Beyond Comfort: information content and perception enhancement

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1. Introduction

Motor vehicle drivers are regularly exposed to vibrational and acoustic stimuli in their vehicles. These stimuli are normally considered to be sources of discomfort, and methods for analysing the noise, vibration and harshness (NVH) properties of road vehicles are in regular use. It can be stated that motor vehicle manufacturers currently dedicate significant attention to the NVH characteristics of their products.

The steering system is case in point. Steering vibration can reach frequencies of up to 300 Hz when driving over certain road asperities (Giacomin et. al., 2004) 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 (Pottinger et al., 1986). The design of the steering components has been the subject of several studies (Pak et al., 1991) and the human subjective response to hand-arm steering vibration has also been investigated in terms of both the perceived sensation (Giacomin et. al., 2004) and the induced fatigue (Giacomin and Abrahams, 2000). While further research is required, much is nevertheless known about the discomfort associated with steering vibration.

A less well understood topic, however, is the question of the information transmitted to the driver by the steering vibration. With the advent of electronically assisted steering and "by-wire" technologies the question of what stimuli should reach the driver assumes great importance. All current methodologies for determining vibrational comfort, whether hand-arm or whole-body, and whether based on the use of frequency weightings (BS 6842, 1987; ISO 5349-1, 2001) or customer correlations, are defined in such a way as to suggest that a uniform reduction in vibrational level is accompanied by a uniform reduction in discomfort. Stated alternatively, less vibration should be judged as better. This may not be appropriate in the case of information, since scenarios can be imagined in which an increase in vibration level might help clarify the nature of the road surface or the vehicle dynamic state. It can be therefore be suggested that the vehicle designer might benefit from metrics which quantify the information content of vehicle stimuli in the same manner that NVH methods quantify the discomfort potential.

2. Information and Perception Enhancement

The question of what information a road vehicle subsystem should transmit to the driver is not a simple one. Vibrational (haptic) stimuli help in the interpretation of many things including the type of road surface, the presence of water or snow, tyre slip (both longitudinal and lateral) and the dynamic state of subsystems such as the engine, the steering and the brakes. The stimuli are perceived, compared to models from long term memory and interpreted, with the consequent interpretation then influencing decision taking (see figure 1).

Figure 1 Elements of the cognitive driving task

The perceptual and cognitive roles to assign to machines has been the subject of some research. Studies have shown that the global performance of the coupled person-machine system can be improved when certain low level perceptual and cognitive functions are assigned to the machine (Quek and Petro, 1993; Rombaut, 1995; Stanton and Pinto, 2000). A useful approach is represented by information theoretic methods. Since the work of Shannon (1949), researchers have applied measures of *information entropy* to problems in human behaviour and control (Corning, 2001; Bea and Marijuan, 2003). In Shannon's terminology *information* refers to the capacity to reduce statistical uncertainty, while *entropy* characterises the degree of uncertainty. The basic premise of such approaches is that a communication channel can be analysed in terms of the *symbols* used, and that the

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probability of occurrence of the symbols can be used as a metric of information flow. If appropriate symbols have been identified (such as the words in the English language), information entropy can be defined to be

$$H = -\sum_{i=1}^{n} p_i \log p_i$$

where H is the information entropy, is the probability obtained from counting the number of occurrences of symbol i, and is the total number of symbols used in the communication.

In recent years information measures have begun to be applied to automotive problems, an example being the measure of steering wheel entropy defined by Nakayama et. al. (1999). Current methods are, however, dedicated and specific, but the possible future availability of generalised approaches opens interesting prospects for road vehicle testing and design. Figure 2 presents one such hypothesis in which vehicle stimuli are judged in terms of both their impact on human comfort and their information content. Further, the availability of generalised information measures would be expected to permit the designer to achieve perception enhancing interfaces, or, more specifically, *Perception Enhancement Systems (PES)*. A possible PES for a by-wire steering system is hypothesised in Figure 3, where vibrational movements at the tyre or wheel hub are returned to the driver through a perception enhancing electronic controller unit which identifies the significant features to amplify and transmit.

n p_i

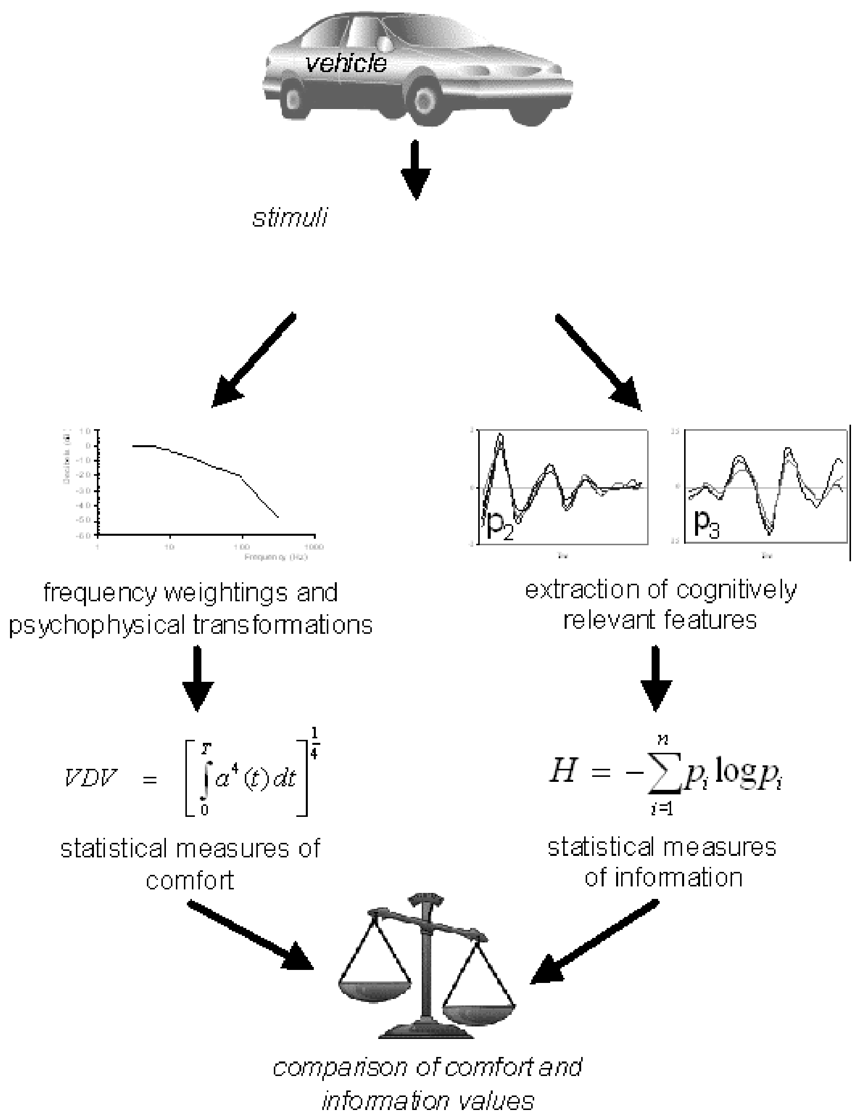

Figure 2 Evaluation of the comfort and information properties of a vibrational stimuli

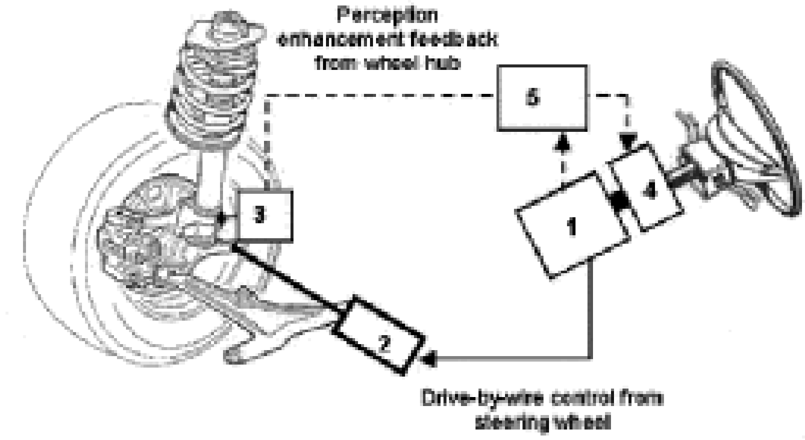

Figure 3 Opportunity for perception enhancement in "by-wire" steering systems

3. An experiment in the identification of road surfaces

A task of the steering interface is to assist the driver in the identification of the road surface, and a parameter which influences identification is the feedback gain of the steering controller. The study described here is a first approach to the question of stimuli scaling. To simulate the possible effect of varying the feedback gain, steering wheel acceleration time histories from a mid-sized European automobile were presented to human test participants in a laboratory setting. While not attempting to determine information theoretic values for the stimuli, the study evaluates the possible influence of one parameter of the steering interface.

3.1 Test stimuli

Steering wheel tangential acceleration time histories measured in a single vehicle when driving over several road surfaces were analysed, and four surfaces were selected for use as stimuli in a laboratory experiment. The four roads, shown in Figure 4, were a tarmac surface, a cobblestone surface a concrete road and a wide, low, bump. The surfaces were considered representative of normal driving and provided steering vibrations having different time domain and spectral statistics. A 10 second data segment was extracted from each data set to serve as test stimuli. The segments were selected such that the root mean square value, kurtosis value and power spectral density were statistically close to those of the complete recording. Figure 5 presents the selected time histories while Figure 6 presents the associated power spectral densities. The original r.m.s. acceleration values of the stimuli were 0.048 m/s^2 for the tarmac surface, 0.271 m/s^2 for the cobblestone surface, 0.249 m/s^2 for the bump and 0.092 m/s^2 for the concrete surface. The original kurtosis values for the same stimuli, which are dimensionless, were 3.00 for the tarmac surface, 3.25 for the cobblestone surface, 10.76 for the bump and 3.83 for the concrete surface.

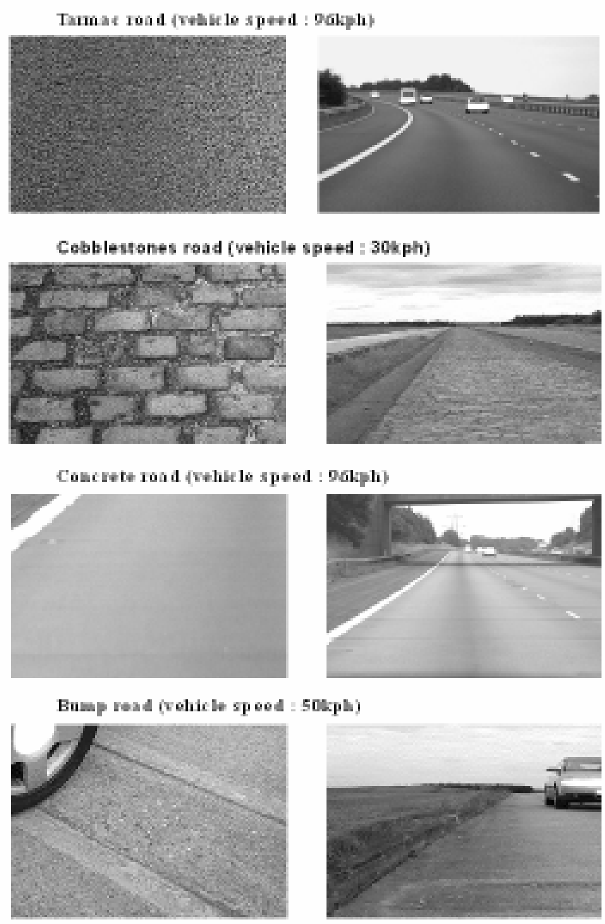

Figure 4 Road surfaces whose stimuli were chosen for use in testing

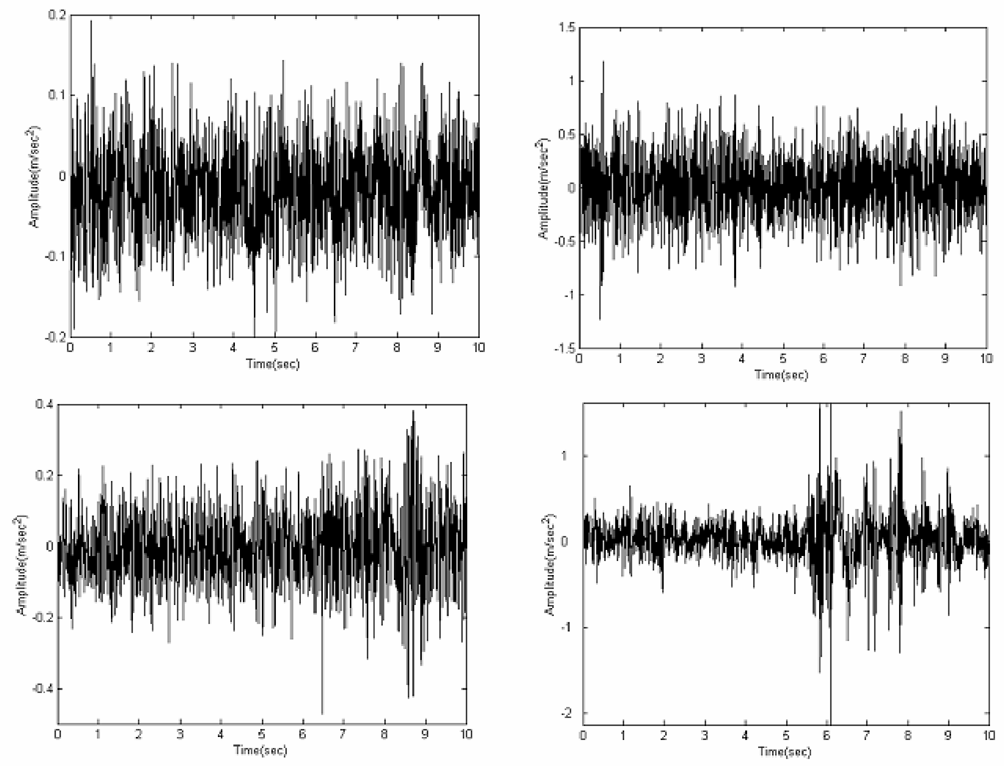

Figure 5 Steering wheel tangential acceleration time histories used as test stimuli

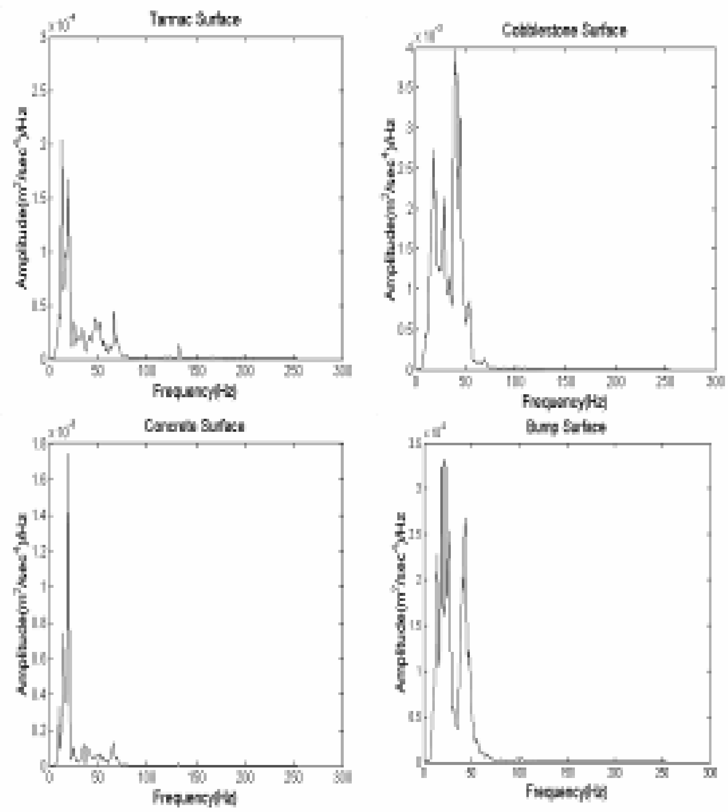

Figure 6 Power spectral densities of the steering wheel tangential acceleration test stimuli

Each of the four steering wheel stimuli was multiplied by each of five different scale values to simulate the action of different steering feedback gains. Gain values of 0.6, 0.8, 1.0, 4.0 and 7.0 were chosen based on both the threshold of human perception of hand-arm vibration stimuli and the operating region of the test equipment. The mathematical operation of scaling was chosen so as to not affect the spectral or phase relationships of the stimuli. The use of five multiplication factors produced a total of 20 stimuli for the experiment.

3.2 Test Facility

All tests were performed using the steering wheel rotational vibration simulator shown in Figure 7. The system consists of a 325mm diameter aluminum wheel attached to a steel shaft which is mounted on two bearings. The shaft is connected to an electrodynamic shaker by means of a stinger-rod. Table 1 presents the principal geometric characteristics of the rig, which were chosen based on data from a small European automobile. The seat is fully adjustable in terms of horizontal position and back-rest inclination as in the original vehicle. Rotational vibration was applied by means of a G&W V20 electrodynamic shaker driven by PA100 power amplifier. The imparted tangential acceleration was measured by means of an Entran EGAS-FS-25 accelerometer attached to the top left side of the wheel and was amplified by means of an Entran MSC6 signal-conditioning unit. Control and data acquisition were performed by means of the LMS EMON software system coupled to a DIFA SCADASIII electronic frontend unit. The software permitted the fixing of safety cutoff limits for the test acceleration, which were set to 20.0 m/s^2 peak acceleration. A unit was also used which incorporated both a manual shutdown and an emergency soft-stop condenser circuit.

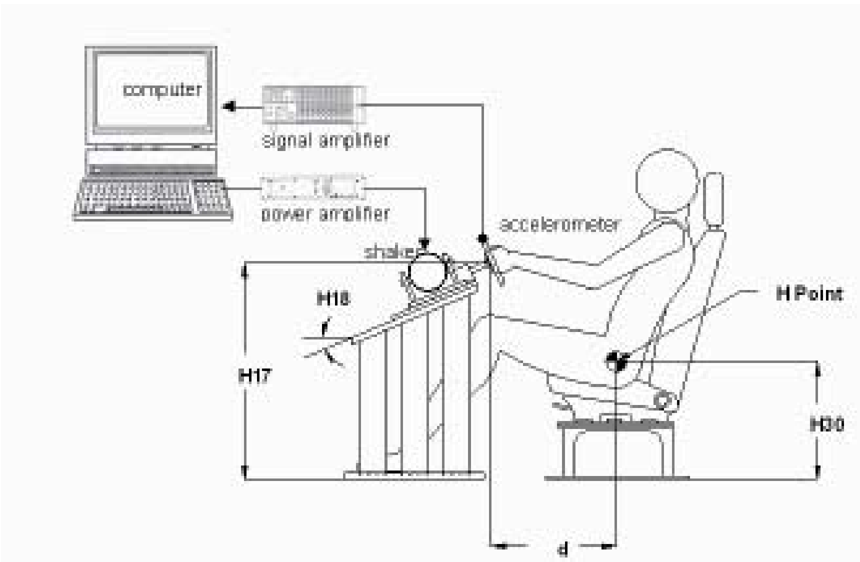

Figure 7 Steering wheel rotational vibration test facility

Geometric Parameter	Value
Steering column angle (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=L11-L51)	390–550 mm
Steering wheel tube diameter	12.5 mm
Steering wheel diameter	325 mm

Table 1 Geometric dimensions of the steering wheel rotational vibration test rig

The steering wheel rig had a first resonance frequency of 350 Hz. When loaded by a human hand-arm system and tested under sinusoidal excitation at frequencies of 4.0, 8.0, 16.0, 31.5, 63.0, 125 and 250 Hz at amplitudes of 0.2, 2.0 and 20.0 m/s^2 r.m.s. the bench provided a maximum total harmonic distortion (THD) of 15% 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. During the tests which measured the tangential direction THD, a linear fore-and-aft direction acceleration measurement was also performed at the same point on the rigid wheel. Fore-and-aft acceleration was found to be no greater than -50 dB with respect to the tangential acceleration in all cases measured. The safety features of the rig and the acceleration levels utilised conform to the health and safety recommendations outlined by British Standards Institution BS7085 (1989).

3.3 Test Protocol

Forty Sheffield University staff and students performed tests. Upon arriving in the laboratory each was issued an information and consent form and was provided an explanation of the experimental methods and the safety features. Sex, age, height, and weight data were then collected, and the participant was requested to state whether he or she had any physical or mental condition which might affect perception of hand-arm vibration, and whether he or she had ingested coffee within the 2 hours previous to arriving in the laboratory. The group consisted of 20 males and 20 females, and had a mean age of 31.6 years, a mean height of 1.68 m and a mean mass of 62.9 kg. No participant declared any physical or mental condition which might affect perception of hand-arm vibration, and none declared having ingested coffee.

Before commencing testing 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 which was as similar as possible to the one normally used in their own vehicle. 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. Each participant was then asked to fix eyes on the board directly in front of the simulator (see Figure 8), which displayed photographs of the road surfaces as seen both from a distance (as during driving) and close up (from approximately 1 meter). He or she was then presented each of the steering vibration stimuli and was asked to chose which of the four possible roads the stimuli was from. The participants were requested to provide their best estimate for each stimuli and to respond even if uncertain. The vehicle speed associated with each stimuli was not provided.

	Minimum	Mean	Maximum	Std. Deviation
age [years]	21.0	31.6	45.0	5.60
height [m]	1.51	1.68	1.84	0.08
mass [kg]	44.0	62.9	90.0	13.1

Table 2 General statistics of the test subjects (n=40)

Figure 8 Participant performing a forced-choice four stimuli test

To permit data averaging, a complete test for a single participant included a total 3 repetitions of each of the 20 test stimuli for a total of 60 identifications. Each 10 second stimuli was separated by a 5 second gap during which the participant indicated his or her choice of road surface. The order of presentation of the 60 stimuli was randomised individually for each participant to reduce learning or fatigue effects. Considering all activities performed from the moment the participant entered the laboratory, the total test time amounted to approximately 27 minutes. The participants were instructed that they could interrupt the test at any point if they should wish. The test facility and protocol were reviewed and found to meet the University of Sheffield guidelines for good research practice.

4.0 Results

Figure 9 presents the results of the laboratory tests, reported in terms of ratio of correct recognition, from 0 to 1 (0 to 100 percent). Three distinct behaviours can be identified from the results of the four road surfaces. A first behaviour is illustrated by the results from the tarmac road surface which suggest that recognition rate is reduced when the feedback gain applied to the steering vibration signal is increased. The tarmac surface is representative of a category of roads whose correct identification is reduced by increases in the size of the vibration stimuli. The qualitatively opposite behaviour is found in the case of the cobblestone road surface, in which human memory and human expectation associate the surface with large vibration amplitudes. In this case the rate of correct identification increases with increases in feedback gain. An intermediate result, and intuitive class of behaviour, is illustrated instead by the concrete and bump road surfaces whose recognition rates decrease with both increases and decreases in feedback gain. In these cases the ability of humans to identify the stimuli appears to be negatively affected by any deviation from the natural vibrational level of the signal.

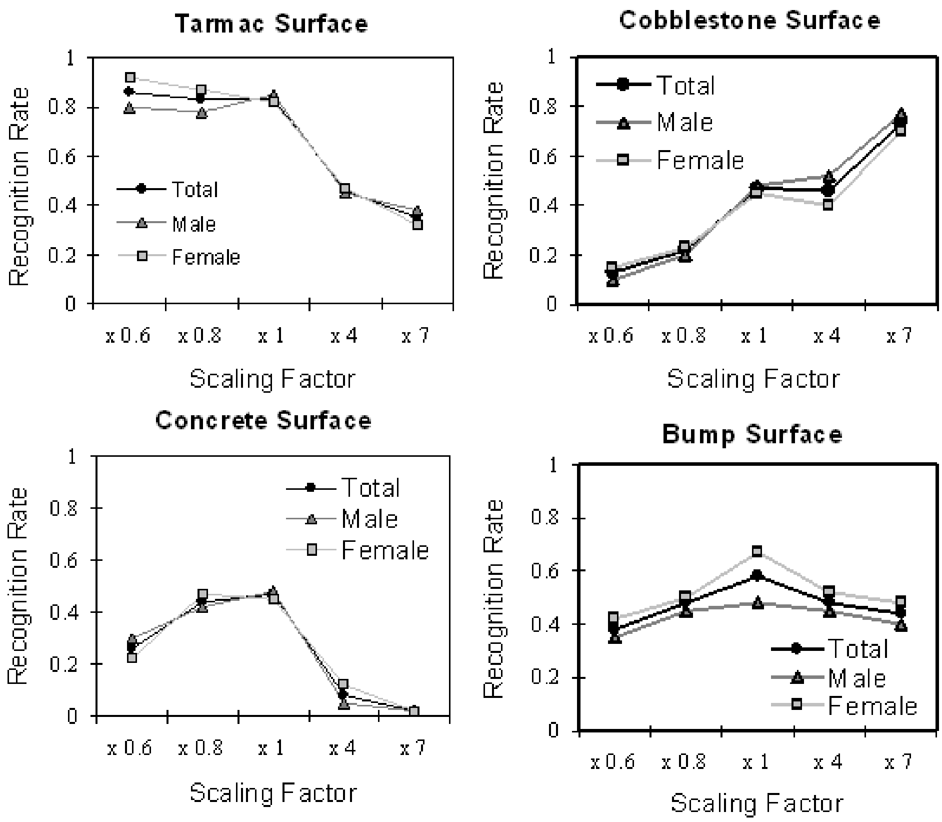

Figure 9 Percent correct identification of the road surfaces at each of 5 scales

Comparison of the ratio of correct recognition across the four road surfaces suggests that some roads are characterized by the possibility of nearly 100 percent accurate identification (tarmac and cobblestone) at selected feedback gains, while others are characterised by lower rates at all feedback values. This suggests the possible existence of statistical features in the stimuli produced by some roads which make them intrinsically easier to separate from the background noise consisting of all stimuli from all roads. Further separation of the data into two subgroups according to gender suggests statistically significant (t-test at $p>0.05$) differences between males and females, with the females providing higher rates of correct recognition for most of the stimuli tested.

5.0 Conclusions

This paper has introduced the possibility of evaluating the information content of vibro-acoustic stimuli occurring in road vehicles. The possibility of measuring the information arriving to the vehicle driver offers a possible new metric which can be used in conjunction with existing metrics of human comfort. Successful metrics of information flow could also serve as one possible basis for the development of Perception Enhancement Systems, which would act as interfaces between the person and the machine elements of the coupled driving system, with the assigned role of identifying and amplifying useful information associated with the dynamic states of the vehicle.

When considering current steering system technology in road vehicles, quantities of immediate interest are the feedback gains and the feedback bandwidth over which electronic or "by-wire" systems should operate. A simple laboratory-based experiment was performed which investigated the effect of feedback gain on human recognition of road surface type. The results suggest that at least three memory models, or categories, of road surface type exist and that successful recognition is highly dependent on the feedback gain. Human perceptual characteristics and the human a-priori knowledge of the road surface produce recognition characteristics which are not simply related to the test stimuli in terms of amplitude or spectral content. Further research is required, and is underway, to determine the optimal range of feedback gains and the optimal frequency bandwidth for electrical power assisted steering systems. An information entropy measure for vehicle stimuli is also being defined.

6. Acknowledgements

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