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Effect of steering wheel acceleration frequency distribution on detection of road type

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Resumen

Esta investigación estudia el efecto de la vibración en el volante basado en la detección humana del tipo de carretera, con el fin de identificar que banda de energía es la más utilizada por los conductores para detectar el tipo de superficie de la carretera. Tres superficies de carretera han sido empleadas en el experimento. Cada estímulo de carretera fue manipulado por medio de filtros digitales Butterworth, eliminando cinco bandas de frecuencia del espectro de aceleración lo que se considera una subdivisión importante de la energía de vibración del vehículo. Los resultados sugieren que los mecanismos perceptivos y cognitivos utilizados por los sujetos de prueba requieren información de la vibración que esta contenido en la banda de frecuencias que contiene el nivel de energía más alto. Estos resultados proporcionan una clara indicación de la banda de frecuencia utilizada por los seres humanos para juzgar tipo de superficie de la carretera al conducir automóviles de producción actual. Por lo tanto, cualquier reducción de la energía de vibración en el volante en este intervalo de frecuencia podría ser perjudicial para la detección humana, y cualquier otra medida de información que pueden ser desarrollados para el sistema de dirección del automóvil.

Abstract

A laboratory-based experiment was conducted to evaluate the effect of the vibrational energy distribution on the human detection of road surface type by means of steering wheel vibration. The study used steering wheel tangential direction acceleration time histories which had been measured in a mid-sized European automobile that was driven over three different types of road surface. The steering acceleration stimuli were manipulated by means of digital Butterworth filters which were used to eliminate five selected frequency ranges from the steering wheel vibration spectrum in the interval from 0 to 150 Hz. The experiment was performed in three parts, one for each road surface studied in which a photograph of one of the three road surfaces was shown. The photograph shown was an image approximately similar to what a driver sees of the road during driving. Fifteen test participants were exposed to both unmanipulated and manipulated steering wheel tangential vibration stimuli, and were asked to indicate, by either "yes" or "no", whether the actuated acceleration stimulus was from the road surface whose photograph was shown on the board directly in front of the test bench. The findings suggest that the frequency band from 20 to 60 Hz, which is most often associated with specific resonances of the steering system such as the column and tyres, plays a key role in the human detection of road surface type in driving situations.

Palabras clave:
Percepción, Información, Detección, Vibración, Volante de automóvil.

Keywords:
Perception, information, road detection, vibration, automobile steering wheel

Notation

r.m.s.	Root mean square (m/s^2)
BS	British Standards
CF	Crest Factor
LMS	Leuven Measurement Systems
LTM	Long-Term Memory
PES	Perception Enhancement Systems
PSD	Power Spectral Density
STD	Standard Deviation

Introduction

The steering wheel is commonly considered the most important source of haptic feedback information for the automobile driver. This is due to the great sensitivity of the skin tactile receptors of the hand [1] as well as the lack of intermediate structures such as shoes and clothing, which can attenuate the transmission of vibrational stimuli to the driver. However, the achievement of higher levels of comfort in modern automobiles has sometimes come at the expense of a lack of driver involvement [2]. The issue of driver involvement can become critical in the case of steer by wire systems [3]. Since these systems do not necessarily have a predetermined path, or transfer mechanism, for carrying stimuli to the driver. The question of what stimuli should reach the driver has therefore assumed great importance.

People have a notable ability to recognise things and to understand aspects of the current state of the world combining all their sensory systems [4, 5]. Among the sources of the cognitively-relevant information used by automobile drivers, vibrational stimuli help in the understanding of many things, such as: 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. When a processed sensory information match with models stored in the long-term memory (LTM) the recognition of an event is taking part [6]. The degree of the match may determine whether the stimulus is interpreted or not, with the consequent interpretation then influencing decision taking.

One means of improving the flow of information to the driver, and thus of making the driving task easier, is to incorporate a perception enhancement system (PES) into the design of the automobile steering (as shown in Figure 1). Such an electromechanical system would have the function of identifying the significant vibrational stimuli, which originate from the road, the tyres and the suspensions. It would also have the function of transforming the stimuli in order to optimize detection and awareness.

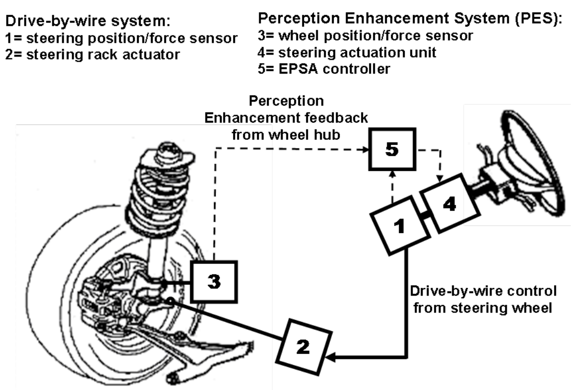

Figure 1: A perception enhancement system for use with "by-wire" automotive steering.

An example of research in this direction is the study by Giacomin and Woo [2, 7], which investigated driver detection of road surface type by measuring the sensitivity of the human detection task to changes in the primary characteristics (scale and bandwidth) of the vibration stimuli. Another example of a research in this direction is the study by Berber-Solano and Giacomin [8], which investigated the problem of features [9] in terms of the number and the scale of the transient events.

Recent research [10] has found that an amplification of selected time domain features or selected frequency bands of the steering wheel vibration signal facilitates road surface type detection. During driving, steering wheel power spectral densities can reach frequencies of up to 350 Hz with vibrational energy mostly present in the range between 10 and 60 Hz [11]. They are typically characterised by low frequency excitation in the range from 8 to 20 Hz due to 1st order tyre non-uniformity forces and tyre-wheel unbalance, and due to 2nd order engine and mechanical unbalance in the frequency range from 20 to 200 Hz [12].

In the case of information a scientific question immediately arises: What frequency regions of the vibration spectra are sources of information about the dynamic state of the vehicle? Could the elimination of vibration energy have an effect on the detection of surface type? To answer this question, the study presented here investigated the effect of vibration energy distribution on the human detection of road surface type. The study was performed by means of laboratory-based experiments involving human participants, and involved digital manipulation of steering wheel tangential acceleration signals, which were measured during road testing of a mid-sized European automobile.

Experimental tests of road surface detection

Test Facility

The experiments used tangential direction acceleration time histories measured in a mid-size European saloon automobile when driving over three road surfaces using the speeds allowed for the Department of Transport (2006) in the UK for each driving condition. The road surfaces that were measured were a motorway surface, a broken concrete surface and a broken lane surface. Figure 2 presents the three road surfaces, as viewed from directly above, and as seen from a distance as when driving. A 10-second segment extracted from the original acceleration time histories of the three base stimuli are presented in Figure 3, while the global statistical properties determined from the data of each of the road surfaces are presented in Table 1. The vibration at the steering wheel achieved root mean square (r.m.s.) acceleration values from a minimum of 1.15 m/s2 (for the motorway surface) to a maximum of 2.36 m/s2 (for the broken lane surface). The kurtosis values were close to 3.0, while the skewness values were close to 0.0 suggesting a Gaussian distributed process for the three road surfaces. The broken lane surface had the highest crest factor (CF) at approximately 4.40.

Figure 2: Road surfaces whose stimuli chosen for use in the laboratory test.

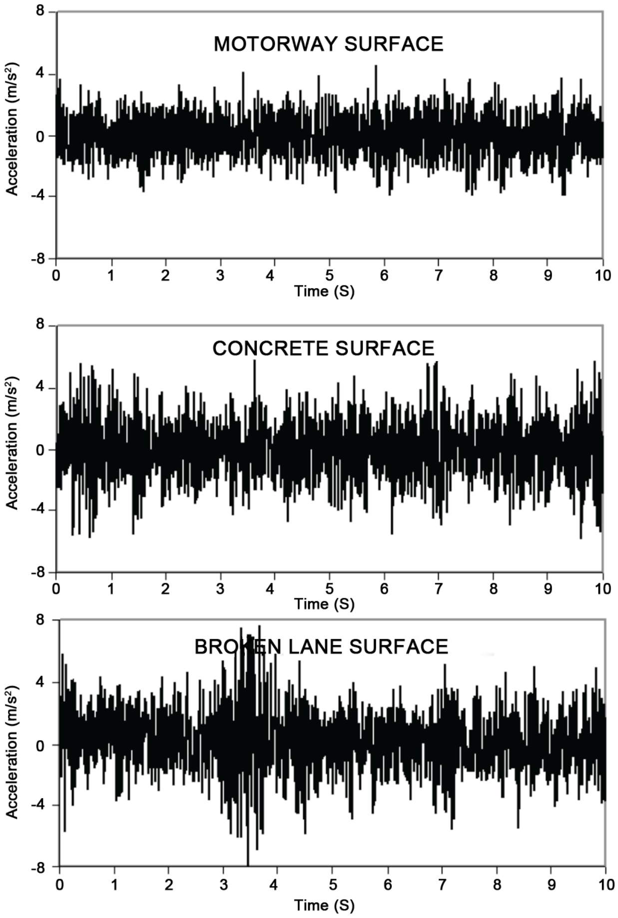

Figure 3: 10 second segments which were extracted from the original steering wheel acceleration time histories to create the laboratory test stimuli.

Table 1: Global statistics of the original three base stimuli used for producing the laboratory test stimuli

Values	Motorway	Concrete Lane	Broken Lane
r.m.s. (m/s^2)	1.15	2.03	2.36
Skewness (dimensionless)	0.20	0.09	-0.01
Kurtosis (dimensionless)	3.49	3.95	3.39
Crest Factor (dimensionless)	3.86	4.49	4.18
Speed (kph)	1.10	50	40

Figure 4 presents the power spectral densities (PSD) of the experimentally acquired steering wheel acceleration signals, along with the frequency bands, which were judged to contain the dominant energy features in the overall distribution. These signals were chosen from a large database of steering wheel measurement such that the stimulus data sent contained steering vibrations which varied across the following logical categories: road surface typology and energy distribution as determined from the power spectral density.

In order to investigate the possible effect of the vibrational energy distribution of the acceleration stimuli on the human cognitive detection of road surface type, individual bands were eliminated from the overall steering wheel signal. By identifying which bands most inhibited to the human detection task when eliminated it would be possible to isolate the most important energy regions.

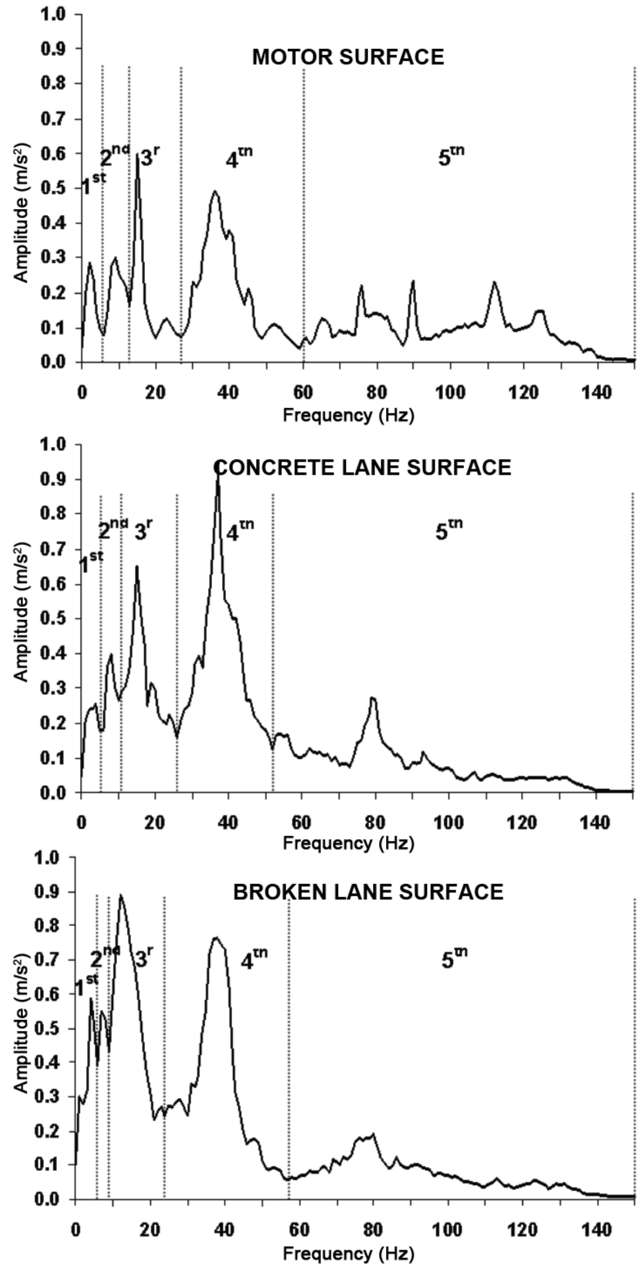

Figure 4 : Power spectral densities of the experimentally acquired steeri wheel acceleration signals, along with the frequency regions which were selected for manipulation.

The selection of the bands to be eliminated was based on the approximate locations of the higher peaks of vibrational energy. The assumption was made that the highest peaks of vibrational energy would most likely have been the result of resonances in the automobile's systems, and that the elimination of information from one of the most important subsystems might deny the driver an important source of information about the road. Each of the three original steering

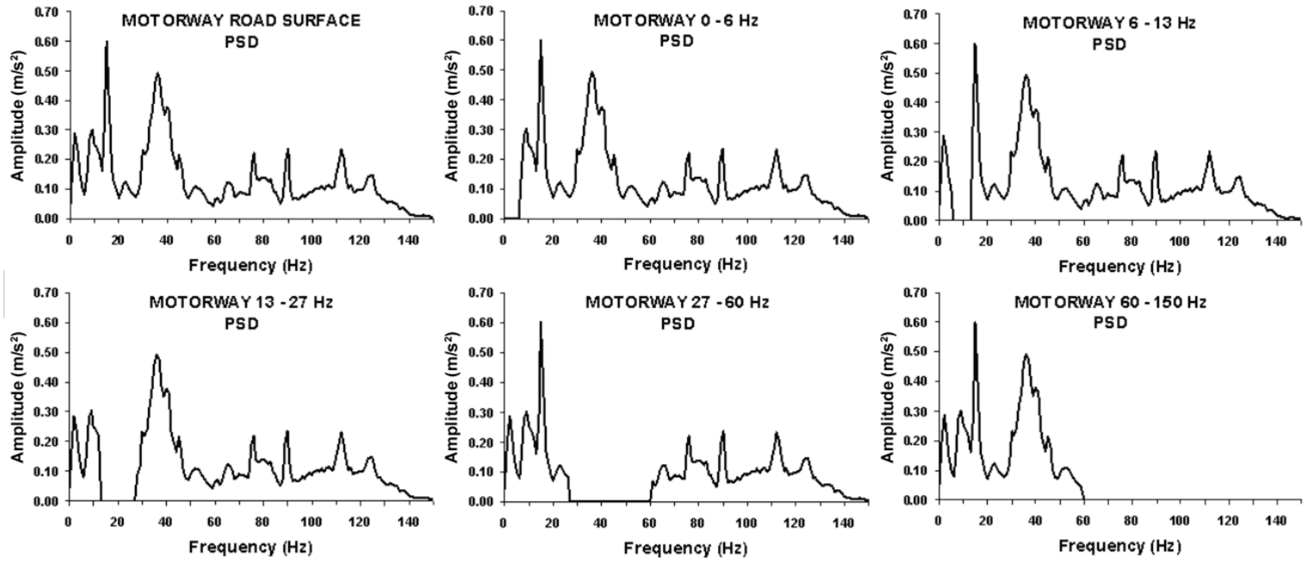

Figure 5: Laboratory test stimuli for the Motorway stimuli that were produced by means of digital Butterworth filters.

Table 2: The r.m.s. values (m/s2) of the six base stimuli used for producing the laboratory test stimuli.

Road Surface Type	**Original**	**1st High energy frequency range eliminated**	**2nd High energy frequency range eliminated**	**3rd High energy frequency range eliminated**	**4th High energy frequency range eliminated**	**5th High energy frequency range eliminated**
Motorway (M)	1.15	1.09	1.07	1.04	0.83	0.99
Concrete (C)	2.03	1.91	1.87	1.73	1.26	1.83
Broken Lane (BL)	2.36	2.13	2.50	1.88	1.95	2.42

wheel time histories was high-pass filtered and band-pass filtered [14] by means of digital Butterworth filters which were constructed in the LMS® TMON software [15] and applied to each original stimulus. Figure 4 presents the five selected frequency ranges from the steering wheel vibration spectrum for each of the original base stimuli. Selected frequency ranges are from 0-6, 6-13, 13-27, 27-60 and 60-150 Hz for the motorway stimuli, 0-6, 6-12, 12-27, 27-53 and 53-150 Hz for concrete stimuli and 0-6, 6-9, 9-22, 22-58 and 58-150 Hz for broken lane stimuli. Each band can be considered an important subdivision of the automobile's vibrational energy, which is dominated by either one, or a small number, of specific frequencies. Energy bands are also associated with specific automobile subsystems. As an example of the high-pass filtering and band-pass, Figure 5 presents power spectral density (PSD) graphs of the un-manipulated and manipulated motorway stimuli. The r.m.s. acceleration values (m/s2) for the eighteen test stimuli obtained are presented in Table 2.

Test Facility

Figure 6 presents the steering wheel test rig that was used. The vertical system consisted of a 325mm diameter aluminium wheel, which had an F1 style shape. It was attached to a steel shaft, which was in turn mounted to linear bearings and connected to an electrodynamic shaker. Table 3 presents the main geometric dimensions of the test rig, which were chosen based on data from a small European automobile. The seat was fully adjustable in terms of horizontal position and back-rest inclination as in the original automobile. Vertical vibration was applied by means of a G&W V20 electrodynamic shaker driven by a PA100 amplifier [16].

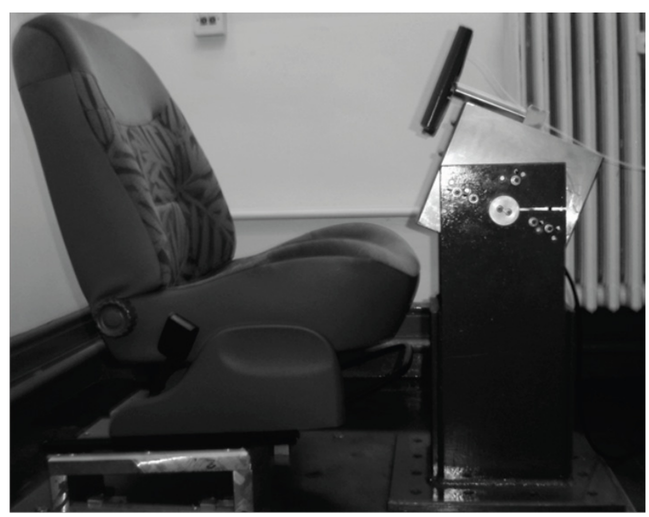

Figure 6: Steering wheel vertical vibration test facility.

The steering wheel vertical acceleration was measured by means of an Entran EGAS-FS-25 accelerometer attached to the top left side of the wheel. The accelerometer signal was amplified by means of an Entran MSC6 signal conditioning unit [17]. Vibration control and data acquisition was performed by means of the LMS® TMON software [15] system coupled to a DIFA SCADASIII electronic front-end unit. The safety features of the rig and the acceleration levels used conform to the health and safety recommendations outlined by British Standards Institution BS 7085 (1989).

Table 3: Geometric dimensions of the steering wheel vertical vibration test ring.

Geometric Parameter	Value
Steering column angle (H18)	23°
Steering wheel hub centre height above floor (H17)	770 mm
Steering wheel diameter (W9)	324 mm
Steering wheel tube diameter	25 mm
Horizontal distance from H point to steering wheel hub centre (d=L11-L53)	390-450 mm
Seat H point height from floor (H30)	310 mm

Test Subjects

Fifteen university staff and students participated in the laboratory experiments (8 males and 7 females). All participants tested were requested to be experienced drivers. A consent form and a short questionnaire were presented to each participant prior to testing and information was gathered regarding their anthropometry and health. The mean age for the group was 28.13 years (STD= 4.5), while the mean height was 1.69 cm (STD= 0.067) and the mean mass was 71.9 kg (STD= 7.8). The mean values and the standard deviation of the height and weight of the test participants were near the 50 percentile values for the U.K. population [19] except in the case of age, which was somewhat lower than the UK national statistics. No test participant declared a physical or a cognitive condition which might affect the perception of hand-arm vibration. All subjects declared themselves to be in good physical and mental health and none declared having smoked or ingested coffee prior to arriving in the laboratory. All had more than two years of driving experience.

Test Protocol

Upon arriving in the laboratory, each subject was asked to sit in the test bench and to adjust the seat so as to achieve a realistic driving posture. He or she was then asked to look at on a board directly in front of the bench, which displayed a picture of a road surface. Before commencing testing, each participant was asked to remove any articles of heavy clothing such as coats, and to remove watches or jewellery. He or she was asked to sit in the test rig and to adjust the seat so as to achieve a realistic driving posture. Since grip type and grip strength [20] are known to effect the transmission of vibration to the hand-arm system, the participants were asked to maintain a constant palm grip on the steering wheel using both hands. The participants were also asked to wear ear protectors to avoid any auditory cues [5]. Room temperature was maintained within the range from 20°C to 25°C so as to avoid significant environmental effects on the skin sensitivity [21].

The detection task was to state, by means of "yes" or "no", whether each vibration stimulus that was actuated during the course of the experiment was from the road surface that was illustrated by the picture. When the actuated vibration had been produced using the base stimuli from the displayed road surface, the response was taken to be a correct detection. False alarms, on the other hand, were taken to be those situations when the participant responded "yes" to a stimulus which was not derived from the displayed road surface. No feedback was provided to the test participant.

Three laboratory experiments were performed. In the three experiments the test stimuli consisted of 3 repetitions of each of the 5 band-pass filtered stimuli and of the original base stimuli for each type of road. Each participant performed 18 identifications for each road type, and a total of 54 identifications in a complete experiment. Each stimulus was separated from each other stimulus by a 5 second gap in which the participant was asked to state his/her judgment of road surface type. The order of stimuli presentation was fully randomised for each participant in each experiment.

Results

Figure 7 presents the results obtained from the experiment in terms of percent correct detection (from 0 to 100 percent). Detection rate is presented along the ordinate while the five different frequency ranges for each road are presented along the abscissa. The original base stimuli are labelled as O. For each frequency range, the hit rate was taken to be the proportion of "yes" responses obtained from the stimuli which were actually from the presented road surface. The false alarm rate was taken to be the proportion of "yes" responses obtained from the stimuli which were not derived from the road surface which was being presented. The percentage of correct detection responses for the three road surfaces were analysed in a between/within-subjects by means of the one factor repeated measures ANOVA. Statistical significance effect in the responses were found in all surfaces tested at a p=0.01 of significance level.

As shown in Figure 7 the percentage of correct detection for the original base stimuli was approximately 58% for the motorway stimuli, 86% for the concrete stimuli and 90% for the broken lane stimuli. The curves of correct detection for the concrete and broken lane stimuli presented in Figure 7 showed similar qualitative behaviour, achieving their optimal detection at the original base stimuli (O), then decreasing in detection until the elimination of the frequency range from 27Hz to 53Hz for the concrete stimuli and from 22Hz to 58Hz for the broken lane stimuli. Qualitatively, the results from the motorway steering stimuli showed a very different behaviour from that of the other two test stimuli, suggesting important differences in the underlying energy content.

Results suggest that the LTM model used by average drivers to judge all three road surface types contains information at the frequency range approximately from 20 to 60Hz. The results suggest that this frequency range where the automobile has its column resonances, steering wheel resonances and chassis resonances seems critical to detection. Elimination of vibrational energy in the range from approximately 20 to 60 Hz made it almost impossible to correctly detect broken surfaces (concrete and asphalt lane) while it dramatically improved detection of the smooth surface (motorway). Clearly, the energy in this band is very important towards determining the surface type

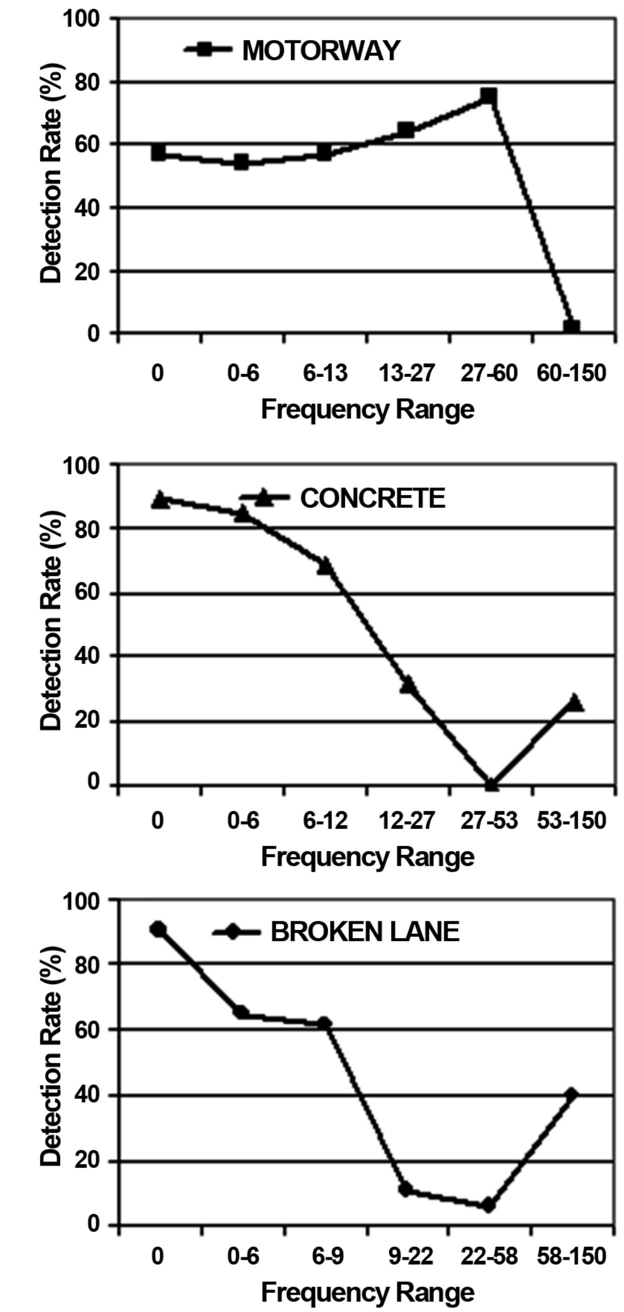

Figure 7: Results of the laboratory experiments regarding the effect of the elimination of vibrational energy on the human detection of road surface type.

Discussion

The detection rate of less than 100 percent for all three road surface types suggests the difficulty of achieving fully accurate detection in a laboratory task in which several key stimuli, notably the acoustical stimuli, are absent. Not withstanding the less than perfect environmental reproduction, the current results suggest that the frequency range from approximately 20 Hz until 60 Hz played a key role in the human cognitive detection of the road surface type for all three surfaces. The current results show some qualitative similarities to previous bandwidth experiments [2, 10] in which the elimination of high frequency energy from the steering wheel vibration signal was found to have a detrimental effect on road surface type detection. The authors of the previous study stated that the LTM model used by average drivers to judge road surface type appeared to contain information to oscillatory frequencies in excess of 60 Hz. The current results suggest that the elimination of the energy contained in the frequency band from 20 to 60 Hz increases the road detection of the types of roads which contain little energy in the band, but decrease the road detection of the types of roads which contain significant energy in the band.
Considering no a-priori knowledge of the possible meaning of the vibration energy in the 20 to 60 Hz band, it would appear from the results that eliminating one of the frequency bands which contains the greatest amount of vibration energy in current production automobiles can be said to deprive the driver an important source of driving information, and thus an important source of steering feel.

A-prior information about this frequency band includes, however, the knowledge that it normally contains more than one resonance of the steering system (tyres, front suspensions, steering column, steering wheel, etc.) thus elimination of this band would appear to remove important feedback to the driver about the dynamic state of those subsystems. Given the resonance behaviours of the automobile in the 20 to 60 Hz frequency band, it may be the case that in current production automobiles the frequency band provides a focus and a principal source of driver perception.

Conclusion

This study performed three tests in which human subjects were exposed to vertical steering wheel vibration stimuli in a laboratory test rig from three different road surfaces. The objective was to establish if the elimination of vibrational energy in any of the main energy regions from 0 to 150 Hz might affect the human detection of road surface type. Five frequency bands from the steering wheel vibration spectrum were selected for each road surface stimulus. The findings suggest that the elimination of vibrational energy in the frequency band from 20 to 60 Hz can be highly detrimental to human detection of road surface type. The findings may be interpreted as suggesting that road surface, steering and suspension in the 20 to 60 Hz frequency band provide vital clues to automobile drivers regarding the roads over which they drive and the dynamic response of the vehicle. Steering feel may be compromised by any reductions in vibrational energy at the steering wheel in this band.

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