Steering System Vibration : Information and Perception Enhancement

J. Giacomin * and Y.J. Woo **

*** Department of Mechanical Engineering, The University of Sheffield**
Mappin Street, Sheffield S1 3JD, United Kingdom
Tel: +44-114-222-7781   Fax: +44-114-222-7890
e-mail: j.a.giacomin@sheffield.ac.uk

**** Chassis Platform Development Team, Research & Development Division**
Hyundai Motor Company, 772-1, Jangduk-Dong, Hwaseong-Si,
Gyeonggi_Do, 445-706, Korea
Tel: +82-31-368-5809   Fax: +82-31-368-3327
e-mail: babelwoo@hyundai-motor.com

1.0 Introduction

Automobile drivers are regularly exposed to vibrational and acoustic stimuli. These stimuli cause discomfort, and methods for analysing the noise, vibration and harshness (NVH) properties of automobiles are in regular use. Most manufacturers currently dedicate significant attention to the NVH characteristics of their products.

NVH criteria are regularly applied to the design of the steering system, whose vibration spectra can reach frequencies as high as 300 Hz. The design of steering components has been the subject of several studies (Pak et al., 1991) and the human subjective response to steering vibration has also been investigated, in terms of perceived intensity (Giacomin et. al., 2004) and induced fatigue (Giacomin and Abrahams, 2000). While further research is required, much is known about the discomfort produced by steering vibration.

A less well understood topic is the information transmitted to the driver. With electronically assisted and by-wire steering technologies (Jurgen, 1999) the question of what stimuli should reach the driver has become important. All current methods for estimating vibrational discomfort, whether hand-arm or whole-body, and whether based on frequency weightings (ISO 5349-1, 2001) or customer correlations (Schoeggl, 2001), are defined in such a way as to suggest that a uniform reduction in vibration level brings a uniform reduction in discomfort. Less vibration is considered better. This may not be appropriate in the case of information, however, since situations can be imagined in which an increase in vibration might prove useful towards understanding the nature of the road surface or of the vehicle dynamic state.

The question of what information the steering should transmit to the driver is not a simple one. Vibrational stimuli help the driver to interpret 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.

A possible approach is the measurement of statistical information. Since the work of Shannon (1949), numerous researchers have applied the concept 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* is the degree of uncertainty. The basic premise is that a communication channel can be analysed in terms of the *symbols* used, and that the probability of occurrence of the symbols can be used as a metric of information flow. In recent years information measures have occasionally been applied to automotive problems, one example being the measure of steering wheel entropy defined by Nakayama et. al. (1999). The availability of a metric for quantifying the information transmitted to the driver provides an important new type of evaluation. As shown in figure 1, stimuli can then be judged in terms of the two, often opposing, criteria of discomfort and information. Further, optimisation of the information transmitting elements of the steering system by the automobile designer leads to a perception enhancing interface, or, more specifically, a *Perception Enhancement System (PES)*. A possible PES for a by-wire steering system is shown in figure 2, where movements at the tyre or wheel hub are returned to the driver through a perception enhancing electronic controller unit, which identifies significant features which are then amplified and transmitted.

Research to define information metrics and perception enhancement systems for automobile steering systems is being performed as part of a collaboration between the Perception Enhancement Systems research group of Sheffield University and the Hyundai Motor Company central research laboratory. This article describes the results of two experiments which have measured the effect of the amplitude and the frequency bandwidth of steering vibration on the human ability to identify road surface type.

2.0 Two experiments in the identification of road surface type

Two experiments were performed in the Sheffield Perception Enhancement Systems laboratory to measure the human cognitive response to changes in the statistical properties of steering vibration. Tangential direction acceleration time histories were used, which had been measured in an Audi A4 when driving over four road surfaces. The surfaces, shown in Figure 3, were a tarmac surface, a cobblestone surface, a concrete surface and a bump. Automobile speeds were 96 kph, 30 kph, 96 kph and 50 kph respectively. A representative 10-second segment was extracted from the time history measured on each road, and was used in the laboratory experiments. The segments are presented in figure 4, while figure 5 presents the corresponding power spectra. The root mean square (r.m.s.) acceleration values of the segments were 0.048 m/s^2 for the tarmac surface, 0.271 m/s^2 for the cobblestone surface, 0.092 m/s^2 for the concrete surface and 0.249 m/s^2 for the bump. The kurtosis values, which are dimensionless, were 3.00 for the tarmac surface, 3.25 for the cobblestone surface, 3.83 for the concrete surface and 10.76 for the bump.

The laboratory experiments were performed using the steering wheel rotational vibration simulator shown in Figure 6. The system consists of an aluminum wheel which is vibrated in the rotational direction by an electrodynamic shaker. The tangential acceleration is measured using an accelerometer. Control and data acquisition are performed by means of the Leuven Measurement Systems EMON software coupled to a DIFA SCADASIII electronics unit. The geometric characteristics of the rig were chosen based on data from a small European automobile (see table 1), and the seat is adjustable as in the original vehicle. The rig has a first resonance frequency greater than 350 Hz and is characterized by values of total harmonic distortion which are in the range from 1 to 3%. Unwanted fore-and-aft acceleration is no greater than -50 dB with respect to the tangential acceleration. The safety features of the simulator and the acceleration levels used conform to the health and safety recommendations of British Standards Institution BS7085 (1989). The test facility and protocol were reviewed and found to meet the University of Sheffield guidelines for good research practice. A complete description of the simulator and of the experimental test protocol can be found in Giacomin and Woo (2004).

Two experiments were performed. The first investigated the effect of steering acceleration level on the human identification of road surface type, while the second investigated the effect of steering acceleration bandwidth. Both shared a common protocol, the only difference being the stimuli used. Each experiment involved 25 participants. After sitting in the simulator and adjusting the posture, each participant was asked to fix his or her eyes on a board directly in front of the simulator which displayed photographs of a road surface, as seen from both a distance (as during driving) and from close up (from approximately 1 meter). A series of 10-second tangential acceleration stimuli were applied, separated by 5-second gaps in which the participant stated his or her judgment. To permit data averaging, a complete test for a single participant included multiple repetitions of each of the vibration stimuli. The participant was asked to state “yes” or “no” with respect to the surface shown on the board. Participants were requested to provide their best estimate and to respond even if uncertain. The vehicle speed associated with each vibration was not provided, nor was any feedback given regarding about whether the identification made by the test subject was correct or incorrect. The 10-second time histories consisted of either the sections of the original data, or modified sections consisting of scaled or frequency filtered versions of the originals. In each experiment the order of presentation of the stimuli was randomised in order to reduce learning effects and fatigue effects.

3.0 Results

3.1 Effect of vibration level

In order to investigate the effect of vibration level, each of the four steering wheel time histories was multiplied by each of five different scale values. Scale values of 0.6, 0.8, 1.0, 4.0 and 7.0 were chosen so as to construct test stimuli which were higher than the threshold of human perception of hand-arm vibration, and lower than maximum steering acceleration values encountered in automobiles. The mathematical operation of scaling was chosen so as to not affect spectral or phase relationships. The use of five multiplication factors produced a total of 20 test stimuli.

Figure 7 presents the results of the laboratory experiment which investigated the effect of vibration level. The results are reported in terms of the ratio of correct detection, a scalar value ranging from 0 to 1. Three distinct behaviours were found. The first is illustrated by the results from the tarmac surface which suggest that correct detection decreased when the vibration level increased. The opposite behaviour was found in the case of the cobblestone surface in which human memory and expectation associated the surface with large vibration amplitudes. In this case the rate of correct detection increased with increases in level. An intermediate result was found instead for the concrete and bump surfaces, whose rates of correct detection decreased with both increases and decreases in level. For these two roads, the human ability to correctly identify the surface was negatively affected by any deviation from the natural level.

A conclusion regarding the effect of vibration level that can be drawn from the experiments is that correct detection is not strictly optimum at the natural vibration level encountered in automobiles. The results from two of the surfaces suggest optimal detection at extreme scale factors, distant from the natural vibration level of the original stimuli. This may be of relevance to the designers of both traditional and by-wire steering systems since careful consideration appears to be necessary when choosing the target level of steering feedback for each driving condition. The results suggest that a single, fixed, feedback gain from the vehicle to the steering wheel will result optimal in only a small number of driving conditions.

3.2 Effect of vibration frequency bandwidth

In order to investigate the possible effect of the frequency bandwidth of the acceleration stimuli on the human identification of road surface type, each of the four original steering wheel time histories was low-pass filtered by means of digital butterworth filters. For each of the original signals, five frequency bandwidths of 0-20 Hz, 0-40 Hz, 0-60 Hz, 0-80 Hz and 0-100 Hz were achieved, producing a total of 20 test stimuli.

Figure 8 presents the ratio of correct detection determined for the tarmac and the cobblestone road surfaces from the bandwidth experiment. These are representative of all four sets of results. In general, a monotonically increasing relationship was found between detection and bandwidth. Detection improved with increases in the bandwidth of the acceleration stimuli, and average rates of correct detection exceeded 80% for stimuli covering the frequency range from 0 to 80 Hz. The results suggest that the long term memory model used by drivers to judge road surface type contains information about oscillatory frequencies in excess of 60 Hz. Further, the differences between the data sets suggest that the energy of the higher frequencies was more important towards the correct identification of the cobblestone surface than of the tarmac surface. For the automobile steering system designer, a bandwidth of at least 60 to 80 Hz appears necessary for efficient detection of road surface type.

4.0 Conclusions

When designing an automobile steering system, quantities of immediate interest are the vibration feedback gain and bandwidth. The laboratory experiment described here has provided some data regarding the effects of these parameters on the human detection of the road surface. The results of the vibration frequency bandwidth experiment suggest that a minimum bandwidth of at least 60 or 80 Hz is required to guarantee efficient detection of the road surface by the driver. The results of the vibration level experiment suggest that human detection of the road surface is a complex process, characterised by specific cognitive models which are used by the driver. Three detection behaviours were found, which are possibly associated with three memory models. From the results, a single, optimal, feedback gain does not appear appropriate for all road types. Further research is required, and is underway, to determine the optimum range of feedback gains for automobile steering systems. Such data is an important prerequisite to the development of a full metric of steering information entropy, which is the final objective of the research programme.

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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 dimension of the steering wheel rotational vibration test rig.

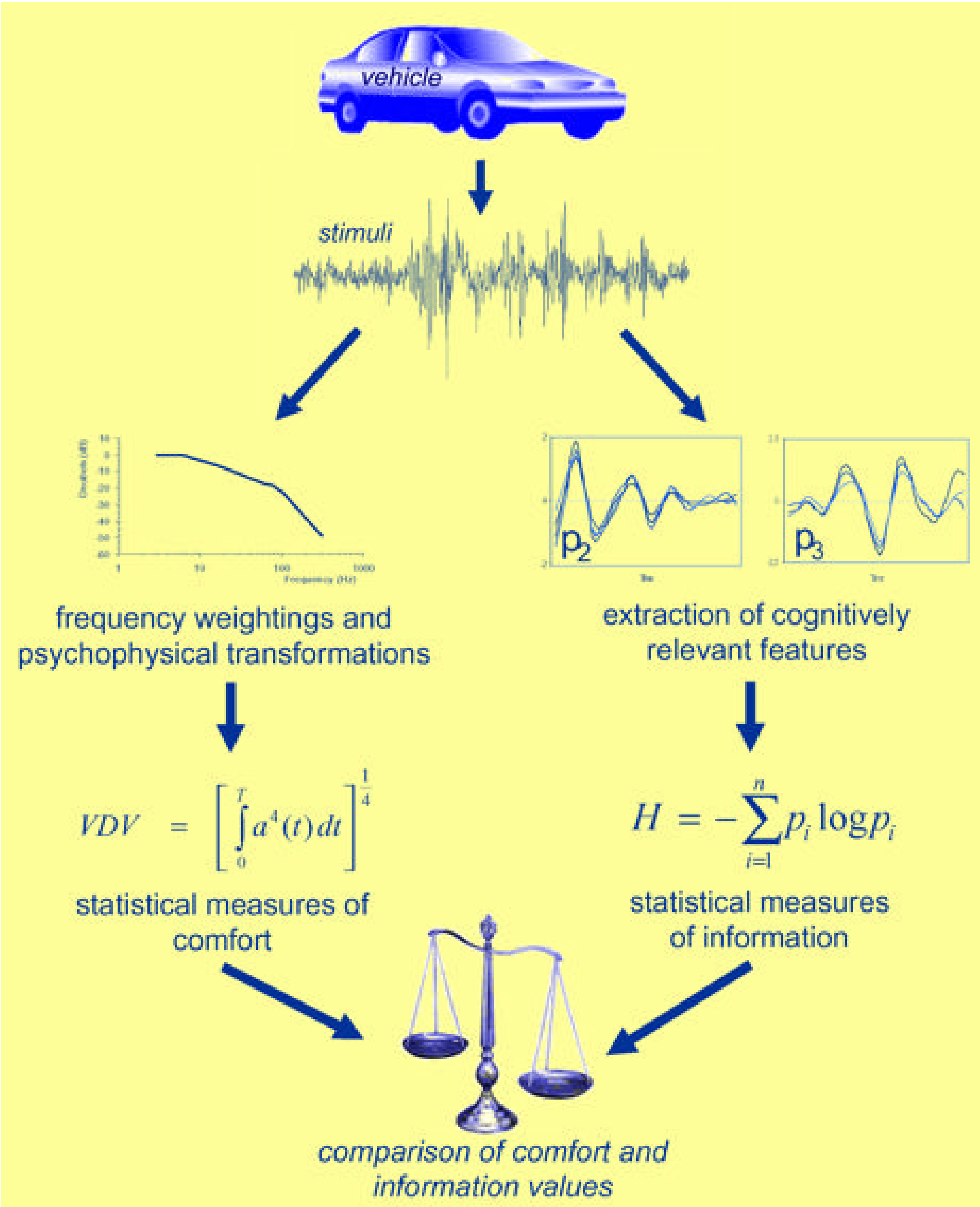

Figure 1 Evaluation of both the comfort and the information properties of vehicle vibrational stimuli.

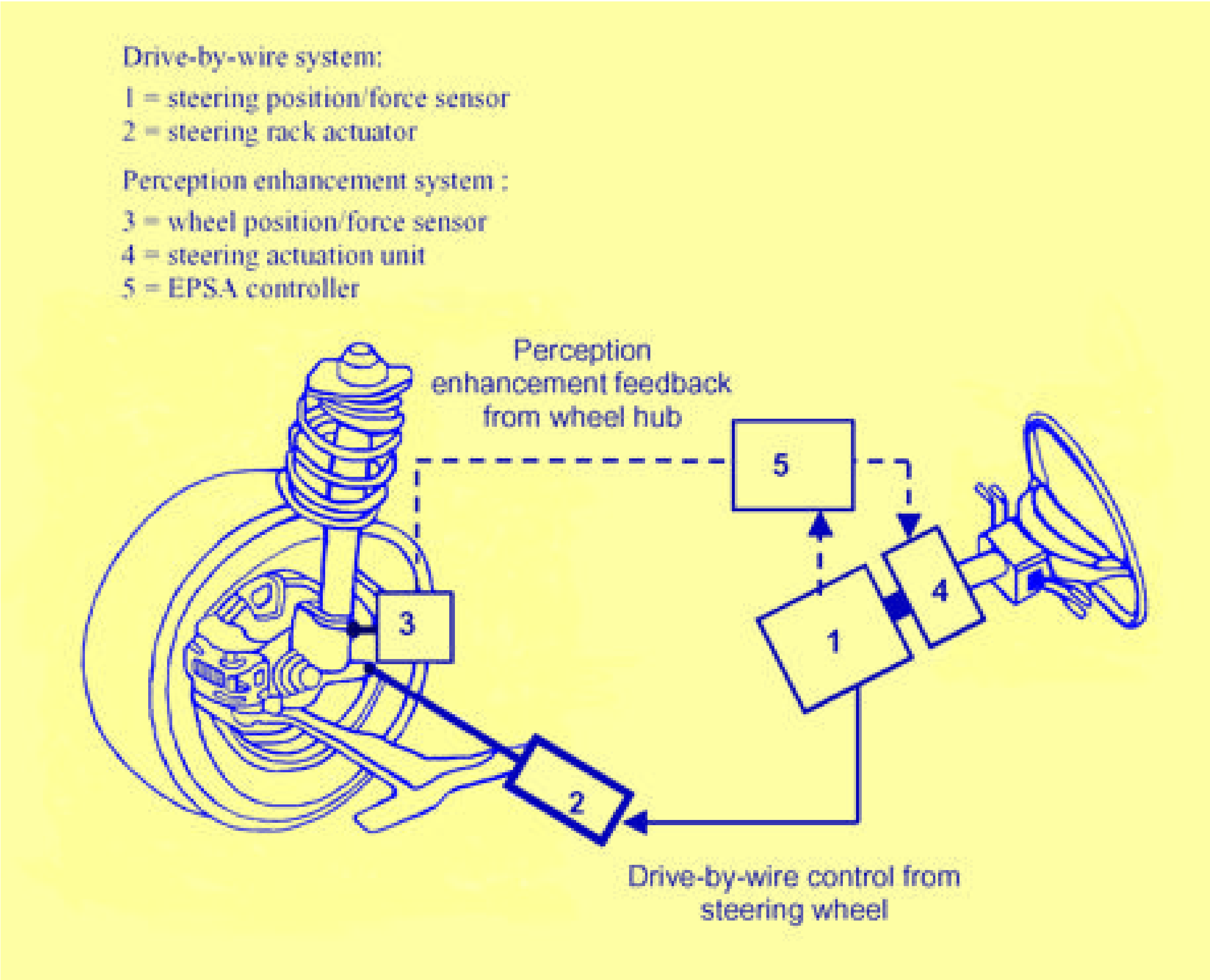

Figure 2 A perception enhancement system for by-wire steering.

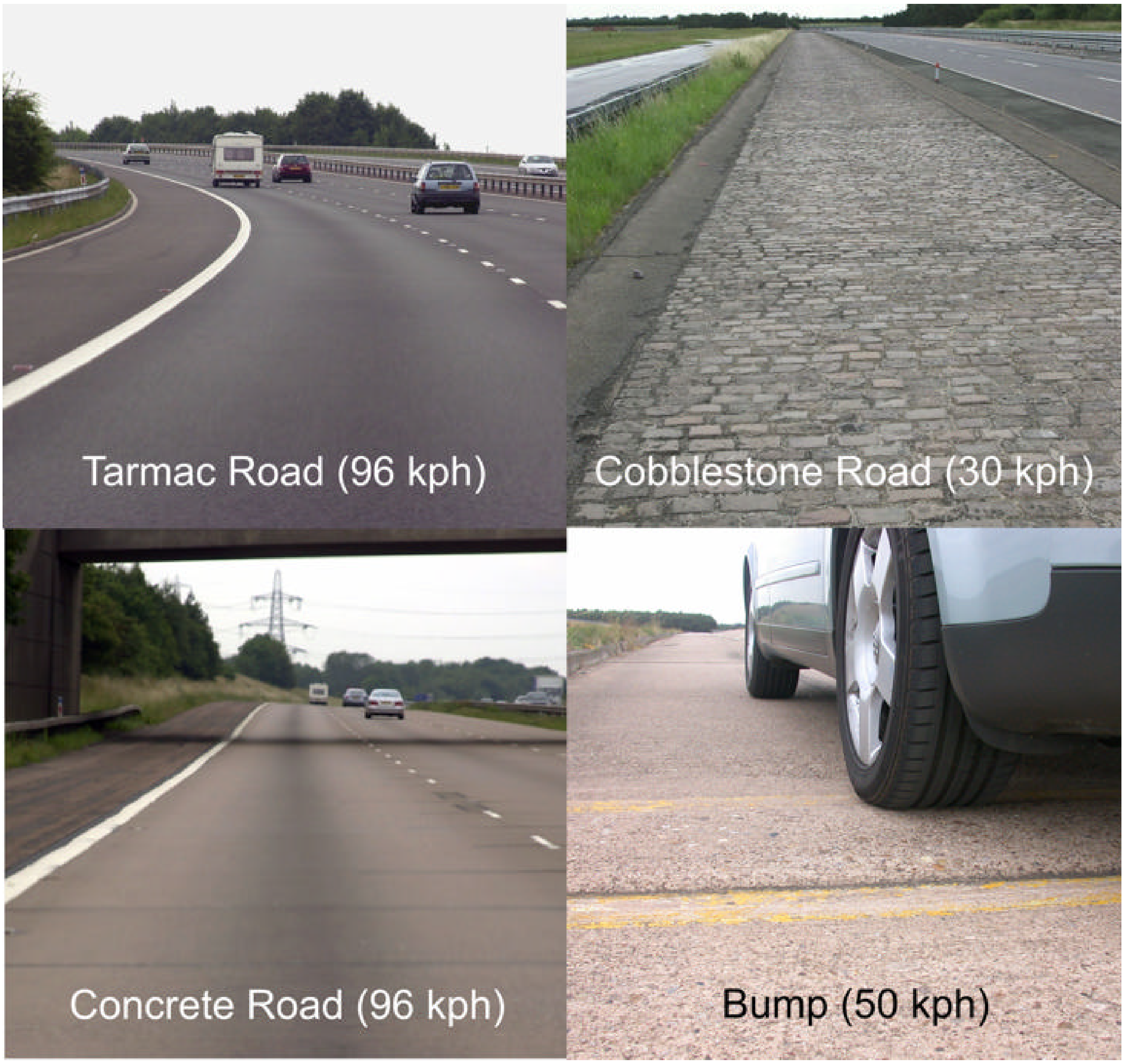

Figure 3 Road surfaces which produced the steering wheel acceleration time histories used in the laboratory experiments.

a) Tarmac road surface (vehicle speed: 96kph).

b) Cobblestone road surface (vehicle speed: 30kph).

c) Concrete road surface (vehicle speed: 96kph)

d) Bump road surface (vehicle speed: 50 kph)

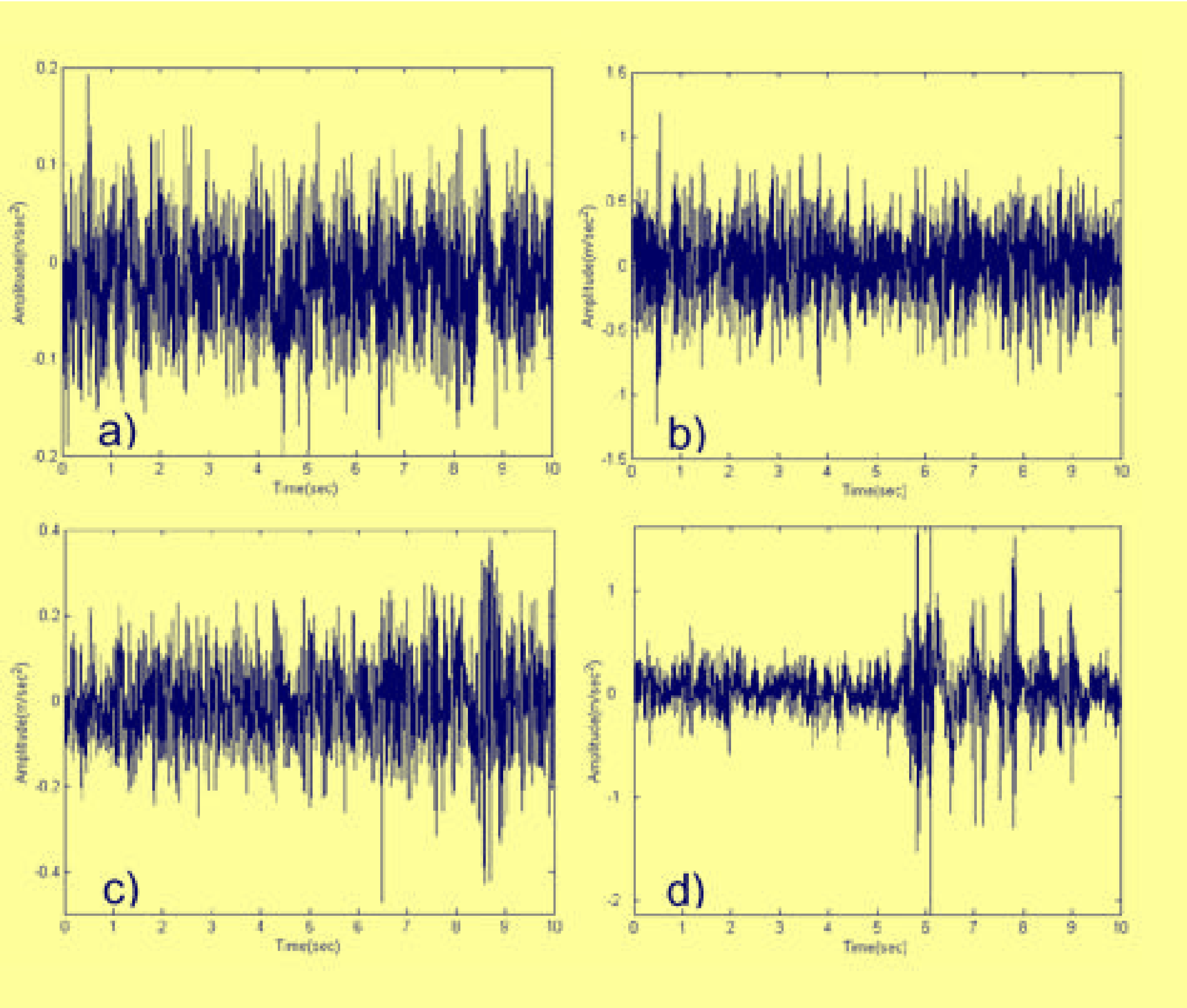

Figure 4 Steering wheel tangential direction acceleration time histories used in the laboratory experiments.

a) Tarmac road surface (vehicle speed: 96kph).

b) Cobblestone road surface (vehicle speed: 30kph).

c) Concrete road surface (vehicle speed: 96kph)

d) Bump road surface (vehicle speed: 50 kph)

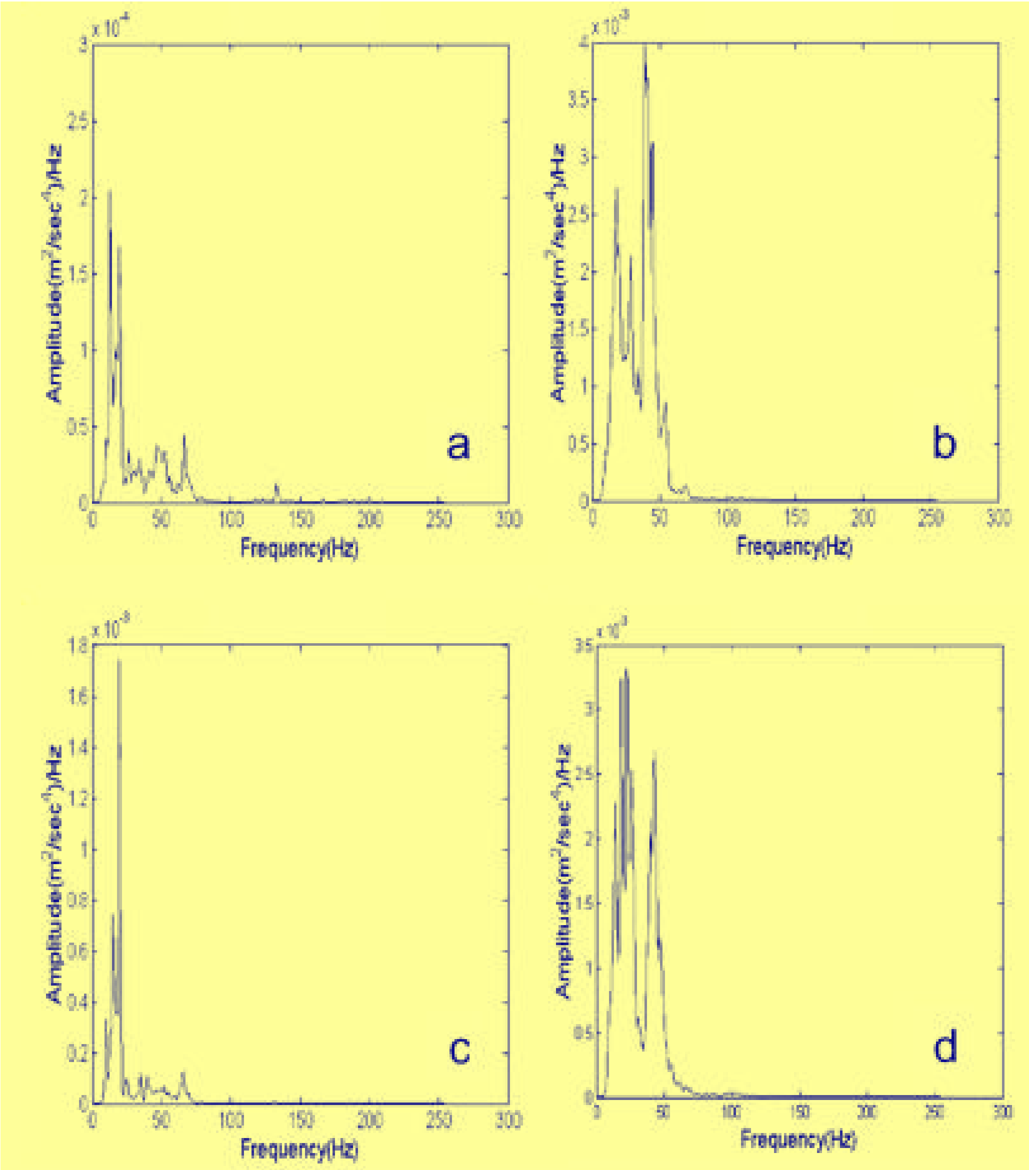

Figure 5 Acceleration power spectral densities of the steering wheel tangential direction acceleration time histories.

a) Tarmac road surface (vehicle speed: 96kph).

b) Cobblestone road surface (vehicle speed: 30kph).

c) Concrete road surface (vehicle speed: 96kph)

d) Bump road surface (vehicle speed: 50 kph)

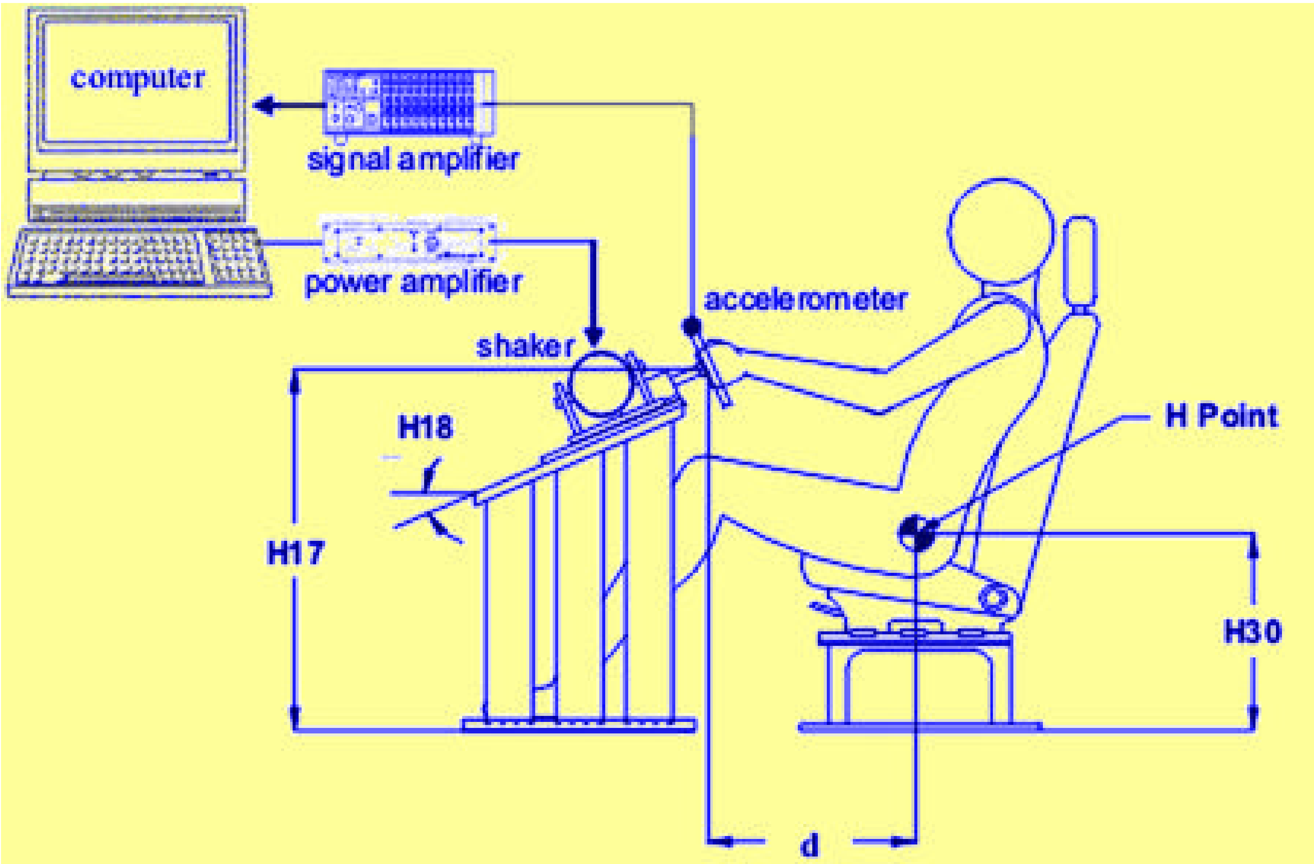

Figure 6 Steering wheel rotational vibration test simulator.

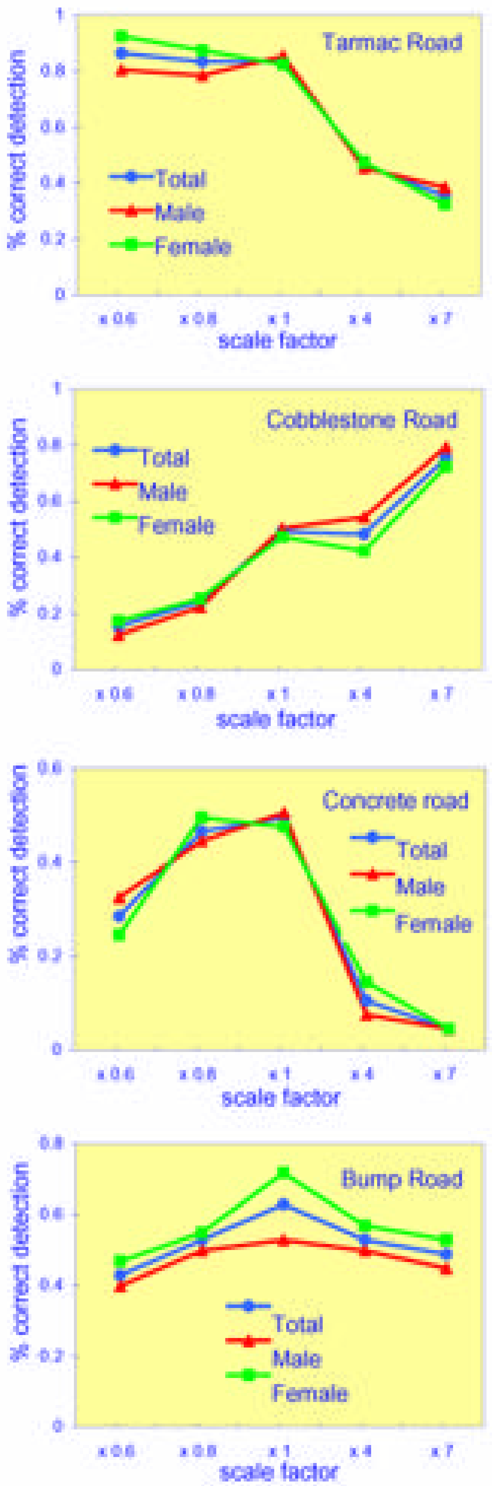

Figure 7 Percent correct detection results from the experiment to investigate the effect of vibration level.

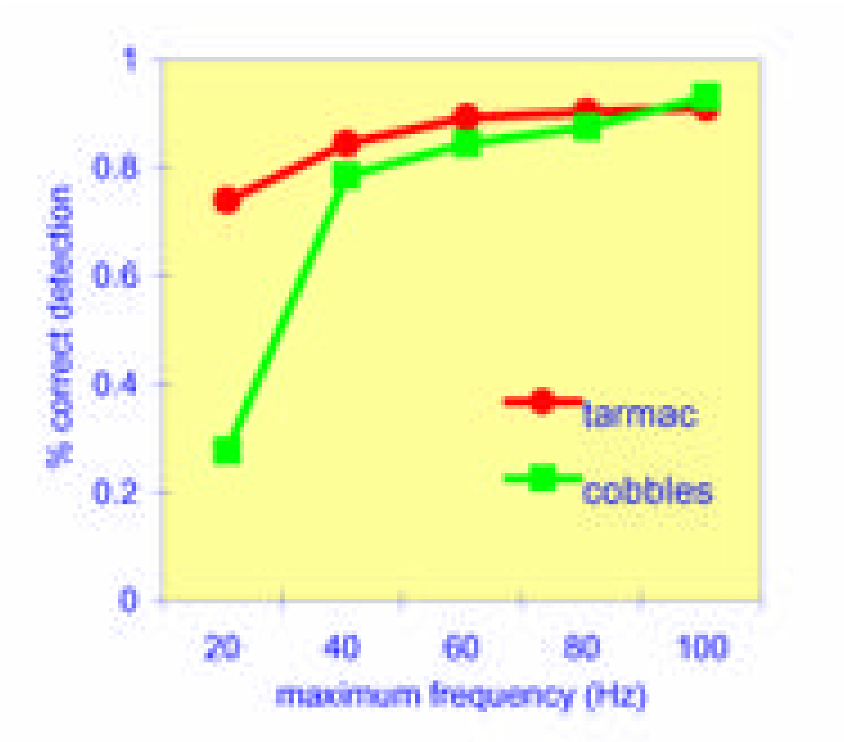

Figure 8 Percent correct detection results from the experiment to investigate the effect of vibration frequency bandwidth.