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Driver estimation of steering wheel vibration intensity: questionnaire-based survey

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Introduction

Automobile drivers are continuously exposed to vibration, therefore automobile manufacturers make much use of methods for quantifying the noise, vibration and harshness properties [10-11] of their vehicles, as well as methods for quantifying vehicle drivability [20]. Drivers perceive vibration through the floor panel, the pedals, the gearshift lever, the seat and the steering wheel. Of these vibrating surfaces, the steering wheel is particularly important due to the great sensitivity of the skin tactile receptors of the hand [14-15] and due to the lack of intermediate structures such as shoes or clothing which can attenuate vibration. Steering vibration can reach frequencies of up to 300 Hz during driving [19] and vibrational modes of the wheel and column can produce large resonant peaks in the steering wheel power spectrum at frequencies from 20 to 50 Hz [4,18].

Drivers' subjective response to steering wheel vibration can be investigated from several different points of view. Research findings have been reported concerning the short-term human perception of steering wheel vibration [8], concerning the long-term fatigue that is induced in the human upper body by steering wheel vibration [6-7], and concerning the cognitive information carried by steering vibration stimuli [9]. Both the short term perception and the cognitive information carried to the driver depend greatly on the perceived intensity of the stimuli. Given the importance of the perceived intensity towards both discomfort and information, it is useful to know what values of this quantity are associated by drivers with the various operating conditions of the automobile.

The study described here has investigated the intensities automobile drivers associate, in their memory, with a set of representative driving conditions. The primary aim was to identify from the research literature an appropriate measurement scale for quantifying the perceived intensity of steering wheel vibration, and to obtain intensity estimates for a set of representative automobile operating conditions. The secondary aim was to establish whether the independent factors of profession and gender affect the memorised intensities. In particular, debate often arises in automotive sector organisations regarding the possible differences between the opinions expressed by driving professionals, such as test drivers and taxi drivers, and those of non-professionals. An awareness of the possible extent of any variations is therefore beneficial.

Questionnaire and survey sample

A self-administered questionnaire was developed to investigate the perceived intensity of steering wheel vibration. Given the widespread use of self-administered questionnaires in research settings, several studies have addressed the question of their applicability and general validity. An example is provided by Schierhout and Myers [21], who suggest that self-reported questionnaires are valid when applied to large test groups.

Of the four basic types of measurement scale (nominal, ordinal, interval and ratio), a ratio scale was desired for use in the current study due to its properties of order, distance and a natural origin to represent zero amount of the stimulus [5]. In the case of ratio scale methods, the test subject is normally requested to report a numerical value expressed as a ratio of the value of the standard stimulus adopted for the study. This form of test can be difficult for the test subject, but does provide data which can be manipulated using the widest possible range of analytical transformations. A less demanding form of subjective evaluation consists of methods based on category scales, which use verbal categories provided by the researcher. When the category labels are well chosen, this approach has the advantage of simplicity. The disadvantage is the limited number of analytical transformations which can be applied to category data. A compromise solution, which combines the best features of both methods, is the Borg CR10 scale [2], which approximates the ease-of-use of a category scale while achieving the analytical flexibility inherent in numbers reported using a ratio scale. By assuming that people use semantic labels such as "weak" and "very strong" to signify similar quantities, and by assuming that the range of perceived sensation varies from a minimum value to a maximum value which are similar for most people, Borg combined the characteristics of the two systems to produce the CR10 (Category-Ratio anchored at 10) scale. From their study of the human perception of hand-arm vibrational discomfort, Wos et. al [22] claimed that the Borg CR10 scale is highly reliable, with reliability coefficients ranging from 0.841 to 0.986. Neely [17] has reported coefficients of determination (r^2) of 0.79 between Borg CR10 results and subjective data obtained by means of a visual analogue scale, and has also reported typical retest coefficients of determination of 0.98. Based on the evidence from the literature, the CR10 scale was chosen for use in the current study.

Figures 1 and 2 present the questionnaire developed for the current study. It consists of four sections labelled A, B, C and D which gather data regarding the respondent, the respondent's opinion of the importance of steering wheel vibration, the perceived intensity of the vibration that occurs during 28 operating conditions, and the respondent's normal grip of the steering wheel when driving. From section A, the factors considered in the current study were profession and gender. A fundamental aspect of section A was the decision, on the part of the respondent, as to whether he or she considered himself or herself to be a professional driver, with cited examples of professionals being racing drivers, test drivers, taxi drivers or drivers of commercial vehicles. The label "professional" was therefore assigned based on the cumulative time spent in an automobile while performing work-related activities, as opposed to any specific driving style. Section C requests that the respondents provide Borg CR10 ratings of the perceived intensity of steering vibration for 28 driving conditions which represent a selection of possible driving conditions. The Borg CR10 scale consists of 17 level points (9 labelled and 8 unlabeled). The value of 10 represents the recommended maximum intensity, but greater values can be chosen if the test subject so wishes.

STEERING WHEEL VIBRATION QUESTIONNAIRE - 1

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The objective of the research being performed by means of this questionnaire is to identify what information drivers obtain from steering wheel vibration. All answers will be used for research purposes only and will remain strictly confidential. Please confirm your consent to participate by completing and signing section A, and please answer all questions in the remaining sections of the questionnaire.

Section A - Personal Information

Full Name :	Signature:	Date:
Email address:	Occupation :	
Sex: ☐Male ☐Female	Age (years):	

1. Do you consider yourself a professional driver (e.g.: racing, testing, taxi or commercial vehicles)? ☐Yes ☐No
If Yes, please provide details regarding your driving activities: ____________

2. How many years of driving experience have you had since obtaining your driving license? [years] ______

3. What type of vehicle do you normally drive?
☐Car ☐Van/MPV ☐Lorry/ Truck/Bus ☐4x4/ Jeep/ SUV

4. Do you have any condition which you feel may modify your perception of visual, sound or tactile stimuli?
☐Yes ☐No. If Yes, please give details: ____________

Section B - Perception of Vehicle Stimuli

1. Based on your driving experience please indicate below how important you consider the following stimuli to be towards understanding the road surfaces over which you drive.

	Very unimportant	Unimportant	Somewhat important	Important	Very important
(1) Sound	☐	☐	☐	☐	☐
(2) Torque- steering resistance	☐	☐	☐	☐	☐
(3) Vibration- steering wheel	☐	☐	☐	☐	☐
(4) Vibration- seat, pedals or gear lever	☐	☐	☐	☐	☐
(5) Vision- straight ahead	☐	☐	☐	☐	☐
(6) Vision- lateral or through mirrors	☐	☐	☐	☐	☐

2. Based on your driving experience please indicate below how important you consider the following stimuli to be towards understanding whether you are driving on a dry or a wet road.

	Very unimportant	Unimportant	Somewhat important	Important	Very important
(1) Sound	☐	☐	☐	☐	☐
(2) Torque- steering resistance	☐	☐	☐	☐	☐
(3) Vibration- steering wheel	☐	☐	☐	☐	☐
(4) Vibration- seat, pedals or gear lever	☐	☐	☐	☐	☐
(5) Vision- straight ahead	☐	☐	☐	☐	☐
(6) Vision- lateral or through mirrors	☐	☐	☐	☐	☐

3. Based on your driving experience please indicate below how important you consider the following stimuli to be towards understanding that your vehicle tyres are slipping.

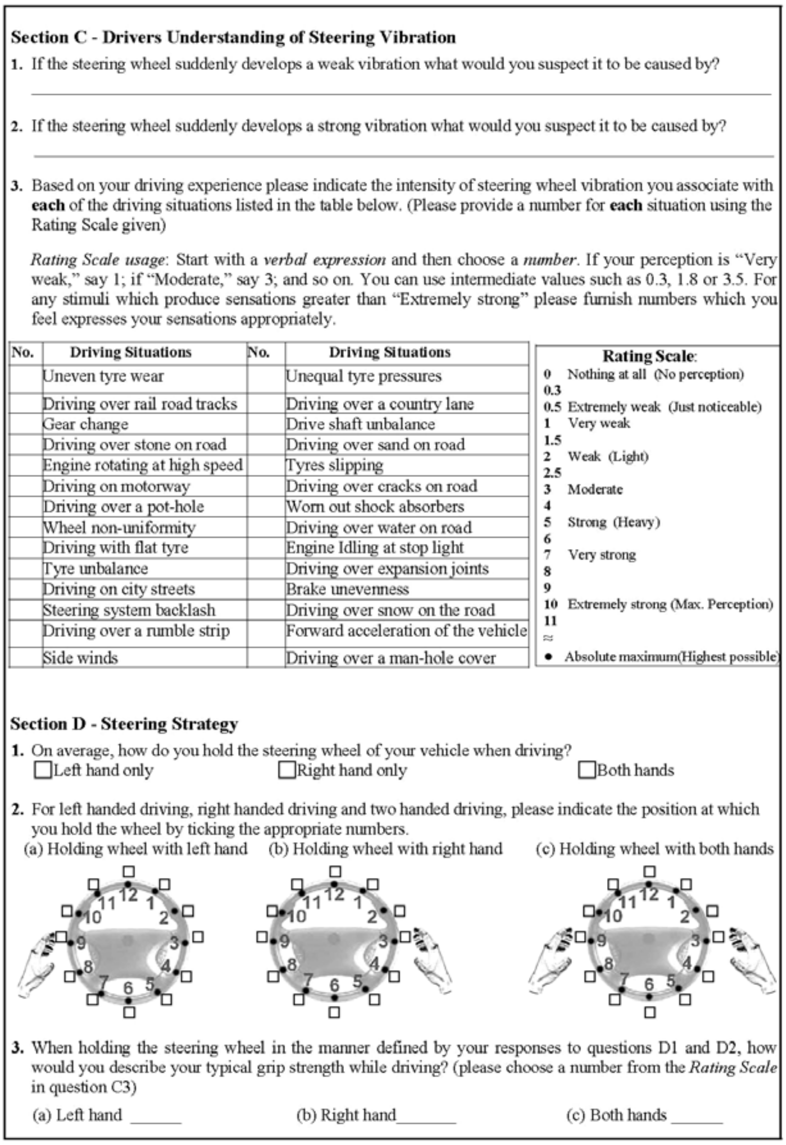
	Very unimportant	Unimportant	Somewhat important	Important	Very important
(1) Sound	☐	☐	☐	☐	☐
(2) Torque- steering resistance	☐	☐	☐	☐	☐
(3) Vibration- steering wheel	☐	☐	☐	☐	☐
(4) Vibration- seat, pedals or gear lever	☐	☐	☐	☐	☐
(5) Vision- straight ahead	☐	☐	☐	☐	☐
(6) Vision- lateral or through mirrors	☐	☐	☐	☐	☐

Figure 1) First page of the steering wheel vibration questionnaire

A preliminary survey involving 20 participants was performed in order to assess the suitability of the questionnaire. Based on feedback from the participants, changes were made to the semantics of some items in order to increase readability, and some items were eliminated. The time required to complete the final questionnaire, in either paper-based or internet-based form, was found, on average, to be approximately 12 minutes. This value was considered an acceptable compromise between the need to gather adequate information and the need to minimise the effort required of the respondents, since previous research [7] has suggested that the number of respondents can drop significantly, and the number of response errors can increase, in the case of questionnaires which require more than approximately 10 minutes to complete. The final questionnaire was then distributed in paper-based form, and via the internet. The definitive sample survey consisted of UK-based individuals with a prevalence of participants based in the north of England. In order to reduce the possible influence of medical condition or disability on the survey results, no data was analysed from respondents who indicated a condition which they felt might modify their perception of visual, sound or tactile stimuli. Table 1 presents the final sample survey, which consisted of 350 participants of which 235 declared themselves to be non-professional drivers and 115 professional drivers.

Results

Figures 3, 4 and 5 present the overall distribution of responses to questionnaire section B, which asked the respondent to state their opinion of the importance of steering wheel vibration towards the understanding of



Section C - Drivers Understanding of Steering Vibration

1. If the steering wheel suddenly develops a weak vibration what would you suspect it to be caused by?

2. If the steering wheel suddenly develops a strong vibration what would you suspect it to be caused by?

3. Based on your driving experience please indicate the intensity of steering wheel vibration you associate with **each** of the driving situations listed in the table below. (Please provide a number for **each** situation using the Rating Scale given)

Rating Scale usage: Start with a *verbal expression* and then choose a *number*. If your perception is "Very weak," say 1; if "Moderate," say 3; and so on. You can use intermediate values such as 0.3, 1.8 or 3.5. For any stimuli which produce sensations greater than "Extremely strong" please furnish numbers which you feel expresses your sensations appropriately.

No.	Driving Situations	No.	Driving Situations
	Uneven tyre wear		Unequal tyre pressures
	Driving over rail road tracks		Driving over a country lane
	Gear change		Drive shaft unbalance
	Driving over stone on road		Driving over sand on road
	Engine rotating at high speed		Tyres slipping
	Driving on motorway		Driving over cracks on road
	Driving over a pot-hole		Worn out shock absorbers
	Wheel non-uniformity		Driving over water on road
	Driving with flat tyre		Engine Idling at stop light
	Tyre unbalance		Driving over expansion joints
	Driving on city streets		Brake unevenness
	Steering system backlash		Driving over snow on the road
	Driving over a rumble strip		Forward acceleration of the vehicle
	Side winds		Driving over a man-hole cover

Rating Scale:
0 Nothing at all (No perception)
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. Perception)
11
≈
• Absolute maximum(Highest possible)

Section D - Steering Strategy

1. On average, how do you hold the steering wheel of your vehicle when driving?
☐Left hand only ☐Right hand only ☐Both hands

2. For left handed driving, right handed driving and two handed driving, please indicate the position at which you hold the wheel by ticking the appropriate numbers.
(a) Holding wheel with left hand (b) Holding wheel with right hand (c) Holding wheel with both hands

3. When holding the steering wheel in the manner defined by your responses to questions D1 and D2, how would you describe your typical grip strength while driving? (please choose a number from the *Rating Scale* in question C3)
(a) Left hand ______ (b) Right hand_______ (c) Both hands ______

Figure 2) Second page of the steering wheel vibration questionnaire

Subgroups	Number of samples	Age [years] (mean ± SD)	Driving experience [years] (mean ± SD)
Non-professional drivers - all	235	35.5 ± 10.1	16.9 ± 10.2
Professional drivers - all	115	39.9 ± 9.1	21.7 ± 9.0
Non-professional drivers - male	135	36.8 ± 10.2	18.1 ± 10.2
Non-professional drivers - female	100	33.6 ± 9.85	15.3 ± 10.1
Professional drivers - male	115	39.9 ± 9.1	21.7 ± 9.0
Professional drivers - female	0	-	-

Table 1) Summary of sample group and analysed (n=350)

the road surface (Figure 3), towards the understanding of whether driving on a dry or wet road (Figure 4) and towards the understanding of whether the vehicle's tyres were slipping (Figure 5). Steering wheel vibration was considered important towards the understanding of road surface and of tyre slip, but it was not considered the most important source of information in any of the three driving scenarios. Vision was considered the most important stimuli when determining both road surface type and whether driving over a dry or a wet road. Steering torque was considered the main stimulus when determining whether the vehicle's tyres were slipping.

Figure 6 presents the overall percentage of drivers who declared using each of the 12 available steering wheel grip positions provided by the questionnaire. The data suggests a tendency towards assuming the "one o'clock" grip position when using a single hand, irrespectively of which hand is used. Regarding the grip type, 12.3% of the respondents declared that they hold the steering wheel with the left hand only, 12.0% declared holding the wheel with the right hand only, and 75.7% declared using both hands. Regarding grip strength, a mean Borg CR10 value of 3.75 was reported for a one-handed grip with a standard deviation of 1.73. For a two-handed grip, the mean value was 3.76 with a standard deviation of 1.54, and for both hands the mean value was 3.80 with a standard deviation of 1.74.

Figure 7 presents the comparison between the perceived intensities of steering wheel vibration reported by the male non-professional drivers and by the female non-professional drivers, along with the percentage difference between the perceived intensities of the two groups. To facilitate data analysis, a baseline difference value of 10% was established, and all driving conditions which produced a difference greater than 10% were analysed statistically. The value of 10% was chosen based on the knowledge that the just-noticeable-difference value (the Weber fraction value) for human perception of vibration varies from a minimum of approximately 5% for needles indenting the skin of the

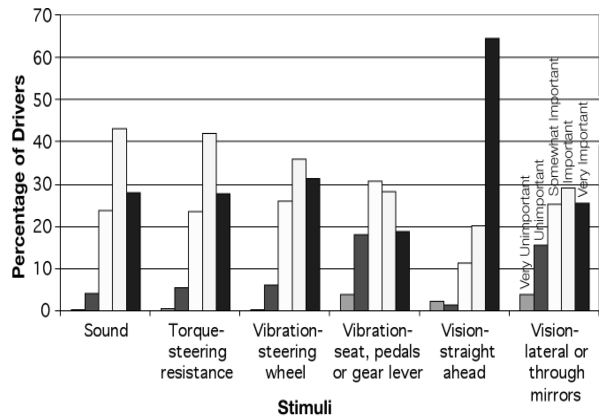


Figure 3) Importance declared by the questionnaire respondents for the various stimuli types towards understanding the road surfaces over which they drive (n=350)

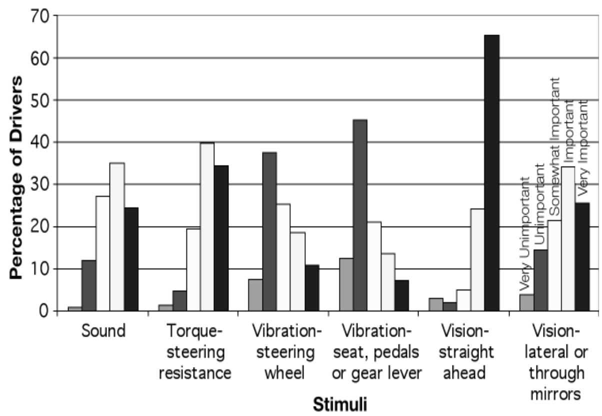


Figure 4) Importance declared by the questionnaire respondents for the various stimuli types towards understanding whether driving on a dry road or a wet road (n=350)

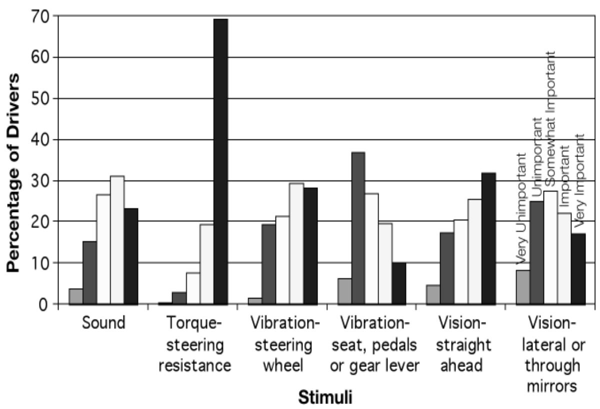


Figure 5) Importance declared by the questionnaire respondents for the various stimuli types towards understanding that the vehicle's tyres are slipping (n=350)

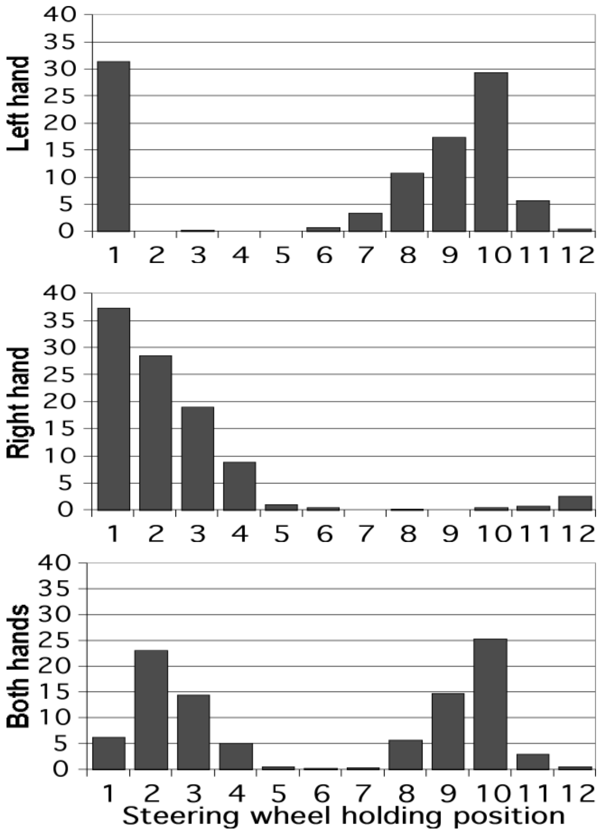


Figure 6) Percentage of drivers holding the steering wheel in each of the 12 positions described in the questionnaire, when gripping the wheel with the left hand only, the right hand only, or both hands (n=350)

fingertips [5], to a maximum of approximately 13% for the perception of seated whole-body vibration [13]. The just-noticeable-difference establishes the physiological difference threshold, therefore analysis of differences smaller than this value are unlikely to prove revealing since such differences are not perceived by humans in practice. Thirteen driving conditions were characterised by differences greater than 10%, while only seven proved statistically significant at a confidence level greater than 5%, as determined using a t-test [3]. The seven characterised by statistically significant differences were: "rail road tracks", "tyre unbalance", "wheel non-uniformity", "brake unevenness", "uneven tyre wear", "side winds" and "sand on road". Four of the seven can be considered technical conditions related to the automobile itself rather than to the road environment.

Figure 8 presents the comparison between the perceived intensities of steering wheel vibration reported by the professional and the non-professional male drivers (unfortunately a similar comparison was not possible for female drivers due to the lack of respondents), along with the percentage difference between the perceived intensities of the two groups. As in the case of the comparison by gender, a baseline difference value of 10% was adopted. In this case, differences of greater than 10% were found in the ratings of eleven driving conditions, while only four proved statistically significant at a confidence level greater than 5%, as determined using a t-test. The four characterised by statistically significant differences were: "stone on road", "sand on road", "engine rotating at high speed" and "gear change".

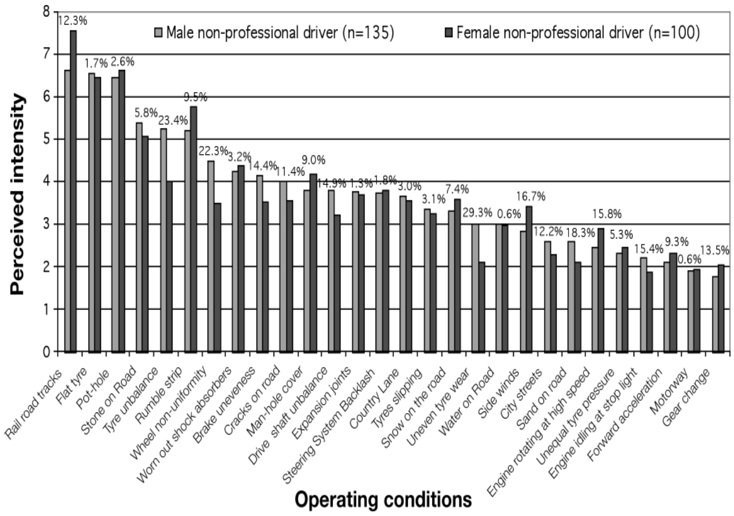


Figure 7) Comparison between the mean perceived intensity of steering wheel vibration of male non-professional drivers (n=135) and female non-professional drivers (n=100), and their respective percentage difference values

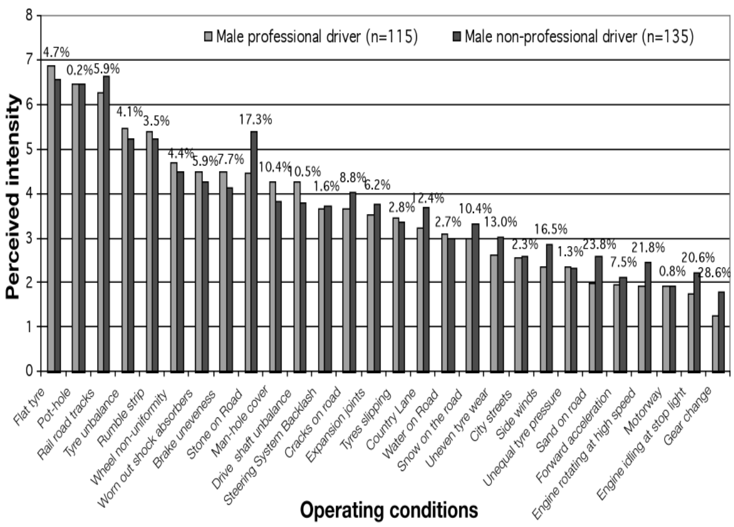


Figure 8) Comparison between the mean perceived intensity of steering wheel vibration of male professional drivers (n=115) and male non-professional drivers (n=135), and their respective percentage difference values

Discussion

The study described here has investigated the intensities that automobile drivers associate, in their memory, with a set of 28 representative driving conditions. The questionnaire gathered both the data of immediate interest, and additional information of use for future studies. An important item of information for putting the current, and future, studies into context is the role that drivers feel steering wheel vibration plays in the driving task. The questionnaire respondents were asked to state the importance of six key driving stimuli towards three safety-critical cognitive tasks. The overall distribution of the responses, presented in Figures 3, 4 and 5, suggests that steering wheel vibration was considered important towards two of the three tasks, particularly towards the identification of the road surface type. Research into the human perception of steering wheel vibration therefore appears justified. Future studies performed in the laboratory or on the road can benefit from the information gathered about the steering wheel hand positions and grip strengths to control test subject posture and grip.

In the case of the intensity comparison based on gender (Figure 7), the mean ratings provided by the male and female drivers were found to be significantly different in only 7 of the 28 automobile operating conditions considered in the current study. This contrasts with the results of the study by Giacomin and Screti [7], in which female drivers were generally found to provide higher CR10 body-part discomfort responses than male drivers, with the differences proving statistically significant at a confidence level greater than 5%. This also contrasts with the results of Neely et. al. [16], who found that the CR10 ratings of perceived intensity and discomfort of hand-arm vibration were, on average, higher for females than for males at all test frequencies. A possible explanation is the use of different semantic descriptors across the three studies. Giacomin and Screti used the semantic descriptor “discomfort“, Neely et. al. used ”discomfort” and “intensity” in conjunction, while the current study used “intensity”. It is not unreasonable to hypothesize that males and females may rate the intensity of a set of external stimuli similarly, but rate the induced discomfort differently. Given the results of the current study, further research appears necessary in order to clarify this point. A further possible explanation for the contrasting findings is the generality of the descriptions of the 28 operating conditions used in the current study. It is unlikely that a single, unique, interpretation of each operating condition was achieved across the complete group of questionnaire respondents. Differences in the interpretation of the driving condition may have produced substantial variance, greater than that introduced by the factor of gender. Support for this possibility can be found in the observation that the coefficients of variation were twice as large, on average, in the current study as in the study by Giacomin and Screti. When performing automotive subjective evaluations by means of CR10 scales, controlling the factor gender would appear to be clearly beneficial in the case of discomfort ratings, and of possible benefit in the case of intensity ratings.

In the case of the intensity comparison based on profession (Figure 8), the mean ratings of the two groups were more similar. The mean difference in the CR10 perceived intensity ratings across all 28 driving conditions was 0.309 when determined between professional and non-professional male drivers, while the same quantity was 0.385 when determined between male and female non-professional drivers. Further, only four driving conditions were found to be characterised by statistically significant differences in rating. The differences between professional and non-professional drivers found in the current study were smaller than those noted in the study of vibration-induced upper body discomfort performed by Giacomin and Screti. As an example, when considering all respondents and all automobiles, the mean CR10 body-part discomfort rating for the forearm region found by Giacomin and Screti was 1.00 in the case of non-professional drivers, but only 0.51 for professional drivers, a difference of 94% in perceived discomfort. When performing automotive subjective evaluations by means of CR10 scales, controlling the factor of driving profession would appear to be clearly beneficial in the case of discomfort ratings, but only possibly beneficial in the case of intensity ratings.

Of the three safety-critical cognitive tasks defined in section B of the questionnaire, the overall distribution of the responses suggested that steering wheel vibration was most useful towards the task of identifying the road surface type. As shown in figure 9, the questionnaire results have therefore been summarised as a reference chart which illustrates the placement of the road surface type along the rating scale. From the original 28 driving conditions, a condition was chosen for the chart if it met two criteria. The first was that the steering vibration be mainly caused by the act of driving over a specific road surface. The second was that the condition was characterised by a subjective intensity response distribution which was Gaussian. The decision as to whether or not the response distribution was Gaussian was taken based on the outcome of a Kolmogorov-Smirnov test [3] which was performed at a 1% confidence level, and which was applied to the complete set of 350 subjective responses. The normality criterion was chosen so as to minimise the risk of choosing a driving condition characterized by ratings which were polarized along lines of either profession or gender. The reference chart of Figure 9 illustrates the nature of the steering vibration occurring in current automobiles, with mean responses spanning the range from “weak” to nearly “very strong” on the CR10 perceptual scale of intensity.

Planned future research into the human subjective estimation of steering vibration intensity includes an experiment to establish the level of correlation between memory-based intensity ratings and direct subjective estimates provided by drivers who are exposed to vibration by means of a steering wheel vibration simulator [8]. Steering acceleration stimuli measured in real automobiles will be applied in a controlled laboratory setting. The subjective estimates provided by the laboratory test participants will be correlated with the memory-based estimates described above, and with the estimates that can be calculated using the methods outlined by standards ISO 5349-1 [12] and BS 6842 [1].

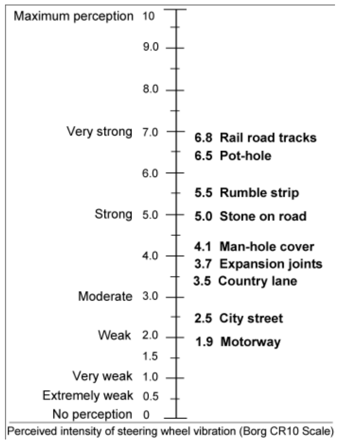


Figure 9) Subjective rating scale for quantifying the perceived intensity of road-induced steering wheel vibration stimuli

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