# Perception Enhancement for Steer-by-Wire Systems

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**Modern automobiles are safer and more comfortable than ever before. If there is one criticism that can be made, however, it is that the achievement of higher levels of comfort has sometimes come at the expense of a lack of driver involvement. The issue of driver involvement can become critical in the case of by-wire systems since these systems do not necessarily have a predetermined path or transfer mechanism for carrying stimuli to the driver. This article discusses the technical requirements of perception enhancing systems for the vehicle steering.**

## 1 Introduction

Automobile 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, whose vibration spectra can reach frequencies as high as 300 Hz, is a good example. The design of steering components has been the subject of numerous 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 nevertheless known about the human discomfort associated with steering vibration.

A less well understood topic is the question of the information transmitted to the driver by the steering vibration. With the arrival of electronically assisted and by-wire steering technologies (Jurgen, 1999) the question of what stimuli should reach the driver has assumed great importance. All current methodologies for estimating vibrational comfort, whether hand-arm or whole-body, and whether based on the use of 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 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, however, since scenarios can be imagined in which an increase in vibration might help clarify the nature of the road surface or the vehicle dynamic state.

## 2 Perception Enhancement Systems

The question of what information a road vehicle subsystem should transmit to the driver is not a simple one. Vibrational stimuli help in the interpretation of many things including the type of road surface, the presence of water or snow, tyre slip and the dynamic states 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. The stimuli needed by the driver might be defined as “those vibrations which permit the highest possible rate of detection of the current driving situation and of the dynamic states of the vehicle”. A definition of this sort considers both the *outside world* of the road environment and the *inside world* of the vehicle. Such a definition is not prescriptive since it does not focus on a specific type or intensity of stimuli, but it can serve to focus attention on the information sources routinely used by the driver.

And what steering hardware and software is required to achieve “the highest possible rate of detection of the current driving situation and the dynamic state of the vehicle” ? Again the question is not a simple one, but it can be suggested that such a system would necessarily require measurement sensors, electronics for signal processing, machine intelligence and actuators for delivering stimuli to the vehicle driver. Figure 1 presents one possibility which consists of a steer-by-wire system to which is added wheel motion measurement, electronics for stimuli selection and feedback actuation. If the system is designed based on knowledge of the human psychophysical and cognitive response, a *Perception Enhancement System* can be achieved.

The technical specifications for a *Perception Enhancement System* depend critically on the perceptual and cognitive characteristics of humans (Lakoff, 1987). Focussing on the process of perception in the first instance, three questions naturally arise which can be defined as the *problem of scale*, the *problem of bandwidth* and the *problem of features*. A detailed understanding of how human situational awareness changes as a function of the steering vibration scale, bandwidth and transient features is required before transfer functions, actuation functions or other technical characteristics can be defined.

## 3 Design Requirements of Perception Enhancement Systems

### 3.1 Experimental Measurements

In order to understand the issues involved, the problem of road surface detection was chosen as a test of the human cognitive response to steering wheel vibration. Road surface information is often gathered by means of the vision sense modality, but many driving scenarios exist in which the steering vibration feedback plays the leading role in the detection task.

A series of experiments (Giacomin and Woo, 2004 and 2004a) were performed in the Sheffield Perception Enhancement Systems laboratory to measure the human cognitive response to changes in the statistical properties of steering vibration. The experiments used tangential direction acceleration time histories measured in an Audi A4 when driving over four road surfaces. The surfaces, shown in Figure 2, were a tarmac surface, a cobblestone surface, a concrete surface and a low bump. Automobile test speeds were 96 kph, 30 kph, 96 kph and 50 kph respectively. The root mean square (r.m.s.) acceleration values of the steering stimuli 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 3. The system consists of an aluminum wheel which is vibrated in the rotational direction by means of an electrodynamic shaker and power amplifier. The imparted tangential acceleration is measured using an accelerometer and signal-conditioning unit. Control and data acquisition are performed by means of the LMS EMON software system coupled to a DIFA SCADASIII unit. The principal geometric characteristics of the rig were chosen based on data from a small European automobile, 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 typical total harmonic distortion values in the range from 1 to 3%. Unwanted fore-and-aft acceleration is no greater than -50 dB with respect to the tangential acceleration. A complete description of the simulator can be found in Giacomin and Woo (both 2004 and 2004a).

Each experiment involved 20 to 25 participants. Each participant was asked to sit in the simulator and to adjust the seat so as to achieve a realistic driving 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 close up (from approximately 1 meter). Upon test commencement, a series of 10 second tangential acceleration stimuli were applied, separated by 5 second gaps in which the participant stated his or her judgment of road surface type. The participant was asked to respond by simply stating “yes” or “no” with respect to the surface on the board. Participants were requested to provide their best estimate and to respond even if uncertain. The vehicle speed associated with each stimulus was not provided, nor was any feedback given regarding whether the identifications were correct or incorrect. The 10 second time histories consisted of either sections of the original data from the four roads, or modified sections consisting of scaled or frequency filtered versions of the originals. In each experiment the order of stimuli presentation was randomised for each participant in order to reduce learning or fatigue effects.

### 3.1 The Problem of Scale

The problem of scale can be defined to be the effect that stimuli level has on human cognitive response. A natural question which arises in the case of a steering perception enhancement system is whether a change in vibration level makes detection of road surface type easier or harder. In order to investigate the possible effect of vibration level, each of the four steering wheel time histories was multiplied by each of five different scale values. Scale factors 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 maximal steering acceleration values encountered in road vehicles. 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 4 presents the results of a laboratory experiment which investigated the effect of scaling. 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 qualitatively 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 rats of correct detection decreased with both increases and decreases in feedback gain. For these two roads, the human ability to correctly identify the stimuli appears to be negatively affected by any deviation from the natural level of the stimuli measured in the automobile.

A conclusion regarding the problem of scale that can be drawn from the experiments is that correct detection is not strictly optimal at the natural vibration level encountered in normal production automobiles. The results from two of the surfaces tested suggest optimal detection at extreme scale factors, distant from the natural vibration level of the original stimuli. Further, the automobile used to provide the acceleration stimuli for the experiments can be considered an average European saloon with average mechanical characteristics, thus the original vibrational stimuli were not unusually low or unusually high in level. This aspect of the detection problem 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 problem of scale suggests 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 The Problem of 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 5 presents the ratio of correct detection determined for the tarmac and the cobblestone road surfaces from the bandwidth experiment. The results for both road surfaces suggest a monotonically increasing relationship between detectability 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 two data sets suggest that the energy content associated with the higher frequencies was more important towards the correct identification of the cobblestone surface than of the tarmac surface.

When reinforced by the presence of visual and/or acoustic stimuli it may be possible that correct detection might be achieved at bandwidths less than the 60 to 80 Hz suggested by the current findings, nevertheless a bandwidth of at least 60 Hz appears necessary for driving conditions in which tactile feedback alone is relied upon for surface identification. This point may be of importance to steering designers since some by-wire steering actuators do not reach these response frequencies. In the case of road vehicle steering systems, the problem of bandwidth appears to have the relatively straightforward implication that “more bandwidth is better”.

### 3.3 The Problem of Features

The problem of features can be defined to be the effect that individual transient events have on human cognitive response. A natural question which arises in the case of a steering system is whether short, sharp, transients of the kind that occur when driving over stones or cracks in the road make the detection of surface type easier or harder. The problem is one of selecting the features which are actually interpretable by humans.

The results from the scaling and bandwidth experiments have suggested that the human detection mechanism is complex. The observation that a single vibration level was not optimal for all road surface types suggests the need to categorise and classify incoming data *before* an optimal choice of steering feedback gain can be made. By induction, it is likely that also the individual transient features of the time history must be checked against human perception *before* an optimal steering feedback can be defined. Figure 6 presents an example of this approach in which individual features which are known to trigger specific human responses are isolated from the vibration stimuli and selected for feedback to the driver. Research is under way to categorise these extracted features and to test for the human response they produce. The results promise to provide a rudimentary “language” of vehicle-driver communication.

## 4 Conclusions

While a single operational frequency bandwidth may be sufficient for by-wire steering systems under all driving conditions, a system characterized by a single, fixed, gain cannot be relied upon to provide optimal detection of road surface type over a range of operating conditions. Individual transient features in the vibration time history appear to be an important source of information to the driver, and further research is attempting to categorise these features and to evaluate their effect on human cognitive response. Based on the results obtained to date an electromechanical system, which can be termed a *Perception Enhancement System,* appears to be necessary in order to optimise steering feedback under different driving conditions.

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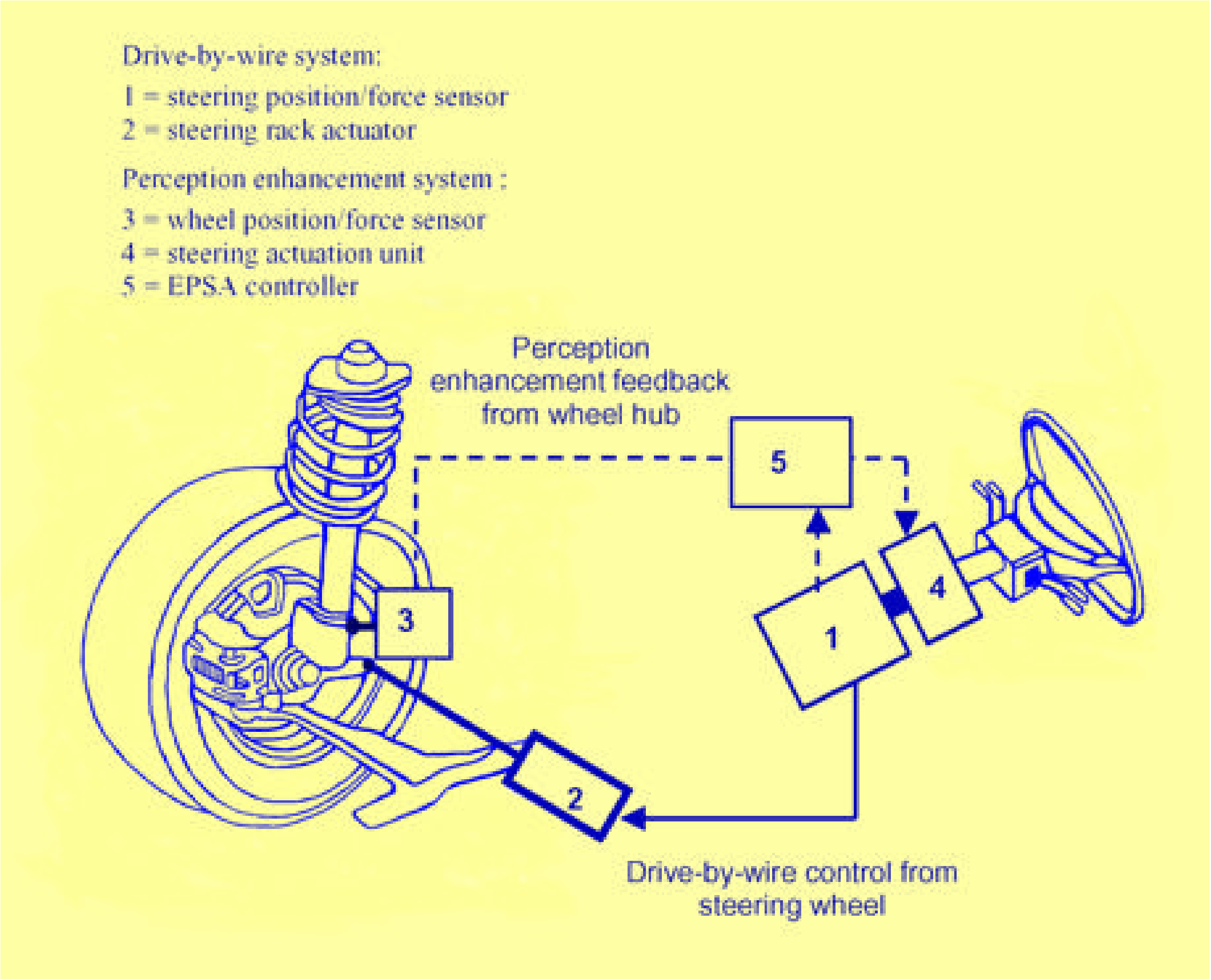

Figure 1 A perception enhancement system for by-wire steering.

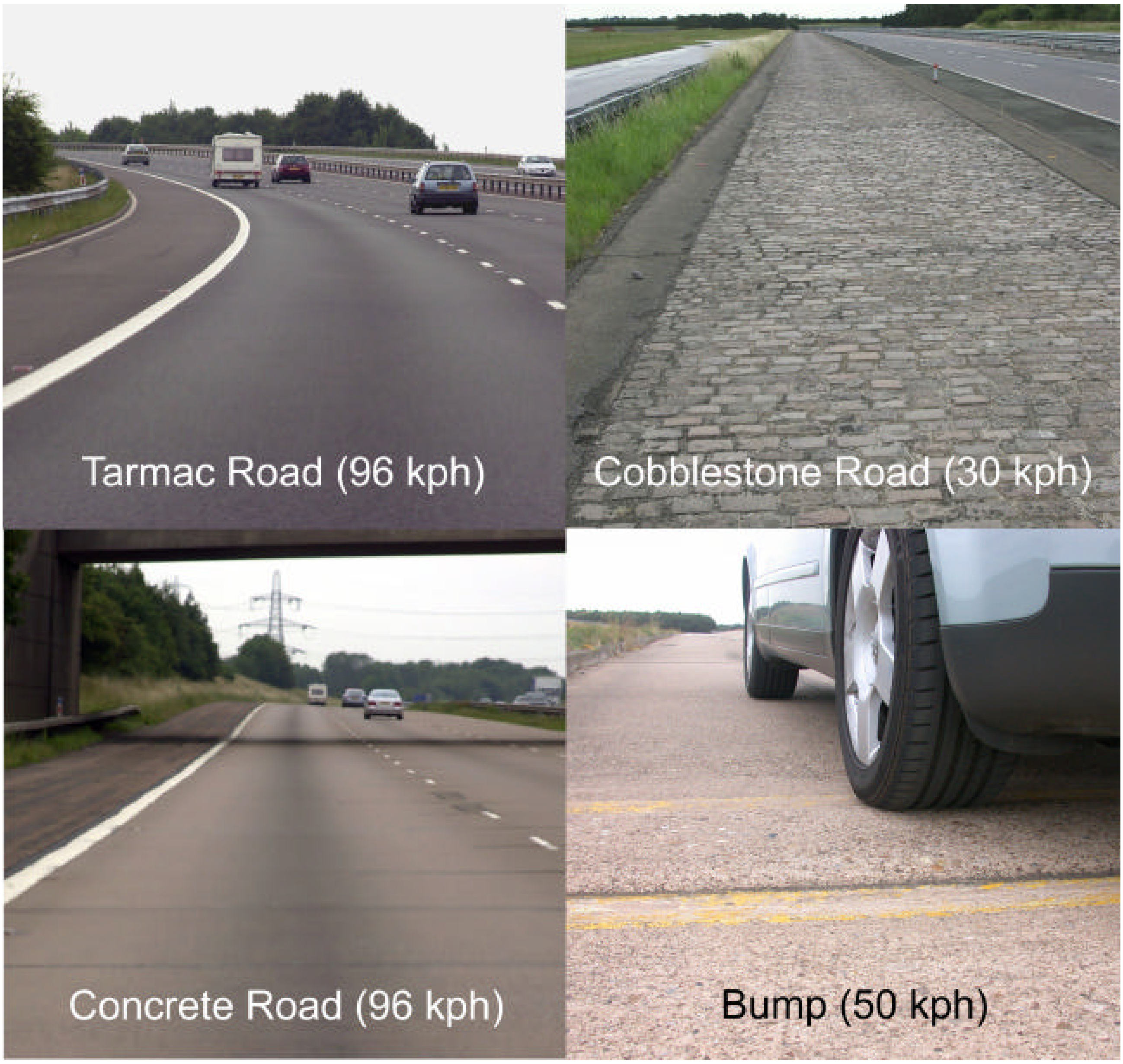

Figure 2 Road surfaces which produced the steering wheel acceleration time histories used in the laboratory experiments.

Figure 3 Participant performing a test.

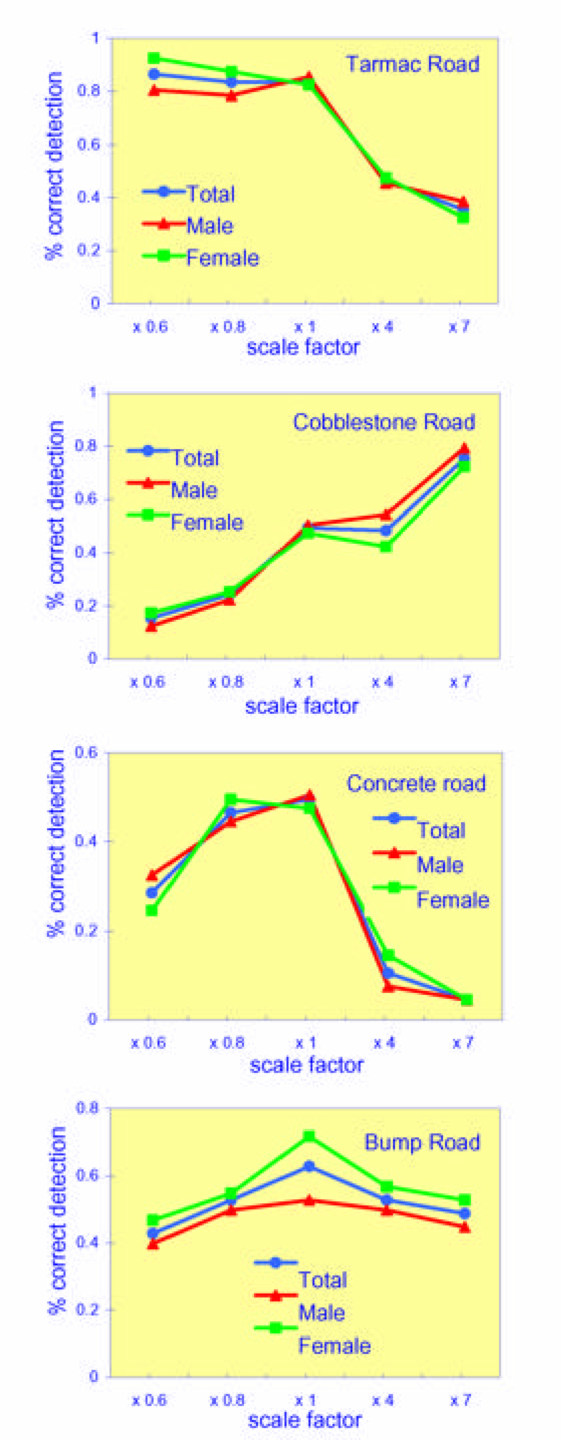

Figure 4 Percent correct detection results from the experiment to investigate the effect of stimuli scaling.

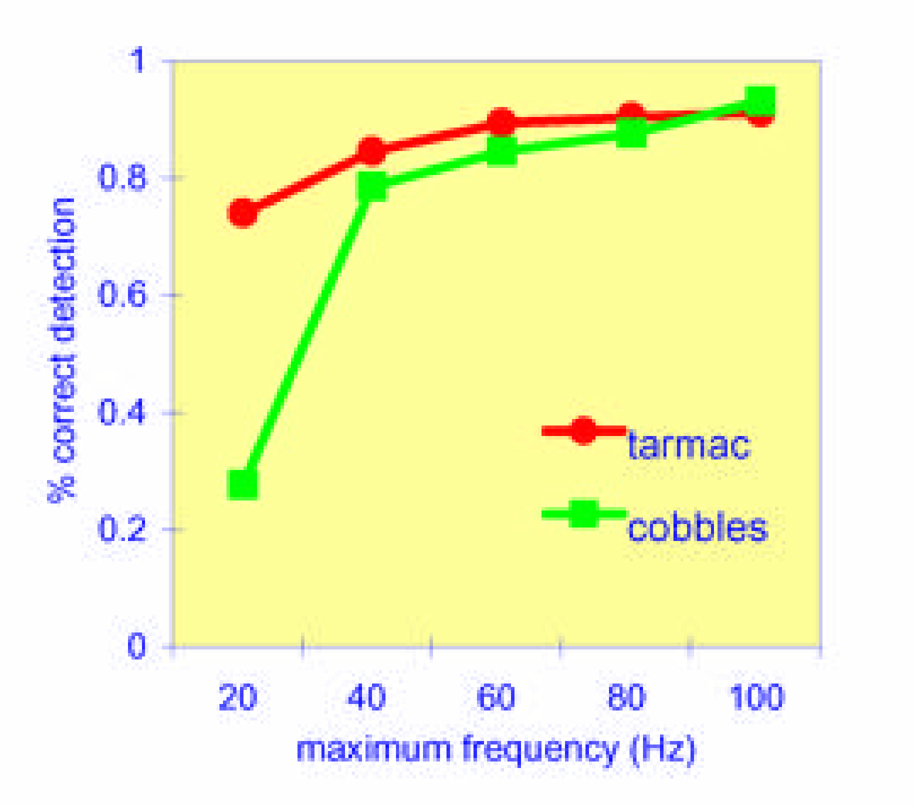

Figure 5 Percent correct detection results from the experiment to investigate the effect of stimuli frequency bandwidth.

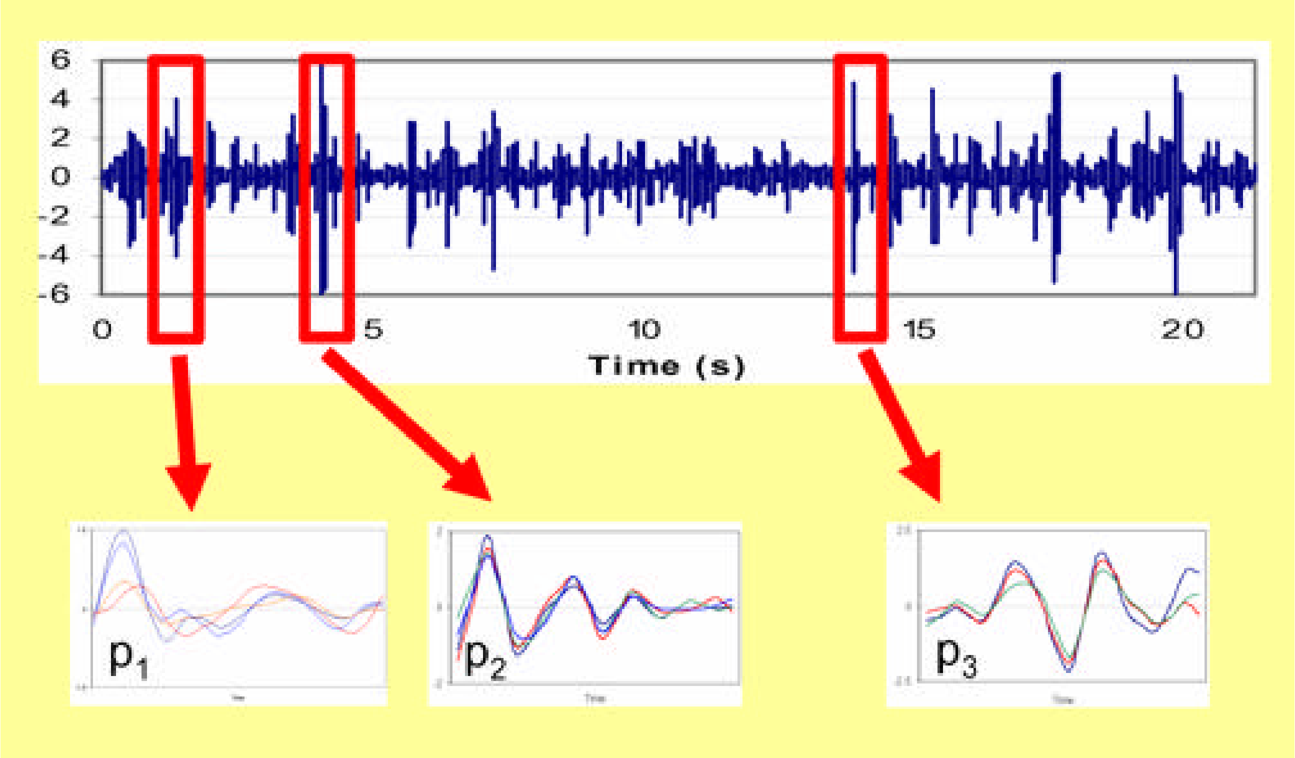

Figure 6 Feature extraction from a steering vibration time history.