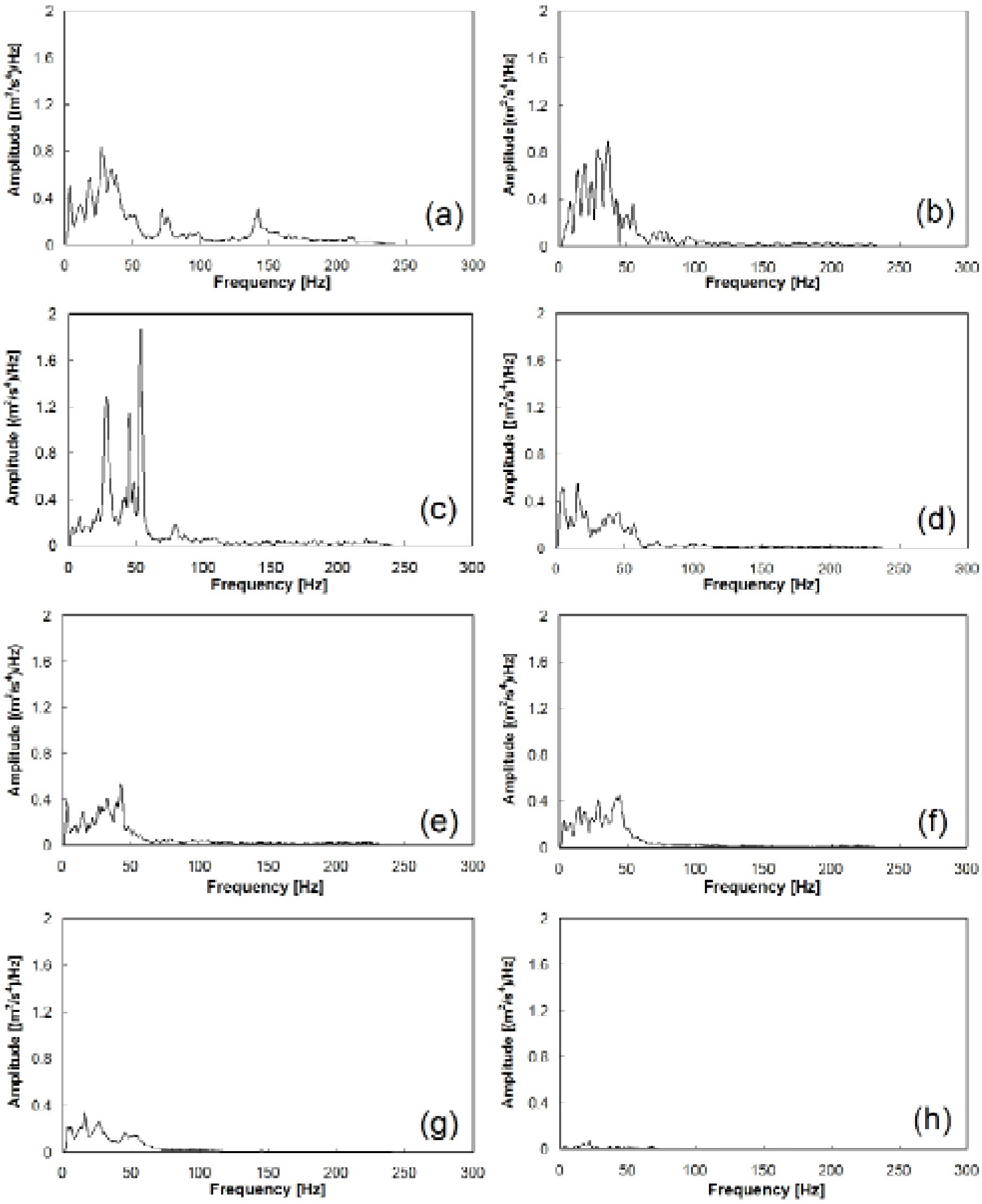


Figure 2) Acceleration power spectral densities of the steering wheel acceleration time histories:
(a) country lane (vehicle speed 80 Km/h), (b) pothole (vehicle speed 60 Km/h),
(c) rumble strip (vehicle speed 60 Km/h), (d) stone on road (vehicle speed 20 Km/h),
(e) manhole cover (vehicle speed 60 Km/h) (f) city street (vehicle speed 50 Km/h),
(g) expansion joints (vehicle speed 16 Km/h) and (h) motorway (vehicle speed 96 Km/h).

rigidly to the steering wheel at the 3 o'clock position by means of a mounting clamp which guaranteed adequate coupling stiffness to frequencies in excess of 300 Hz. While the single accelerometer did not differentiate the rotational and the translational components of the steering acceleration, the approximation was made in the current study to associate the acceleration time history with the wheel rotational axis. Though non-negligible, the error implicit in this choice was considered acceptable in the current study due to the use of the acceleration signals as representative stimuli, rather than exact replications of specific automobile and road conditions. Each had been recorded at a sampling rate of 512 Hz while the automobile was driven over a specific road surface at a single representative speed. Each had a time duration of from 8 to 60 seconds.

A short but statistically representative [8] segment of data was extracted from each of the eight acceleration time histories. The segments were selected such that the root mean square (r.m.s) value, the kurtosis value, the crest factor and the power spectral density were close to those of the complete time history. In the case of the driving conditions which involved significant transient events, the segment duration was taken to be either 2 or 10 seconds depending on the physical time interval of the principal acceleration event. In the case of the mildly non-stationary driving conditions the segment duration was taken to be 10 seconds so as to remain within human short term memory [2]. Figure 1 presents the acceleration time history segments which were used as test stimuli while Figure 2 presents the associated power spectral densities.

**2.2 Test Facility**

All tests were performed using the steering wheel rig presented in Figure 3. The rotational system consisted of a 325mm diameter aluminium wheel attached to a steel shaft which was mounted to bearings and connected to an electrodynamic shaker. Table 2 presents the main geometric dimensions of the rig, which were chosen based on data from a small European automobile. The seat was fully adjustable in terms of horizontal position and back-rest inclination as in the original automobile. Rotational vibration was applied by means of a G&W V20 electrodynamic shaker and PA100 power amplifier. Steering wheel tangential acceleration was measured by means of an Entran EGAS-FS-25 accelerometer attached to the top left side of the wheel and an Entran MSC6 signal-conditioning unit. Vibration control and data acquisition was performed by means of the EMON software system coupled to a DIFA SCADASIII electronic frontend unit. The EMON software permitted the fixing of safety cutoff limits which were set to 20.0 $m/s^2$ peak acceleration. The safety features of the rig and the acceleration levels used conform to the health and safety recommendations outlined by British Standards Institution BS7085 [4].

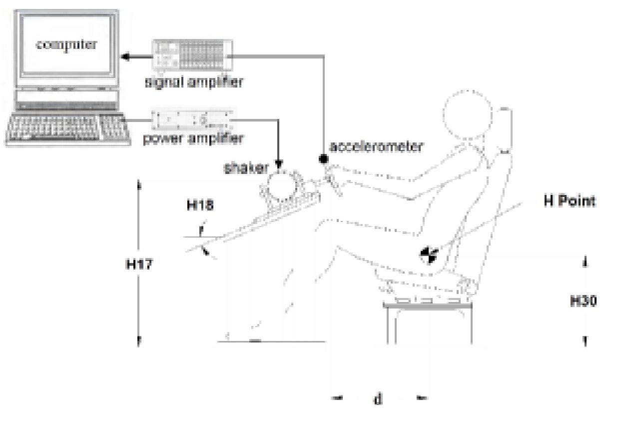


Figure 3 Schematic representation of the steering wheel rotational vibration test facility.

| Geometric Parameter | Value |
|---|---|
| Steering column angle with respect to floor (H18) | 23 ° |
| Steering wheel hub centre height above floor (H17) | 710 mm |
| Seat H point height from floor (H30) | 275 mm |
| Horizontal distance adjustable from H point to steering wheel hub centre (d) | 390-550 mm |
| Steering wheel handle diameter | 12.5 mm |
| Steering wheel diameter | 325 mm |

Table 2) Geometric dimensions of the steering wheel rotational rig.

The rig has a first resonance frequency which is greater than 350 Hz under normal loading conditions. A set of calibration tests was performed involving three participants and sinusoidal excitation at frequencies from 4 to 250 Hz and amplitudes from 0.2 to 20.0 $m/s^2$ r.m.s.. A maximum total harmonic distortion (THD) of 15% was found at 4 Hz and 20 $m/s^2$. With both increasing frequency and decreasing amplitude the THD dropped to a minimum of 0.002% at 250 Hz and 0.2 $m/s^2$. Fore-and-aft acceleration was found to be no greater than -50 dB with respect to the tangential acceleration. A further set of calibration tests was performed involving four participants and each of the eight test stimuli, which were reproduced four times with each participant. In this case the maximum error in the r.m.s amplitude of the reproduced stimulus was found to range from 1.6% for the country lane acceleration time history to 4.7% for the manhole cover acceleration time history.

**2.3 Test Protocol**

A total of 20 university staff and students participated in the experiment. Upon arriving in the laboratory, each was issued an information and consent form and was provided an explanation of the experimental methods and of the laboratory safety features. Sex, age, height, weight and driving experience data were then collected, and the participant was requested to state whether he or she had any physical or mental condition that might affect perception of hand-arm vibration, and whether he or she had ingested coffee within 2 hours prior to arriving in the laboratory. The group consisted of 12 males and 8 females. Age ranged from 23 years to 42 years with a mean value of 28.5 years, driving experience ranged from 3 years to 24 years with a mean value of 9.9 years, height ranged from 1.58 m to 1.85 m with a mean value of 1.72 m and mass ranged from 53 kg to 94 kg with a mean value of 67.2 Kg. No participant declared any condition which might effect the perception of hand-arm vibration, and none declared having ingested coffee. All had more than one year of driving experience.

Before commencing, each participant was asked to remove any articles of heavy clothing such as coats, and to remove watches and jewellery. He or she was then asked to adjust the seat so as to achieve a driving posture that was as similar as possible to the one normally adopted in their own automobile. He or she was next asked to grip the steering wheel using both hands, applying the grip strength that would be used when driving on a winding country road. The participant was then asked to fix eyes on the board directly in front of the simulator which displayed a Borg CR10 scale [5,9].

The order of stimulus presentation was randomized for each participant so as to minimise fatigue and learning effects. Each was of either 2 or 10 seconds in duration, and was separated from the next by a 3 second gap which was used to verbally provide the intensity estimate using the Borg CR10 scale. Each of the eight stimuli was presented four times to each of the 20 subjects for a total of 80 intensity estimates for each driving condition. Participants were requested to provide their best estimate and to respond even if uncertain. The automobile speed associated with each stimulus was not provided, and no feedback was provided about the possible correctness of judgement. Considering all activities performed from the moment the participant entered the laboratory, the total time to perform the experiment was approximately 25 minutes. Room temperature was from 20 to 25° C during all tests.

**3. Results**

Table 3 presents the mean Borg CR10 intensity estimates for the eight stimuli along with the standard deviation from the mean. Table 3 also presents the unweighted, the $W_h$ weighted and the $W_s$ weighted r.m.s acceleration amplitudes as determined by means of two IIR digital filters [15] which were implemented in the LMS TMON software following the frequency specifications and tolerances outlined in ISO 5349-1 [12] and in Giacomin et al. [10]. As can be seen from the table, neither the unweighted nor the $W_h$ weighted nor the $W_s$ weighted r.m.s. acceleration amplitudes produced the same stimuli ranking as the mean experimental direct perceived intensity estimates. None of the currently available estimation methods is therefore capable of fully representing the human perception of steering wheel rotational vibration. Over the set of eight test stimuli used in the current experiment, however, the $W_s$ weighting appears to have provided a slightly better ranking than the $W_h$ weighting, but the differences were found to not be statistically significant at a 5% significance level when evaluated by means of a Wilcoxon signed-ranks test [11].

Figure 4 presents the experimental direct perceived intensity estimate plotted as a function of the unweighted, the $W_h$ weighted or the $W_s$ weighted r.m.s. acceleration amplitude of the eight test stimuli. Also presented are the Stevens Power Law exponent [7] and the coefficient of determination $r^2$ which were determined from the data of each graph by means of least squares regression [11]. In all cases the power law exponents were found to be less than unity, suggesting that the perception of steering wheel rotational vibration intensity is a negatively accelerating function of the r.m.s acceleration amplitude. The coefficients of determination suggest that either form of frequency weighting ($W_h$ or $W_s$) provides a more accurate estimate of human perceived intensity than does the unweighted acceleration, and that the two frequency weightings provide approximately similar

| Road Surface | unweighted r.m.s. ($m/s^2$) | $W_h$ weighted r.m.s. ($m/s^2$) | $W_s$ weighted r.m.s. ($m/s^2$) | Borg CR10 Intensity Mean (Std. Deviation) |
|---|---|---|---|---|
| country lane | 1.88 | 1.08 | 0.66 | 6.60 (1.30) |
| pothole | 1.34 | 0.87 | 0.45 | 6.40 (1.22) |
| rumble strip | 2.02 | 0.94 | 0.43 | 5.60 (1.52) |
| stone on road | 0.89 | 0.55 | 0.52 | 5.50 (1.37) |
| manhole cover | 1.07 | 0.59 | 0.40 | 4.90 (1.26) |
| city street | 1.10 | 0.66 | 0.40 | 4.70 (1.23) |
| expansion joints | 0.71 | 0.48 | 0.34 | 4.20 (1.17) |
| motorway | 0.10 | 0.07 | 0.04 | 1.00 (0.38) |

Table 3) Root mean square amplitudes of the unweighted, the $W_h$ weighted and the $W_s$ weighted acceleration signals, and corresponding Borg CR10 subjective intensity estimates (n=20).

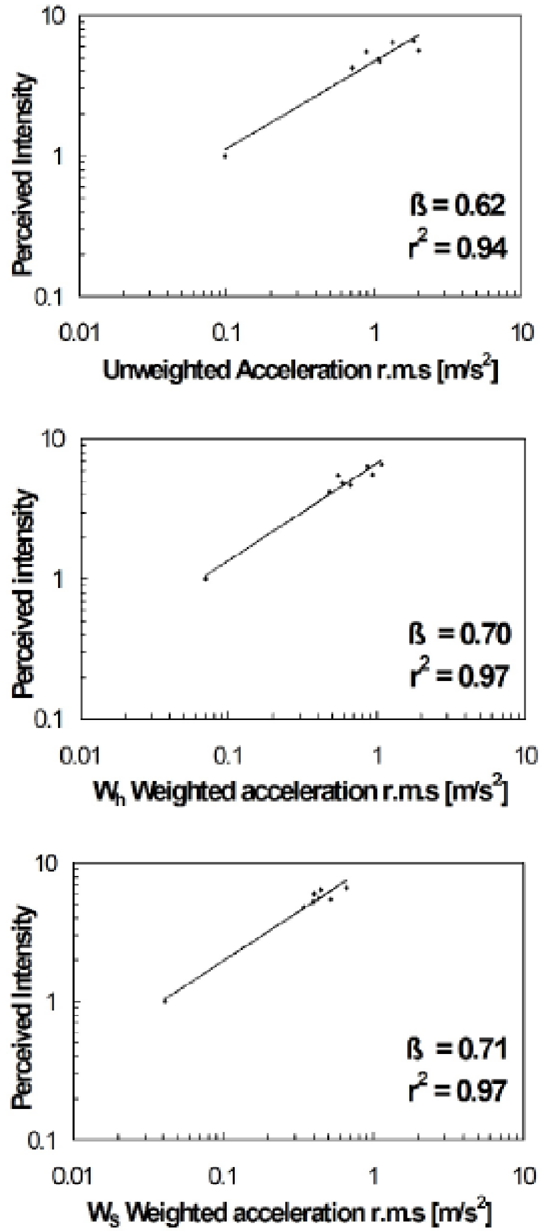


Figure 4) Mean Borg CR10 perceived intensities as a function of the unweighted, the $W_h$ weighted and the $W_S$ weighted r.m.s. acceleration amplitudes if the eight test stimuli ($m/s^2$).

results. A possible explanation of the similarity may be the fact that the r.m.s. acceleration amplitudes of the sinusoidal test stimuli used to define $W_s$ [10] were significantly lower than the r.m.s. amplitudes of the broadband coloured road vibration stimuli used in the current study. Analogous to the case of the Decibel A, B and C weightings of psychoacoustics, the current results may suggest the hypothesis that different vibration perception weightings are required for different amplitude ranges of steering wheel rotational vibration. A further possible explanation for the similarity of the $W_h$ and the $W_s$ results may be the small amount of vibrational energy found in each of the eight test stimuli at frequencies less than 6.3 Hz, where the greatest qualitative differences are found between the $W_h$ and $W_s$ weightings.

Figure 5 presents the comparison between the mean perceived intensities of steering wheel vibration directly reported in the laboratory experiments (n=20) of the current study and those indirectly reported from memory for the same general class of driving condition by the respondents (n=350) of the questionnaire-based study [9]. It can be seen that five of the eight driving conditions have percentage difference values less than 20%. These driving conditions, namely pothole, rumble strip, stone on road, manhole cover and expansion joints, can all be broadly classified as transient events. The three driving conditions which were found to produce percentage difference values greater than 20 %, namely country lane, city street and motorway, can all be broadly classified as mildly non-stationary signals. The data suggest a greater ease of interpretation of transient events on the part of humans, or, alternatively, a smaller variation in the statistical properties of the typical transient events encountered during driving.

**4. Conclusions**

The laboratory-based investigation described here was performed as part of a research programme aimed at quantifying the accuracy of the preliminary $W_s$ frequency weighting specification which had been developed for use in quantifying the perceived intensity of automotive steering wheel rotational vibration. Eight steering wheel acceleration time history segments were used as test stimuli to represent eight typical automobile driving conditions. The results suggest that either form of frequency weighting, the internationally standardised $W_h$ or the recently proposed $W_s$, provides a more accurate estimate of perceived intensity than does the unweighted acceleration. The differences between the $W_h$ and the $W_s$ estimates were found, however, to be small. A possible explanation of the similarity may be that the r.m.s. acceleration amplitudes of the test stimuli used in the current study were significantly higher that those used to develop $W_s$. Analogous to the Decibel A, B and C weightings of psychoacoustics, different weightings may be required for different amplitude ranges of steering wheel rotational vibration. A further possible explanation may be the small amount of vibrational energy found in each of the eight test stimuli of the current study at frequencies less than 6.3 Hz, where the greatest qualitative differences are found between the $W_h$ and $W_s$ specifications.

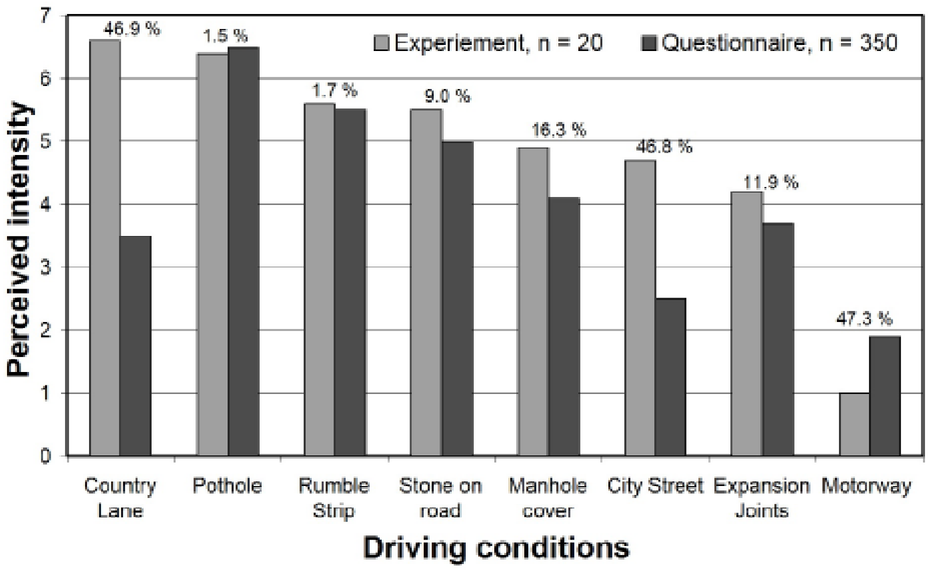


Figure 5) Mean Borg CR10 perceived intensities of steering wheel vibration reported in the laboratory experiments (n=20) and by means of the self-administered questionnaire (n=350), along with the percentage difference between the two.

Comparison of the mean perceived intensities of steering wheel vibration directly reported in the laboratory experiments (n=20) of the current study to those indirectly reported from long-term memory for the same driving condition by the respondents (n=350) of the previous questionnaire-based study suggest that the intensity estimates were more similar in the case of transient events than in the case of mildly-nonstationary stimuli.

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