The Role of the Scale and the Frequency Bandwidth of Steering Wheel Vibration on Road Surface Recognition

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Automobile drivers are regularly exposed to vibrational stimuli in their vehicle. Of the automobile subsystems, the steering wheel is one of the most important due to its role in controlling the vehicle. In particular, the steering wheel plays an important role in transmitting information about the road and about the vehicle to the driver. This paper investigates the effect of steering system feedback gain and steering system feedback bandwidth on the human interpretation of the driving information transmitted by the steering wheel. Human recognition of road surface type was found to be highly dependent on the feedback gain and the feedback bandwidth of the steering wheel vibration. The results provide some basic guidelines for designing the control logic of steer by wire systems.

Topics/Steering assistance control, Others

1. INTRODUCTION

The steering is one of the most important automobile subsystems due to its central role in controlling the vehicle and due to the importance of hand-arm system as a source of feedback to the driver [1][2]. The hand is one of the areas of the human body which is most sensitive to tactile stimuli, therefore the hand at the steering wheel plays an important role in transferring both information and discomfort.

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 discomfort, whether hand-arm or whole-body, and whether based on the use of frequency weightings [3] or customer correlations, are defined in such a way as to suggest that a uniform reduction in the vibrational level is accompanied by a uniform reduction in discomfort. Stated alternatively, less vibration should be judged as better. This may not be appropriate, however, in the case of information.

In recent years information measures have begun to be applied to automobile problems [4]. 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, tire slip and the dynamic state of subsystems such as the engine, the steering and the brakes. The vibrational stimuli are perceived, compared to models from long-term memory and interpreted, with the consequent interpretation then influencing decision taking.

Section 2 of this paper presents the theory of signal detection which was adopted as the basis for the current research investigation. Section 3 describes the experiments which were performed with human test subjects, who had the task of recognizing a road surface based on steering wheel vibratory stimuli.

2. SIGNAL DETECTION THEORY

Signal detection theory is a model of how humans detect signals in a background of noise. Signal detection theory evolved from studies performed in the 1950s which used statistical decision theory as a basis for approximating how people behave in detection situations [5]. Figure 1 presents a typical distribution curve of noise and signal plus noise.

The human considers a particular event and decides whether it is signal or noise. Signal detection theory assumes that there is an overlap between the distribution of signal and noise. In general, there are four possibilities in the decision matrix of the observer.

1. The observer decides a noise when it is a signal (called a miss)
2. The observer decides a signal when it is a signal (called a hit)
3. The observer decides a noise when it is a noise (called correct rejection)
4. The observer decides a signal when it is a noise (called a false alarm)

These responses can be summarized as a 2 x 2 table as shown in Table 1.

	Signal type	Response	
		Yes	No
Stimulus	Signal + Noise	*Hit*	*Miss*
	Noise	*False alarm*	*Correct rejection*

Table 1 Stimulus-response outcome matrix.

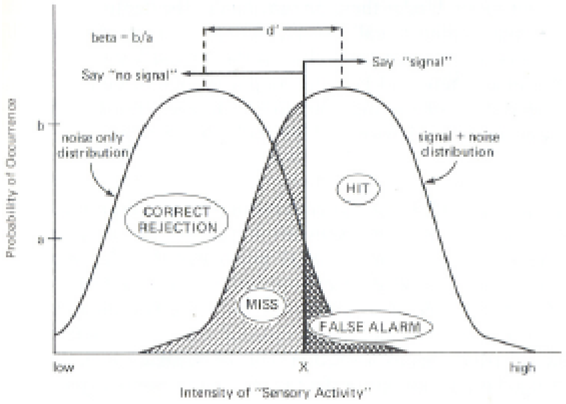


Figure 1 Noise and signal plus noise distributions [6].

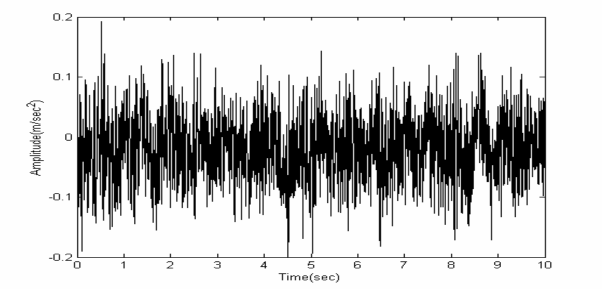
Signal detection theory has been applied in a variety of subject areas over the years including human biomechanics [7], the modeling of animal behavior [8], the modeling of the operation of the human visual system [9] and even the problem in metal fatigue [5].

3. AN EXPERIMENT IN THE RECOGNITION OF ROAD SURFACE TYPE

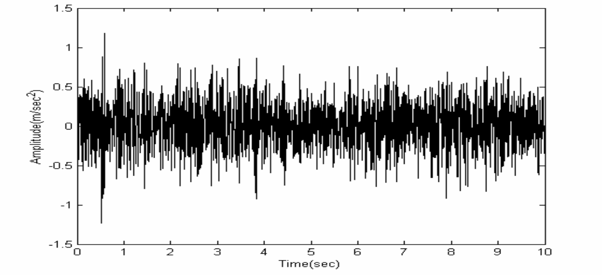
A task of the steering interface is to assist the driver in the identification of the road surface type, and parameters which influence the identification include the feedback gain and the feedback bandwidth of the steering vibration. These two parameters would be expected to be fundamental technical specifications of any modern electronic steering system, particularly of drive-by-wire steering systems [10]. The study described here is a first investigation of the effects produced by stimuli scaling and frequency bandwidth limitation. To simulate the possible effect of varying the feedback gain or the frequency bandwidth of the stimuli, steering wheel acceleration time histories from a mid-sized European automobile were presented to human test participants in a laboratory setting.

3.1 Test stimuli

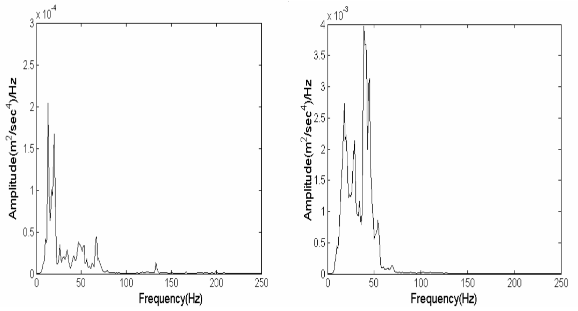
Steering wheel tangential acceleration time histories measured in a single vehicle when driving over several road surfaces were analyzed as described by Giacomin and Woo [6]. Acceleration data from two of the road surfaces was selected for use as test stimuli in a laboratory experiment. The acceleration data from the two roads is shown in Figure 2. One road was a tarmac surface while the other was a cobblestone surface. The surfaces were considered representative of normal driving and provided steering vibrations having different time domain and spectral statistics.



Tarmac Road



Cobblestone road

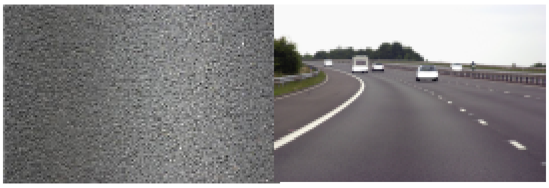


Tarmac Cobblestone

Figure 2 Time history and acceleration power spectral density of the tarmac and cobblestone steering acceleration signals.

A 10 second data segment was extracted from each data set to serve as the test stimuli. The segments were selected such that the root mean square value, the kurtosis value and the power spectral density were statistically close to those of the complete recording.

The original r.m.s. acceleration values of the stimuli were 0.048 m/s^2 for the tarmac surface and 0.271 m/s^2 for the cobblestone surface. The original kurtosis values for the same stimuli, which are dimensionless, were 3.0 for the tarmac surface and 3.245 for the cobblestone surface. The road surfaces used, and the vehicle speeds measured, are shown in Figure 3.



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

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

Figure 3. Road surfaces whose stimuli were chosen for use in testing

For the amplitude scaling test, each of the steering wheel vibration 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 [11] and the operating region of the test equipment. For the frequency bandwidth test, each stimulus was constructed by low pass filtering the original vibration signal using frequency cutoffs of 20 Hz, 40 Hz, 60 Hz, 80 Hz and 100 Hz.

3.2 Test facility

All tests were performed using the steering wheel rotational vibration simulator shown in Figure 4. The geometric dimensions of the rig its stimuli reproduction accuracy are described in detail in Giacomin and Woo (2005). 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. The geometry of the rig was defined based on data from a small European automobile. The seat is fully adjustable in terms of horizontal position and backrest inclination as in the original vehicle. Rotational vibration was applied by means of a G&W V20 electrodynamic shaker driven by PA100 power amplifier.

Figure 4. Photograph of the test rig.

3.3 Test protocol

50 University staff and students participated in the experimental tests. Upon arriving in the laboratory each was issued information and a consent form, and was provided an explanation of the experimental methods and of the safety features. Gender, 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 effect the 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 which performed the feedback gain test consisted of 23 males and 2 females, and had a mean age of 28.7 years, a mean height of 1.77 m and a mean mass of 73.8 kg. The group which performed the feedback bandwidth test consisted of 21 males and 4 females, and had a mean age of 31.7 years, a mean height of 1.75 m and a mean mass of 69.9 kg. No participants declared any physical or mental condition which might effect the perception of hand-arm vibration, and none declared ingesting coffee or the use of vibration-producing tools as part of their work.

Before commencing testing each participant was asked to remove any articles of heavy clothing such as coats, and to remove watches and jewelry. The participant 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. The participant 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 photograph of one of the road surfaces, as seen both from a distance (as during driving) and close up (from approximately 1 meter).

The two experiments shared a common protocol, the only difference being the stimuli applied. Each of the experiments was divided into two sessions, with the tarmac surface being the subject of the first session and the cobblestone surface the subject of the second. In each session the road surface in question was displayed on a board in front of the subject. In each session the test stimuli consisted of 13 repetitions of each of the 5 scaled, or bandpass filtered, stimuli from the displayed road surface plus a further 15 stimuli chosen randomly from the stimuli sets of the other three road surfaces. Each participant therefore performed 80 identifications in a session, for a total of 160 identifications in a complete experiment. Due to the large number of identifications, each participant was asked to perform only a single experiment (both sessions). In each session the order of presentation of the stimuli was randomised for each participant in order to reduce learning or fatigue effects.

Each test participant was presented each of the steering vibration stimuli, and was asked to state “yes” or “no” to indicate whether he or she felt that the test stimuli was from the road surface which was shown. The participant was requested to provide his or her best estimate for each stimulus and to respond even if uncertain. The vehicle speed associated with each stimulus was not provided.

4. RESULTS

4.1 Feedback gain test

Figure 5 presents the results of the laboratory tests, reported in terms of ratio of correct recognition from 0 to 1 (0 to 100 percent). As can be seen in Figure 5, the human responses for the two road surfaces are contrary to each other. A first behavior 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 behavior 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.

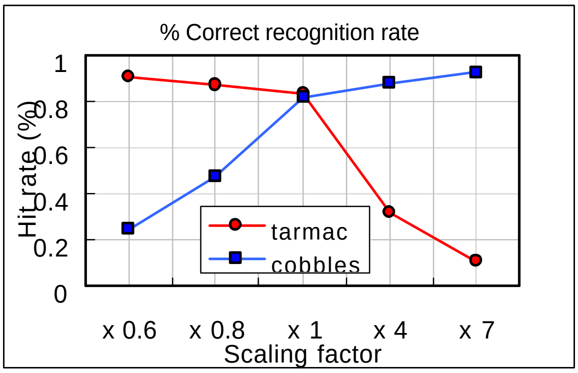


Figure 5 Rate of correct recognition for the tarmac and cobblestone road surfaces.

The data can also be quantified in terms of signal detection sensitivity. In signal detection theory the sensitivity, *d’* is the distance between the means of the signal plus noise distribution and the noise distribution. It is calculated from the Z scores of the experimentally determined false alarm and hit rates. For the current experiment the human sensitivity *d’* can be calculated as

$$Zn = 0 - p \text{ (false alarm)} \tag{4.1}$$

$$Zsn = 1.0 - p \text{ (hit)} \tag{4.2}$$

$$d' = Zn - Zsn \tag{4.3}$$

Figure 6 presents the sensitivity *d’* as a function of the amplitude scaling factor. In signal detection theory, the higher the *d’* value the higher the hit rate and the lower the false alarm rate. In other words, the greater the *d’* value, the more sensitive is the observer to the particular signal. The sensitivity for the tarmac surface decreased with increasing amplitude scaling factor, while the sensitivity for cobblestone surface showed a tendency to increase with increasing amplitude scaling factor.

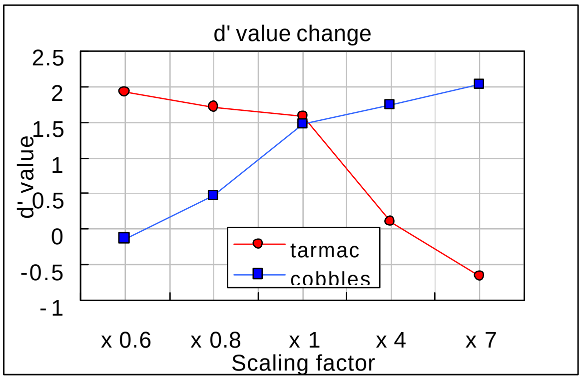


Figure 6 Observer sensitivity *d’* for the tarmac and cobblestone road surfaces.

4.2 Feedback frequency bandwidth test

Figures 7 and 8 present the rate of correct recognition rate and the observer sensitivity *d’* as a function of the frequency bandwidth of the test stimuli. As seen in Figures 7 and 8, the greater the maximum frequency the greater the rate of correct recognition and the d’ value for both road surfaces. Although small differences occurred due to the differences in the distribution of the vibrational energy (differences in the power spectral density), the human response for two road surfaces showed a similar tendency in recognition rates and sensitivity *d’*.

A further signal detection representation of the test results is provided by Figure 9, which presents the receiver operator characteristic points for the cobblestone surface. Receiver operating curves are defined as the plot of the hit rate as a function of the false alarm rate for each stimuli. The data of Figure 9 confirm that human correct detection of the road surface type improved greatly for steering wheel stimuli which contained vibrational energy up to frequencies of approximately 30 Hz.

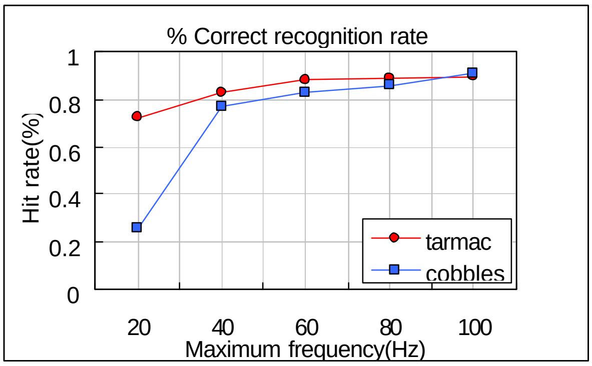


Figure 7 Rate of correct recognition for the tarmac and cobblestone road surfaces.

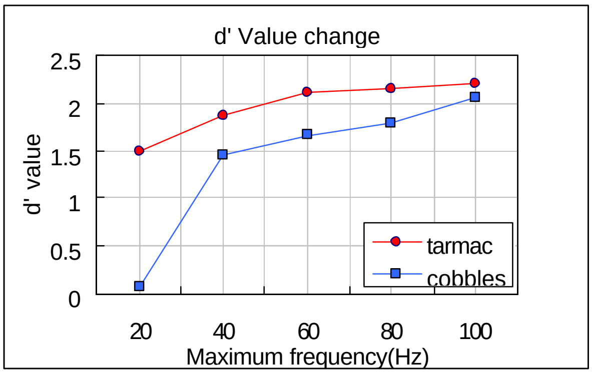


Figure 8 Observer sensitivity d' for the tarmac and cobblestone road surfaces.

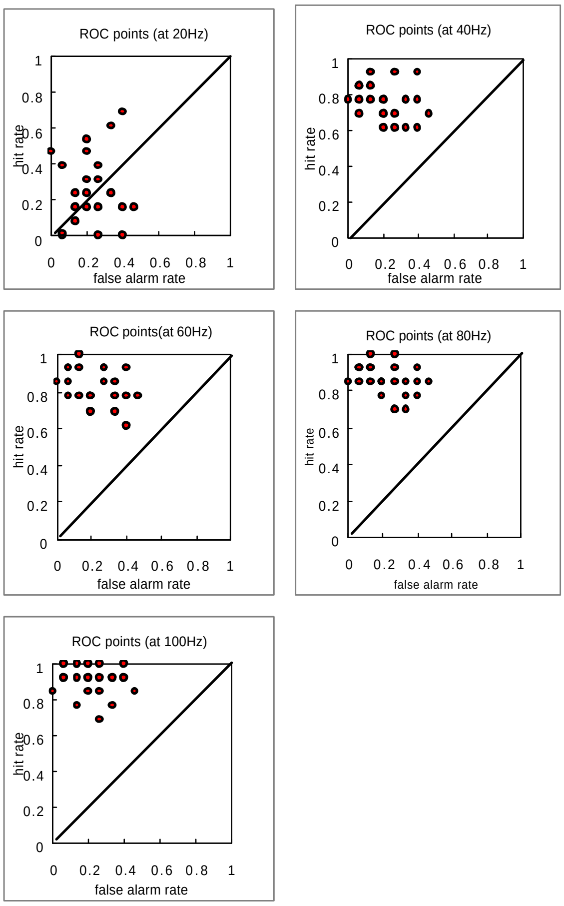


Figure 9 ROC points for the cobblestone surface for the feedback bandwidth test.

5. DISCUSSION

Currently, research is being undertaken to improve the detection and recognition accuracy in several noisy environments. Detection and recognition studies for sonar systems have been performed [12]. Speech recognition in automotive environments has also been studied [13], and several factors have been identified which disturb recognition in the automobile, including noise sources such as the tires, the wind, the engine, the car audio system, the fan and the turn signal indicator. It has been shown that noise cancellation reduces recognition error rate, especially at low vehicle speeds. The error rate has been found to be in the neighborhood of 50 % for all conditions tested. Similarly, for video text detection and recognition [14] several algorithms have been developed so as to obtain better recognition results or to reduce the false alarm rates. In this field, the recognition rate is normally found to be higher than 50 %, which is considered to be the threshold for the recognition criterion [14]. Even in studies of pattern recognition, detection rates higher than 50% have been selected as reasonable values for applications of automatic target recognition [15].

Based on the references described above, a target value of 50% correct detection would appear to be appropriate also in the case of the automotive steering system. If 50% is taken as the target criteria, it can be estimated from Figures 5 and 7 that the optimal steering feedback gain parameter range is from approximately 0.8 to 3, and that the optimal steering feedback frequency bandwidth should be greater than 30 Hz, with little possibility of further improvement for bandwidths greater than 100 Hz. A simple summary of the findings is presented as Figure 10, which presents a "steering feedback operating envelope" based on the two parameters used in the current study and based on the steering acceleration stimuli of the tarmac and of the cobblestone road surfaces. The representation provides a basic reference for deciding the control logic parameters for either tradition electrical, or drive-by-wire, steering systems.

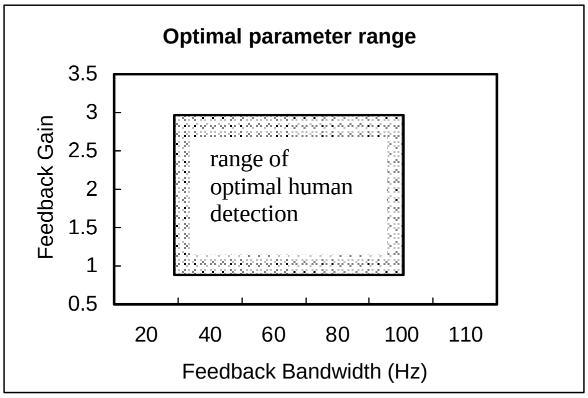


Figure 10 Steering feedback operating envelope.

6. CONCLUSION

This paper describes research which investigated the human ability to detect different types of road surface. The steering tangential acceleration stimuli parameters which were varied were the scale (size) of the test signal and the frequency bandwidth of the test signal. The experimental test results have suggested that:

1. In terms of the feedback signal gain, the tarmac surface is representative of a category of roads whose correct identification is reduced by increases in the size of the vibration stimuli, while the cobblestone surface is representative of a different category of roads whose correct identification is increased by increases in the size of the vibration stimuli.
2. In terms of the feedback signal frequency bandwidth, the greater the maximum frequency, the greater the sensitivity *d'* value and the correct recognition rate. Feedback bandwidths of more than 100 Hz do not, however, appear necessary in the case of current production automobiles.
3. Based on the results for the two road surfaces used in the research which is described in this paper, the optimal range for steering system feedback gain and frequency bandwidth have been determined. Steering feedback gain would appear to be most effective when in the range from approximately 0.8 to 3, while steering feedback frequency bandwidth would appear to be best if in the range from 30 to 100 Hz.

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