Facilitating the driver detection of road surface type by selective manipulation of the steering wheel acceleration signal.

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Abstract

Previous research has investigated the possibility of facilitating the driver detection of road surface type by means of selective manipulation of the steering wheel acceleration signal. In the previous studies a selective increase in acceleration amplitude has been found to facilitate road surface type detection, as has the selective manipulation of the individual transient events which are present in the signal. The previous research results have been collected into a first guideline for the optimisation of the steering wheel acceleration signal, and the guideline has been tested in the current study. The test stimuli used in the current study were ten steering wheel acceleration time histories which were selected from an extensive database of road test measurements performed by the research group. The time histories, which were all from mid-sized European automobiles and European roads, were selected such that the widest possible operating envelope could be achieved in terms of the steering acceleration root mean square value (r.m.s.), kurtosis value, power spectral density function and the number of transient events present in the signal. The time histories were manipulated by means of the Mildly Non-stationary Mission Synthesis (MNMS) algorithm in order to increase, by a factor of two, both the number and the size of the transient events contained within the frequency interval from 20 to 60 Hz. The ensemble composed of both the unmanipulated and the manipulated time histories was used to perform a laboratory-based detection task with 15 participants, who were presented the individual stimuli in random order. The participants were asked to state, by means of “yes” or “no”, whether each stimulus was considered to be from the road surface that was displayed in front of them by means of a large photograph on a board. The results suggest that the selectively manipulated steering wheel acceleration stimuli produced improved detection for 8 out of the 10 road surface types which were tested, with a maximum improvement of 14 percentage points in the case of the broken road surface. The selective manipulation did lead, however, to some degradation in detection for the motorway road stimulus and for the noise road stimulus, thus suggesting that the current guideline is not universally optimal for all road surfaces.

Keywords: detection, perception, enhancement, vibration, automobile, steering, road.

NOTATION

d'	Detectability index value
$p(x)$	Probability distribution of a variable x
$r.m.s.$	Root mean square (m/s^2)
Z	Standard score
BS	British Standards
CF	Crest Factor
FFT	Fast Fourier Transform
LMS	Leuven Measurement Systems
MNMS	Mildly Non-stationary Mission Synthesis
OWT	Orthogonal Wavelet Transform
TTL	Threshold Trigger Level
VDV	Vibration Dose Value

1. Introduction

Humans have a remarkable ability to interpret the state of the world around them based on sound. Research in the field of Auditory Scene Analysis [5, 16, 19] has identified several mechanisms which are used by the human nervous system to process and interpret environmental sound stimuli. In recent years the knowledge regarding the human ability to estimate sound source location, motion and material properties has been deployed during the design of systems ranging from video games to military avionics.

Unfortunately, the human ability to interpret environmental vibration is less well understood. While the basic psychophysics of the skin, muscle and tendon receptors is relatively well understood in terms of properties such as amplitude response, frequency response and masking effects, less in known about the integrative and interpretative characteristics of the nervous system. Even less is known about the human ability to detect stimuli and interpret phenomena in specific operational environments such as the automobile. Few studies have investigated the relationship between the vibrational properties of driving stimuli on the one hand and the resulting human detection performance on the other, despite anecdotal evidence from drivers suggesting that they use stimuli such as those of the steering wheel when interpreting road and vehicle conditions. The possible role of vibrational stimuli towards informing drivers of conditions such as road surface type, the presence of water or snow, tyre slip or the dynamic state of subsystems such as the engine, the steering or brakes is not well understood.

Within the context of this general situation a small number of studies [3-4, 10-11] have been performed to date in order to begin to understand how the characteristics of automotive steering wheel vibration might influence the human detection task. The motivation behind these studies has been the possibility that knowledge regarding the effect of the steering wheel vibration signal characteristics on human detection might be used as the basis for the development of steering perception enhancement systems [8] which would improve steering feel and driver situation awareness.

Giacomin and Woo [10-11] investigated driver detection of road surface type by measuring the sensitivity of the human detection to changes in the amplitude and frequency bandwidth of the steering wheel acceleration stimuli. Steering wheel acceleration time histories from automobiles which had been driven over selected road surfaces were manipulated in post processing so as to produce a set of test stimuli which differed from the original signals only in terms of the amplitude or the frequency bandwidth. The results from laboratory tests which exposed human participants to the modified stimuli suggested that a single, optimal, acceleration gain did not exist which could improve the detection of all road surface types. The results also suggested that the detection of the road surface type was not always strictly optimal at the natural acceleration magnitude encountered in the original automobile, meaning that current production automotive steering systems do not always provide the most informative feedback to the driver regarding the road surface type. The laboratory test results from the frequency bandwidth experiment suggested that steering wheel acceleration frequencies in excess of 60 Hz were used by the human participants for purposes of road surface type detection, thus that any frequency bandwidth less than 60 Hz would be expected to result in poor road surface type detection in actual automobiles.

Berber-Solano and Giacomin [3] investigated driver detection of road surface type by measuring the sensitivity of the human detection task to changes in the number and size of the transient events present in the steering wheel acceleration stimuli. Steering wheel acceleration stimuli from automobiles which had been driven over selected road surfaces were manipulated by means of the Mildly Non-stationary Mission Synthesis (MNMS) algorithm [9] in order to produce test stimuli which varied in terms of the number and size of the transient events which they contained. The results from laboratory tests which exposed human participants to the modified stimuli suggested that increasing the size of the individual transient events proved beneficial towards increasing the human detection of the road surface type up to a scale value of approximately 2.0, after which detection rates dropped in the case of some road surfaces. A small increase in the size of the individual transients therefore proved beneficial while large increases appeared to de-nature the detection task. Regarding instead the possible benefit of increasing the number of transient events per unit time, the laboratory test results did not provide conclusive evidence. A doubling of the number of transient events per unit time (compression factor of 2) was found to provide the best detection rates when considered across all road surface types, but the improvements in detection rate were not always large, and not always statistically significant.

Berber-Solano [4] investigated driver detection of road surface type by measuring the sensitivity of the human detection task to the elimination of regions of vibrational energy from the power spectral density of the steering wheel acceleration signal. The base stimuli used for performing the detection tests were steering wheel acceleration time histories from road tests of a midsized European automobile which was driven over three roads. Power spectral density analysis of the time histories suggested the presence of five frequency intervals within the range from 0 to 150 Hz which were characterised by significant vibrational energy. The experimental hypothesis that was adopted was that the elimination of the energy from any of the five regions might cause the human detection of the road surface type to become more difficult due to the elimination of vital vibrational cues. To test the hypothesis each time history was manipulated so as to eliminate, in turn, each one of the five frequency intervals. The resulting ensemble of original and modified steering wheel acceleration stimuli was used to perform laboratory tests in which participants were asked to detect the road surface type. The results of the laboratory tests suggested that the elimination of vibrational energy in the frequency interval from 20 to 60 Hz proved highly detrimental to the road surface type detection task, suggesting the particular importance of this specific frequency interval towards steering feel and driver situation awareness.

Review of the research performed to date suggests a small number of observations, or guidelines. Considering the amplitude of the steering acceleration signal, the studies described in references 3, 10 and 11 have suggested that small amplifications of the steering wheel acceleration signal, whether performed globally over the complete signal or locally for only the individual transient elements, increased the percentage of correct detection. A possible explanation for this behaviour may be that the amplification helped to raise some information carrying transient events above the threshold of human tactile perception. The studies described in references 3, 10 and 11 have also suggested that large amplifications, greater than approximated 2.0, have had a negative impact on the detection of some road surface types. A possible explanation for this behaviour may be that large increases in amplitude migrate the stimuli outside the range of amplitudes normally encountered in real automobiles, thus outside the range of sensations which drivers have come to associate with the road from their own driving experiences. A maximum increase in the steering wheel acceleration amplitude of approximately 2.0 with respect to the values in current production automobiles appears beneficial. By performing this amplification on only the transient components of the steering acceleration signal, detection might be increased while producing only a minimal effect on the overall root mean square (r.m.s.) value of the steering wheel acceleration, meaning only a minimal effect on driver comfort.

Review of the research performed to date suggests that a doubling of the number of transient events per unit time (time compression factor of 2.0) increased the percentage of correct detection for most road surface types. The studies described in references 3 and 4 have suggested that a small number of repetitions of the transient events found in steering wheel acceleration signals help to increase the correct detection of road surface type, while large redundancies in the signal degrade detection performance. A possible explanation for this result is that a small amount of redundancy may help to reduce the probability, or extent, of masking which can occur due to an individual transient event being close in time to another, large, signal component.

Review of the research performed to date suggests that the frequency interval from 20 to 60 Hz plays a key role in the process of road surface type detection. Studies described in reference 4 have shown a large and general reduction in correct detection of road surface type whenever the vibrational energy in the 20 to 60 Hz interval is reduced. A possible explanation may be the presence of important vibrational resonances of the steering column and of the other steering system components in this frequency interval in most current production automobiles. Such vibrational amplification in current production automobiles may lead to this frequency interval becoming an important source of information for drivers, who would presumably learn from their routine driving experiences to rely on this high energy region for information about the road surface and the vehicle.

The first objective of the research which is described here was to investigate the possible effectiveness towards the detection of road surface type of implementing a factor of 2 amplification, and a factor of 2 redundancy, of the individual transient events which are present in the steering wheel acceleration signal in the frequency interval from 20 to 60 Hz. Since all previous research consisted of tests in which a single signal parameter (i.e. amplification, transient event redundancy or frequency interval) was varied at a time, the new research was performed to ascertain whether the simultaneous application of the selective modifications would still produce improvements in road surface detection, a result which is not automatically guaranteed due to the nonlinearities of both the perceptual and the cognitive elements of the human nervous system. A second objective of the research which is described here was to investigate how effective the steering wheel acceleration guideline might prove over a wide range of road surfaces whose steering wheel acceleration signals are characterised by widely different statistical properties.

2. Experiment

2.1 Test Stimuli

The test stimuli used were ten steering wheel acceleration time histories which were selected from an extensive database of road test measurements previously performed by the research group. The ten time histories were all from mid-sized European automobiles which were driven in a straight line over the test road at a speed which was consistent with the surface type [7]. The time histories were selected such that the widest possible operating envelope could be achieved in terms of the steering acceleration root mean square value (r.m.s.), kurtosis value, power spectral density function and in terms of the number of transient events present in the signal.

Figure 2 presents the ten road surfaces which had produced the steering wheel acceleration time histories, as viewed from directly above and as seen when driving. The names assigned to the individual road surfaces for organisational purposes were: broken, broken concrete, broken lane, cobblestone, cobblestone city, concrete, country lane, motorway, noise and tarmac. For each road the steering wheel acceleration had been measured by means of an accelerometer which was rigidly clamped to the surface of the steering wheel at the 60° position (two o'clock position) with respect to top centre, which is the most common grip position adopted by nonprofessional driver's [12]. The accelerometer had been mounted so as to measure the acceleration in the direction which was tangential to the steering wheel rotation. For all roads and automobiles the accelerometer type and the mounting clamp used were appropriate for the frequency range from 0 to 300 Hz.

Since none of the steering wheel acceleration time histories contained significant vibrational energy at frequencies greater than 120 Hz, the decision was taken to apply a bandpass digital Butterworth filter to limit the vibrational energy to the frequency range from 3 Hz to 120 Hz, the lower cut-off value of 3 Hz having been chosen in recognition of the frequency response limitations of the electrodynamic shaker unit of the laboratory test bench. Figure 3 presents the resulting time history segments while Figure 4 presents the respective power spectral densities. Within Figure 4, two vertical lines are used to indicate the frequency interval from 20 to 60 Hz whose vibrational energy content would be modified in the experiment. The global statistical properties calculated for the complete original recording over each road surface is presented in Table 1.

The ten bandpass filtered acceleration time history segments served as the base stimuli from which a further series of new stimuli were constructed for use in the laboratory experiments of road surface type detection. The Mildly Nonstationary Mission Synthesis (MNMS) algorithm was used to introduce controlled variations in the statistical properties of the time history segments. The MNMS algorithm, which is described in detail in reference [9], uses the Fast Fourier Transform (FFT) and the Orthogonal Wavelet Transform (OWT) to first divide signals into target frequency intervals then selectively manipulate the transient (shock) events within each frequency interval. Within the context of the current study, MNMS was used to manipulate the signal content within the target frequency interval of 20 to 60 Hz, modifying the size and the number of the transient events which were found within the target frequency interval.

Adopting the guideline which summarised the most successful signal manipulations found in the previous research studies of road surface type detection, the MNMS algorithm was set to implement a signal threshold trigger level (TTL) value of 2.6, a signal time compression ratio of 2.0 and a transient event scale factor of 2.0. The transient event reinsertion method selected was the maximum reinsertion method, meaning synchronization procedure 2, which does not affect the amplitude or phase relationships within each transient event [9].

2.2 Test Facility

Figure 1 presents a schematic representation of the steering wheel rotational vibration test rig used to perform the laboratory experiments, along with the associated signal conditioning and the data acquisition system used. Table 2 presents the main geometric dimensions of the test rig, which are based on data from a small European automobile. The test rig seat was fully adjustable in terms of horizontal position and back-rest inclination as in the original automobile.

The steering wheel itself was 325mm in diameter, was manufactured from aluminium, and had an F1 style shape. The steering wheel was attached to a steel shaft which was in turn mounted to bearings and connected to an electrodynamic shaker. Rotational vibration was applied by means of a G&W V20 electro dynamic shaker driven by PA100 amplifier [2]. The steering wheel acceleration was measured by means of an Entran EGAS-FS-25 accelerometer attached to the top left side of the wheel and the acceleration signal was amplified by means of an Entran MSC6 signal conditioning unit [1]. Control and data acquisition were performed by means of the Leuven Measurement Systems (LMS) Cada-X 3.5 F software system coupled to a DIFA SCADASIII unit [15].

The maximum stroke of the test rig shaker unit (±10 mm) limited the maximum achievable acceleration at the steering wheel which, in turn, limited the minimum test frequency to 3 Hz. For frequencies lower than approximately 3 Hz accurate acceleration signals could not be achieved at the rigid steering wheel. 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).

In order to determine the stimuli reproduction accuracy of the test rig facility an evaluation was performed. The procedure evaluated the complete chain composed of the LMS software, the front end electronics unit, the electro-dynamic shaker, the accelerometer and the signal conditioning unit. The accuracy of the target stimuli reproduction was quantified by measuring the r.m.s. difference between the actuated signal and the target signal. Eight participants were used in the pre-test process so as to consider also the possible differences in bench response which are caused by differences in impedance loading on the steering wheel from people of different size. Results suggested that the maximum percent of error between the r.m.s. acceleration level of the target signal and the actuated signal was found to be less than 5% for all stimuli used in the pre-test.

2.3 Test Subjects

A total of 15 university students and staff participated in the experiment, of which 9 males and 6 females. A consent form and a short questionnaire were presented to each participant prior to testing and information was gathered regarding their anthropometry and health. Table 3 presents a basic summary of the physical characteristics of the group of test participants. The mean values and the standard deviation of the height and weight of the test participants presented in Table 3 were near the 50 percentile values for the U.K. population [17] 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.

2.4 Test Protocol

Before commencing testing each subject was required to remove any heavy clothes such as coats and to remove any watches or jewellery. They were then asked to adjust the seat position and backrest angle so as to simulate a driving posture as realistically as possible. Since grip type and grip strength [18] are known to effect the transmission of vibration to the hand-arm system, the subjects were asked to maintain a constant palm grip on the steering wheel using both hands. The subjects were also asked to wear ear protectors so as to avoid auditory cues. Room temperature was maintained within the range from 20°C to 25°C so as to avoid significant environmental effects on the skin sensitivity [14].

The complete experiment consisted of ten individual tests, one test for each of the reference roads. During each test a large photograph of the reference road was displayed in front of the participant on a board which was placed about 1 meter ahead at eye level. During each test a series of ten second steering wheel acceleration stimuli were presented to the participant in random order, using a 5 second gap between each stimulus. The applied steering acceleration stimuli consisted of five repetitions of the base stimuli from the road which was on display, five repetitions of the optimised stimulus which had been developed for that road through selective manipulation using the MNMS algorithm and ten randomly chosen stimuli from among the original or the optimised stimuli associated with the other nine other roads. The stimuli from the other roads served to form the noise background for the study, against which the detections of the correct stimuli from the actual road were being made.

The test stimuli were separated from each other by means of a 5 second gap in which the participant was asked to state by “yes” or “no” his or her judgment of road surface type. In order to minimize any possible bias resulting from learning or fatigue effects, the order of presentation of the test signals was randomized for each subject. Each participant performed 20 detections for each road surface type, for a total of 200 detections in a complete experiment. A complete experiment lasted approximately 50 minutes for each test participant.

3. Results

Figure 5 presents the percentage of correct detections achieved by both the base stimuli and the optimised stimuli which had been produced through selective manipulation by means of the MNMS algorithm. The histogram compares the correct detections of the two steering acceleration stimuli, the original and the optimised, for each of the ten roads which had been tested.

From Figure 5 it can be noted that the manipulation of the base stimuli by means of the MNMS algorithm lead to improvements in detection for 8 of the 10 road surface types which were tested. A maximum improvement in detection of 14 percentage points was obtained in the case of the optimised broken road test stimulus. The eight road surface types whose detection improved due to signal manipulation were further analysed by means of a between-subjects one factor repeated measures ANOVA [13]. The differences between the original stimuli and the manipulated stimuli were found to be statistically significant in all cases, except for the tarmac road, at a $p=0.05$ significance level with a $F(1,14)$ spanning from 5.385 to 10. In the case of the tarmac road the differences were not found to be statistically significant at a $p=0.05$ significance level.

From Figure 5 it can also be noted, however, that the manipulation leads to a degradation in detection for the motorway road stimulus and the noise road stimulus. While the reduction in correct detection was relatively small in both cases, 2 percentage points, the result does suggest that the optimisation strategy adopted is not guaranteed to lead to improvements in driver feel and situation awareness for all roads. However, for the two roads the differences between the original stimulus and the manipulated stimulus were found to not be statistically significant at a $p=0.05$ significance level when evaluated by means of the one factor repeated measures ANOVA.

In order to facilitate the comparison of the current results for road surface type detection to findings from other research fields, the data was normalised by means of the detectability index d’ which is commonly used in signal detection applications [10, 20]. For experimental protocols such as the current one in which the test subjects are requested to provide a simple “yes” or “no” response, the detectability index d’ can be estimated from the experimentally determined hit rates and false alarm rates by means of the resulting normalised deviate values (the Z scores) using the relations provided below.

$$d' = Z_n - Z_{sn}$$

$$Z_n \, [1.0 - p(false\,alarms)]$$

$$Z_{sn} \, [1.0 - p(hit)]$$

where Z_n is the Z-score associated to the Gaussian probability distribution of the human sensory responses to the background noise (N distribution) and it is calculated by subtracting the false alarm rate from 1.0 and converting this value to a Z-score, whereas Z_{sn} is the Z-score associated to the Gaussian probability distribution of the human sensory responses to the combination of background noise plus signal (SN distribution) and it is calculated by subtracting the hit rate from 1.0 and converting this value to a Z-score [20].

Figure 6 presents the detectability index d’ calculated for both the base stimuli and the optimised stimuli which had been produced through selective manipulation by means of the MNMS algorithm. All d’ values are distant from a situation in which detection is not possible, near d’=0 standard deviations, with most being in the vicinity of d’=1.0. Such values are relatively common in human detection testing performed with sound or vibration stimuli, however in the case of the tarmac and the broken lane roads the d’ values approach 2.0 which is a highly positive result.

4. Discussion

From Figure 5 it can be noted that for none of the road surfaces investigated in this study was a 100 percent correct detection rate achieved. The maximum percent correct detection achieved was 90 percent for the optimised tarmac road stimulus, while the minimum percent correct detection achieved was 60 percent for the optimised motorway road stimulus. The correct detection of less than 100 percent obtained for all the road surface types would suggest the difficulty of achieving fully accurate detection in a laboratory task in which several key stimuli, notably the acoustical stimuli, are absent.

Inspection of the global statistics of Table 1, of the time histories of Figure 3 and of the power spectral densities of Figure 4 suggest that the ten steering wheel acceleration time histories chosen for use in the current study covered a wide range of statistical properties, thus a wide range of actual operational conditions in automobiles. The test stimuli differed from each other in terms of either r.m.s. amplitude, power spectral density or transient event content (number of individual events which could be identified and manipulated by means of the MNMS algorithm). It is therefore a promising development that the manipulations to the steering wheel acceleration which were performed as part of the current study should lead to improvements in road surface type detection for 8 of the 10 road surfaces, while simultaneously producing only minor reductions in detection for the remaining 2 road surfaces. While meriting further investigation, the current results seem to suggest that the individual signal manipulations which had been found in the previous research to improve road surface type detection still prove beneficial when performed in conjunction, a result which was not fully guaranteed beforehand due to the known nonlinearities in the both the frequency response characteristics and the integrative properties of the human tactile sensory system. While not implying linearity of the human sensory and cognitive response, the current results do suggest the possible advantage of implementing more than a single signal transformation as part of the feedback strategy of the automotive steering system.

The manipulation of the steering wheel acceleration signals performed in the current study lead to a degradation in detection performance for the motorway road and for the noise road. While the reduction in correct detection was relatively small in both cases, the result suggests that the stimulus optimisation strategy did not universally lead to improvements. While a full explanation of this result requires further experimentation and investigation, one possible explanation may be the presence of large tyre resonances (see the sharp peaks in the power spectral densities of Figure 5) at frequencies above 60 Hz, which would result untouched by the optimisation settings adopted during the current study. For the motorway and noise roads used in the current study it is possible that the road type detection is based in part on the vibrational energy associated with the high frequency tyre harmonics, a task which may have been rendered slightly more difficult by the increases in signal level in the 20 to 60 Hz region produced by the current stimulus optimisation settings. Further research should investigate whether the optimisation strategy which was implemented in the current study in only the 20 to 60 Hz frequency interval should be applied to all peaks of significant vibrational energy in the steering wheel vibration signature.

5. Conclusions

Laboratory based tests of road surface type detection were performed using steering wheel acceleration time histories from mid-sized European automobiles and European roads. Ten steering wheel acceleration time histories were selected which provided the widest possible operating envelope in terms of the steering wheel acceleration root mean square value, kurtosis value, power spectral density function and in terms of the number of transient events present in the signal. Ten further steering wheel acceleration time histories were produced by means of the Mildly Non-stationary Mission Synthesis (MNMS) algorithm which was used to simultaneously increase, by a factor of two, both the number and the size of the transient events contained within the frequency interval from 20 to 60 Hz for each of the original ten steering wheel stimuli. The ensemble composed of both the unmanipulated and the manipulated time histories was used to perform a laboratory-based detection task with 15 participants.

The detection test results suggest that the simultaneous application of the individual single parameter signal manipulations, which had been found to be successful in previous research studies, did improve the human detection of road surface type for most roads. No major cross-parameter effects seem to have negated the individual positive benefits of the individual signal manipulations which had been established in previous research studies. Improved detection was achieved for 8 out of the 10 road surface types, with a maximum improvement of 14 percentage points in the case of the broken road surface. The selective manipulation of the stimuli did lead, however, to some degradation in detection in two cases, the motorway road and the noise road, thus suggesting that the current set of manipulation settings, or guideline, is not universally optimal for all road surfaces. Research is strongly recommended to investigate the benefits of extending the current manipulation technique to all the frequency intervals of significant vibrational energy in a steering wheel acceleration signature.

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Figure

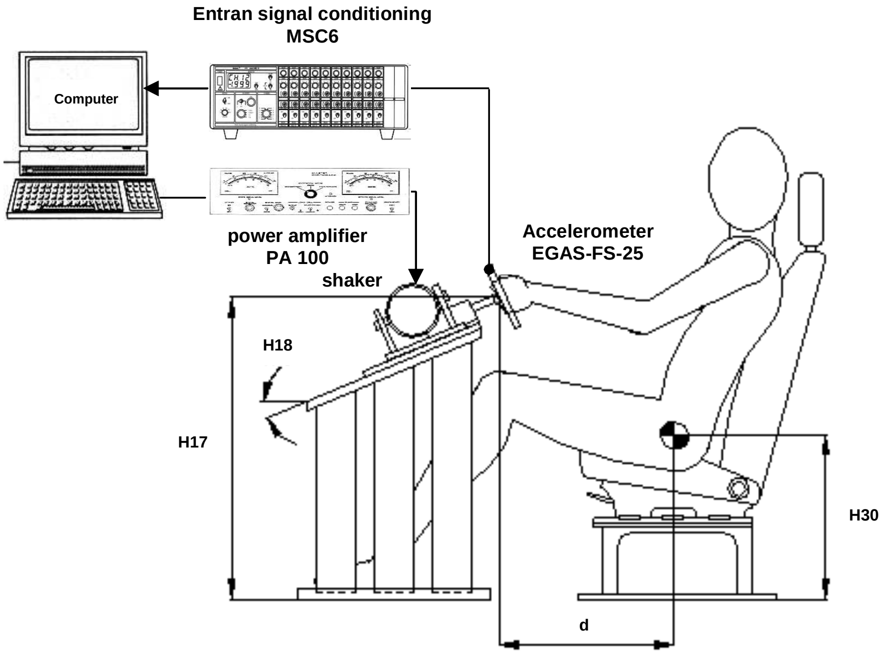


Figure 1. Schematic representation of the steering wheel test rig

Broken (vehicle speed 40 Km/h)

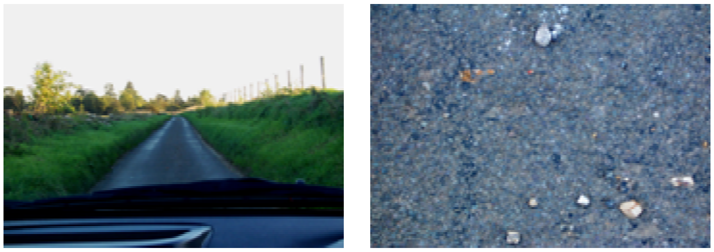
Broken Concrete (vehicle speed 50 Km/h)

Broken Lane (vehicle speed 40 Km/h)

Cobblestone (vehicle speed 30 Km/h)

Concrete (vehicle speed 96 Km/h)

Country Lane (vehicle speed 40 Km/h)



Motorway (vehicle speed 110 Km/h)

Noise (vehicle speed 80 Km/h)

Cobblestone City (vehicle speed 40 Km/h)

Tarmac (vehicle speed 96 Km/h)

Figure 2. Road surfaces and vehicle speeds whose stimuli were chosen for use in the laboratory tests.

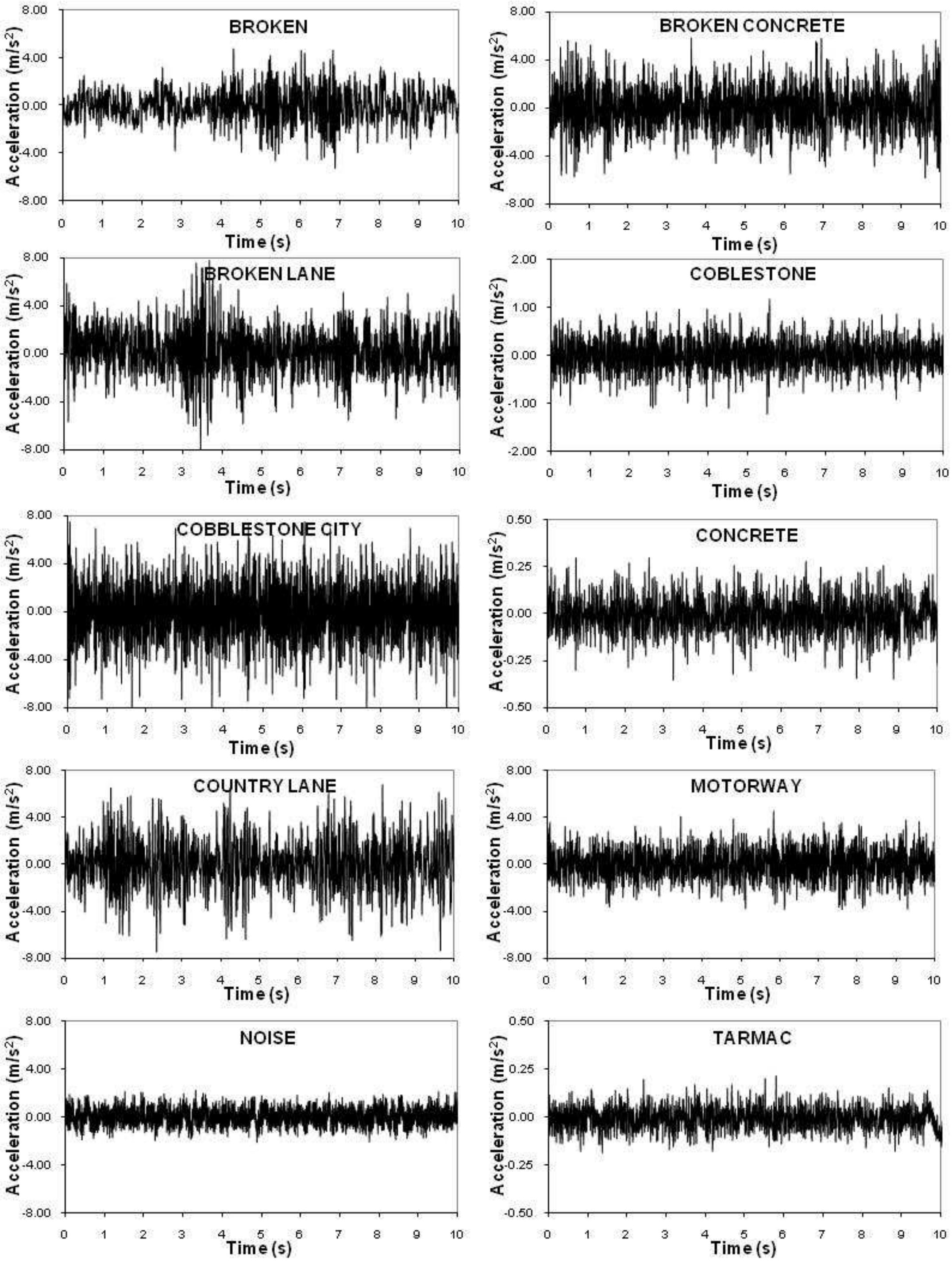


Figure 3. The ten steering wheel acceleration time history segments which were extracted from the road test recordings for use as laboratory stimuli.

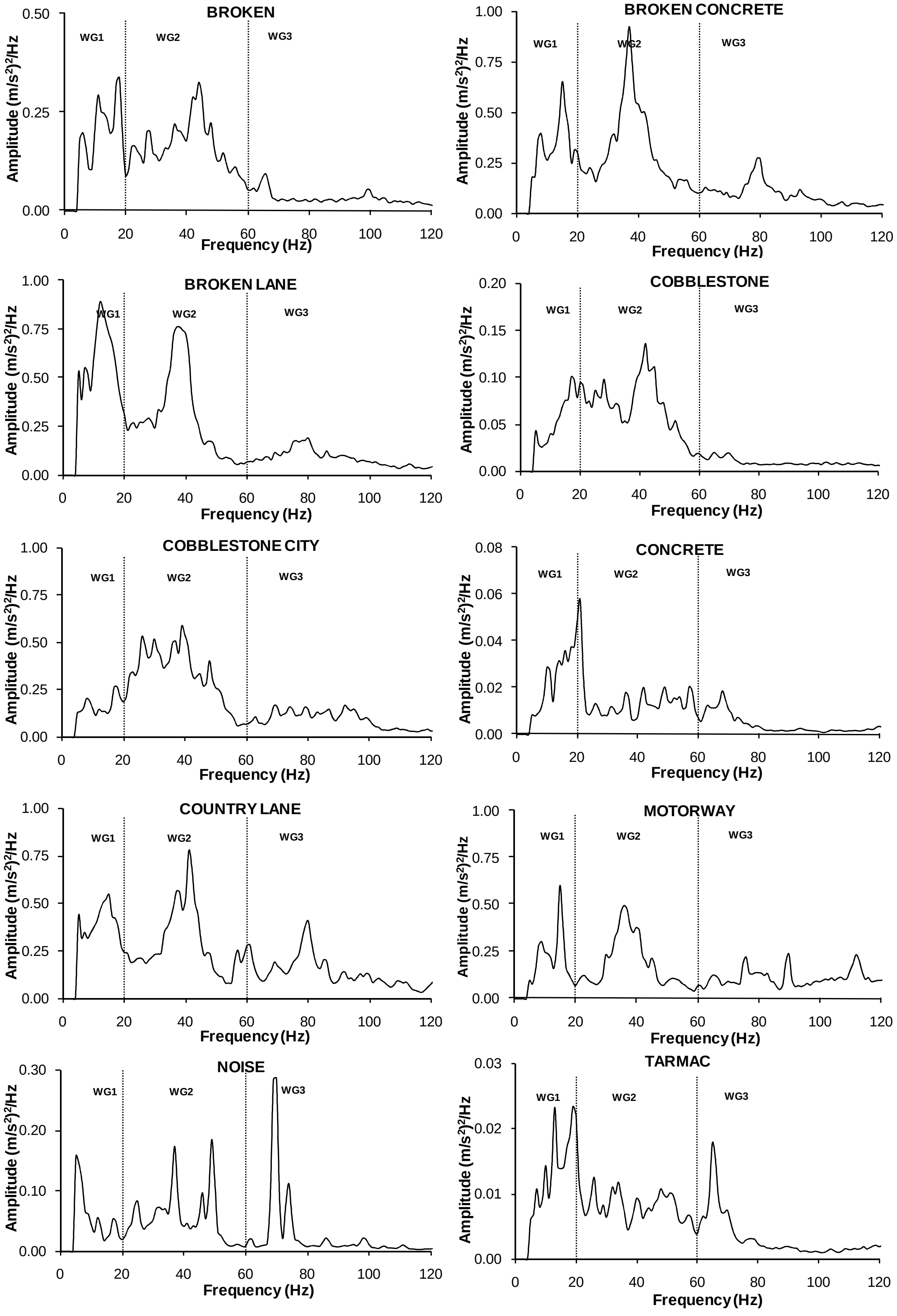


Figure 4. The Power Spectral Densities (PSD) calculated from the ten steering wheel acceleration time history segments after they had been bandpass filtered to be within the frequency range from 5 to 120 Hz.

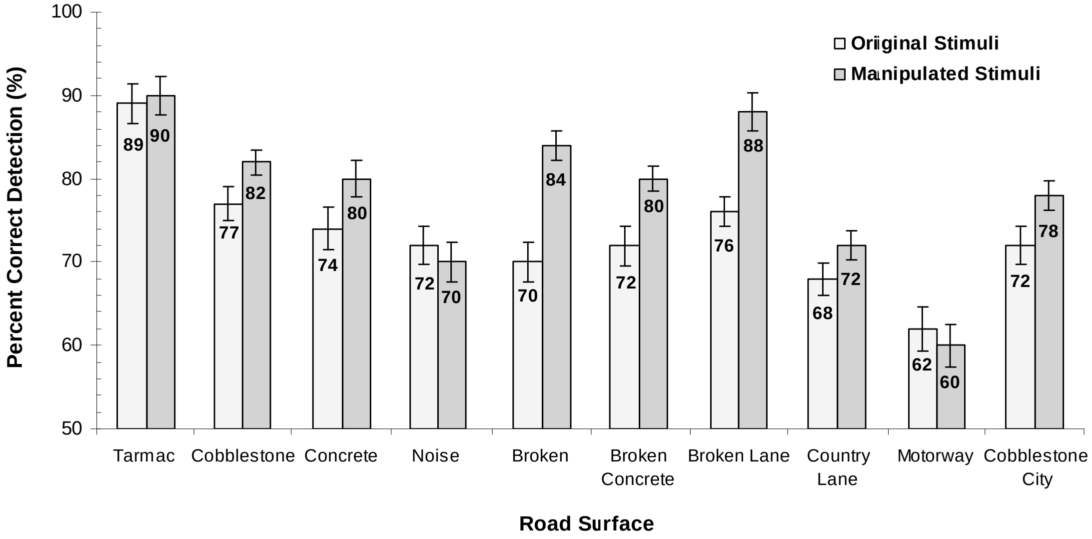


Figure 5. Percent correct detection rate of the ten road surfaces used in the laboratory experiment obtained using both the base stimuli and the optimised stimuli (n=15 people).

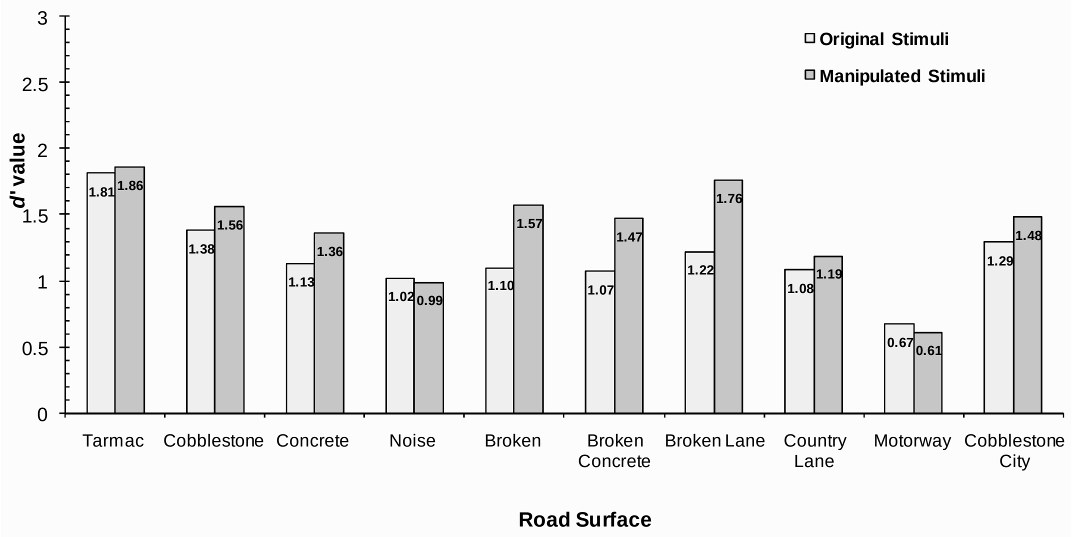


Figure 6. Detectability *d*' value detection rate of the ten road surfaces used in the laboratory experiment obtained using both the base stimuli and the optimised stimuli (n=15 people).

Table

Table 1) Global statistical properties of the ten steering wheel acceleration time histories which were used as the base stimuli in the experiments.

Type of Road Surface	***r.m.s*** **(m/s^2)**	**Kurtosis (dimensionless)**	**Skewness (dimensionless)**	**CF (dimensionless)**	**VDV ($ms^{-1.75}$)**
Broken	1.230	3.775	-0.048	3.920	3.200
Broken Concrete	2.028	3.210	0.010	3.360	4.127
Broken Lane	2.355	3.630	-0.030	4.400	4.380
Cobblestone	0.287	3.465	-0.002	4.710	0.736
Concrete	0.099	3.114	0.073	4.280	0.222
Country Lane	2.180	3.630	-0.030	4.400	4.897
Motorway	1.147	3.080	0.030	3.550	2.783
Noise	0.710	2.726	0.092	3.200	1.620
Tarmac	0.056	2.997	0.052	3.872	0.130

Table 2) Geometric dimensions of the steering wheel rotational vibration test rig.

Geometric Parameter	**Value**
Steering column angle (H18)	23°
Steering wheel hub centre height above floor (H17)	710 mm
Steering wheel diameter (W9)	325 mm
Steering wheel tube diameter	25 mm
Horizontal distance from H point to steering wheel hub centre (d= L11-L53)	390–550 mm
Seat H point height from floor (H30)	275 mm

Table 3) Physical characteristics of the group of test participants involved in the laboratory experiments (n=15).

Characteristics		**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Age	**(years)**	29.93	3.75	22	35
Height	**(m)**	1.69	0.08	1.58	1.80
Mass	**(kg)**	68.67	6.85	58	76