



Driver behaviour and fired soil nails

**Prepared for Quality Services, Civil Engineering, Highways
Agency**

M W Pickett, G J Harris, S Burton and S M Gray

1 Introduction

Soil Nailing Limited has developed a compressed air powered firing mechanism which propels nails into embankments as a means of stabilising them. Use of this device has generated a great deal of interest in respect of the relatively low operating costs when compared with other methods currently used to stabilise embankments. Use of this device also enables highway engineers to undertake embankment stabilisation with minimal disruption to traffic as the operator claims that the highway does not need to be closed during the remedial work.

The nail firing mechanism is currently attached to the hydraulically controlled jib of a crawler tracked vehicle. A reservoir of compressed air is generated for use in firing a nail into the soil. This firing, which is achieved through the release of the reservoir of compressed air, generates a high level of noise. In view of the high, impulsive noise levels generated there is concern that the noise could induce startle reactions to drivers passing the device when a nail is fired. It was felt that this reaction and its subsequent interpretation by drivers could lead to driver behaviour changes which increased the risks of accidents occurring.

In view of these concerns the Highways Agency commissioned the Transport Research Laboratory (TRL) to study the likely effect of soil nail firing on the driving behaviour of motorists when undertaken in proximity to passing traffic.

2 Review of background literature

2.1 Introduction

In order to appreciate the potential influence of high noise levels on human subjects and to help design an appropriate experiment it was considered important, at the outset, to carry out a review of relevant literature. The review is described in Appendix A and examines the nature and definition of startle and, where possible, the influence of startle on human performance. The potential medical effects of exposure to high levels of impulsive noise levels are also covered.

This section contains a brief overview of the main findings of the literature review described in the Appendix.

2.2 Definition of startle

The Encyclopedia Britannica gives the following definition of startle:

‘Startle reaction or pattern is an extremely rapid psychophysiological response of an organism to a sudden and unexpected stimulus such as a loud sound or blinding flash of light. In human beings it is characterised by involuntary bending of the limbs and a spasmodic avoidance movement of the head. Musculature returns to normal in less than one second, although elevations in heart rate, respiration and skin conductance persist slightly longer. The startle pattern occurs in all normal human beings and all mammals when tested in a relatively normal

manner. The pattern is resistant to extinction or modification by learning, although its intensity may be reduced by repetition or anticipation’.

For the driving task the important aspects are the involuntary nature of startle, its resistance to modifications by learning, and that its intensity may be reduced by anticipation.

However, in addition to the autonomic effects induced by startle, drivers may interpret such noises in different ways which could lead to driver behaviour changes of importance. In a previous study of driver reactions to noise from a gunnery range, it was found that some drivers had difficulty maintaining their lane or speed which continued for some considerable distance beyond the range expected from autonomic reaction. Other behaviours resulted from concern over the mechanical condition of the vehicle or concern that the vehicles tyres had burst. Clearly, these as well as autonomic responses need to be considered in the experimental design.

A comprehensive review of the literature on startle effects on humans found no published research that considered the effect of startle on the vehicle driving task. Previous work on human startle is found mostly in the areas of sonic boom, the sudden rise time of noise from low flying military aircraft, the effect of simulated startle on human task performance, and the medical effects of startle.

2.3 Sonic booms

While much of the reported research on sonic booms concentrates on the annoyance caused to neighbouring populations rather than startle response specifically, some studies have dealt directly with startle response to both real and simulated sonic booms. In one study (Thackeray et al, 1973) subjects were exposed to real sonic booms from fighter aircraft flying at various heights and their performance assessed on a hand-arm steadiness task. Results showed that boom overpressures ranging from 26 to 35 N/sq. m (122-125 dB) (indoors) produced reflexive arm-hand movements in about 10 per cent of the subjects. Booms of 67 N/sq. m (130 dB) (indoors) and greater produced responses in 75 per cent of subjects. Between these extremes of overpressure there appeared to be a critical range between 40 and 46 N/sq. m (126-127 dB) (indoors) in which an abrupt increase in startle response occurred.

2.4 Effect of startle on human performance

A review of the literature on startle contains papers on the startle reaction of rats to loud sounds among other stimuli, mostly in journals in the psychological and physiological fields, and work on human startle reaction which appears more generally in relation to sonic booms, gunfire noises from army ranges, the advent of sudden noise from low flying military jet aircraft and the effect of startle on human behaviour. Much of the reported work on human reaction to impulsive noise is concerned with medical effects related to certain mental or physiological conditions. Some of the more relevant papers concerned with human reaction to impulsive noise are summarised in Appendix A.

There is, however, some evidence of the effect of startle performance with various tasks given in papers by Fosse et al (1989) and Thackeray and Touchstone (1983). Fosse described the effect on a target aiming task while Thackeray considered the degradation of performance in subjects monitoring a simulated air traffic control radar display and also a secondary information processing task. The authors concluded that recovery time for simple perceptual-motor responses during the initial shock phase of an emergency is quite rapid (of the order of 1-3 seconds); but if the shock phase evokes heightened emotion-physiological arousal, as in the case of startle, information-processing ability may be impaired for approximately 30-60 seconds following the stimulus event.

2.5 Medical effects

The medical effects of startle from low flying military aircraft have been examined by Curio and Michalak (1993). The main finding was that a high rise rate of sound (onset rate) is the physical parameter which leads to more physical symptoms being cited by subjects and also to more myokinetic effects of an objectively measurable nature. The authors found that whereas younger healthy subjects had short term increases in blood pressure, older people with impaired circulation regulatory systems may experience higher blood pressure increases over the initial value for longer periods.

Evidence that elderly men and women are less responsive to startling noises than young people, as measured by eye blink-rate, is given in a paper by Ford et al (1995). The results showed that even when the noises were set relative to the subjects' thresholds, older subjects (mean age 65 years) were less responsive to startling auditory stimuli than were the younger age group (mean age 22 years).

2.6 Summary

This review contributes important results on what appears to be a previously unexplored aspect of human reaction to startle from impulse noise. The evidence from the study of sonic booms is that startle effects may begin to emerge when the noise levels reach 122-125 dB, and that startle effects occurred in most subjects at 130 dB or more. There appeared to be a critical range around 126-127 dB where there was a marked increase in startle response. Other research suggests that while startle and shock effects may occur in some subjects for a relatively short period following the impulse noise, other subjects may be disturbed for a period of 30-60 seconds after the onset of the noise event. A study of the medical effects also showed that in physiological terms older people were affected less from startle reactions than younger people.

Clearly, although the literature review did not expose previous studies which have a direct bearing on this particular study, there are several indications from the literature review which do help guide the experimental design. For example, it is clear that any study of driver behaviour change should examine both the immediate (autonomic) reaction to the noise as well as monitoring driver behaviour changes for some considerable time after the noise event occurred. It is also

clear that noise levels below a peak of 126 dB would not expect to produce significant autonomic reactions in drivers. These and other aspects of the experimental design are considered further in the next section.

3 Experimental design

The main objectives of this study were to:

- i determine drivers' reaction to the soil nailing firing noise;
- ii discuss whether the observed reactions significantly affect safety and accident risk.

This section describes the main study design features that address the objectives set out above.

3.1 Exposure to soil nailing noise

In designing this study a number of options were considered for exposing drivers to soil nail firing noise. These included tests on a real road where the test vehicle would be driven passed a site as a soil nail was being fired into the ground; using simulated nail firing noise with the test vehicle running on the TRL test track; or using simulated soil nail firing noise in the driving simulator.

Given the nature of the study, the experience from a similar study on gun fire noise and the distinct possibility that drivers might react adversely to the soil nail firing noise, it was considered not possible to carry out the study on the highway. However, something close to real driving conditions was needed, particularly where there was interaction with other vehicles. The option of using the test track could not simply provide these conditions and there would be a safety issue that would need to be addressed. A further disadvantage was that it would be necessary to simulate at the driver's ear position the levels of noise potentially capable of being generated by the soil nail firing equipment at the roadside. The test track option also posed potential difficulties in arranging identical driving conditions for all subjects exposed to the tests.

The TRL Driving Simulator offered distinct advantages when compared with the other two options. Firstly, the simulator was capable of producing a variety of realistic but safe driving conditions that could be simply and identically reproduced for each subject. Secondly, it could also incorporate the testing of a large number of subjects. The examination of the potential effects on subjects in different age groups could also be simply incorporated in the study design.

There remained the problem of achieving an accurate simulation of the soil nail firing noise at the levels required. However, as the simulator was housed indoors in an enclosed space, it was felt that the simulation of soil nail firing noise would be easier to achieve under these conditions than on a moving vehicle in an outdoor environment.

3.2 Measurements to assess driver reactions

Various measures of driver response can be measured directly using the driving simulator's control features.

These include monitoring the steering wheel position and vehicle path, brake and accelerator pedal pressures, and speed. It would also be possible to measure physiological responses such as heart rate, electro-dermal skin response and blood pressure to assess autonomic changes in driver behaviour.

Physiological measurements of drivers were considered when determining the study design, but these measures were ultimately not included because of their complexity, inappropriateness to the study and cost. Such measurements require instrumentation to be attached to the subjects by medically trained professionals. By instrumenting the subjects in this way it is highly likely that subjects would not behave in a realistic manner when asked to carry out the driving task. It was also felt that physiological responses merely measure changes at a micro level, and although such measures could be indicative of startle reactions, it was really how these reactions translate into observable driver behaviour performance that was important to this study.

To supplement the physical measures of driver performance the study design included a questionnaire which the subjects were required to complete at the end of the test. The objectives would be to determine whether the subjects heard the soil nailing noise, whether they were startled by it, and whether they thought it affected their driving performance. Finally, it was decided that the measurements of driver behaviour would include a video showing facial reactions and upper body movements of each subject. It was anticipated that these observations would also help to confirm the existence of startle reactions.

3.3 Ethical considerations

In designing an experiment where subjects are to be exposed to relatively high levels of noise consideration must be given to the welfare of the subjects. To achieve the aims of the experiment the subjects could not be told beforehand what was going to happen, but the question of experimental ethics needed to be considered carefully before deciding on the final experimental design.

Guidance on ethical considerations was obtained by consulting the British Psychological Society's Code of Conduct for experiments. For subjects the Code identifies two types of response. Firstly for low level non-painful/low shock experiments subjects should be told that a distraction study was being conducted and afterwards told the exact nature of what happened. Secondly, for high level noise, where there is risk of pain or serious shock, warning signs should be shown, or subjects briefed on the basis of a study into the distracting effects.

In this study it was concluded that the experimental design fell into the first category. Consequently in the briefing to subjects prior to their tests they were warned that there might be some distractions during their drive. It was not necessary, according to the Code, to detail the exact nature of the distractions. This meant that while the soil nail firing noise should still be capable of inducing startle, the subject would not be exposed without some degree of forewarning. It was thought that this degree of

forewarning should not influence the outcome of the experiment. Details of the briefing given to the subjects are described in section 5.6.

4 The driving simulator

The TRL Driving Simulator is based on a real medium-sized saloon car - a Rover 414SLi. The car is surrounded by three 3 metre x 4 metre screens to the front providing 210° front/side image and one rear screen providing normal rear vision using the vehicle mirrors.

Four forward facing Barco projectors project the image on to the screens; three linked to give continuous front/side image; a fourth at the rear of the car. A fifth projector located behind the front screen. The image from this fifth projector is back projected on to a small area of the front screen, overlaying the main forward view and providing a high resolution image used to improve the legibility of signs.

State of the art Silicon Graphics Reality computers generate the images. A further Silicon Graphics computer provides the Simulator Operator Station with an interface to the experiment. The operator used a monitor to display a bird's eye view of the road layout and the position of all vehicles in the driving scenario. This same display provides a continuous representation of the use of the vehicle controls and vehicle speed.

The system provides intelligent vehicles whose behaviour can relate to that of the simulator vehicle (within the confines of a described behaviour pattern) or behave as autonomous intelligent vehicles operating collision detection and avoidance with driving styles ranging from 'passive' through 'normal' to 'aggressive'.

The car bodyshell is, in the position of the shock absorbers on the original car, mounted on hydraulic rams which supply some motion to simulate the tilt and roll experienced in normal braking, acceleration and cornering.

The car has engine noise and external noise of passing traffic or road tyre noise. There are video cameras mounted in the car and subjects' behaviour can be recorded during their drive. There is an in-car intercom system enabling the experimenter to give instructions to the subjects.

The fully interactive simulator offers the advantages of providing a safe environment to study situations where the risks involved would be preventative in the real world. It provides control of conditions enabling repetition and reproducibility. This combined with efficient data collection is an ideal research tool for studies of this nature.

5 Method

5.1 Introduction

The study consisted of three main stages:

- i measurement in the field and reproduction in the laboratory of soil nail firing noise;
- ii testing of subjects' reactions to the noise by use of driving simulator, questionnaire survey and analysis of video images;
- iii analysis of data.

5.2 Measurement of the soil nail firing noise

Measurements and recordings of the noise emission from the soil nail launcher were initially taken in January 1997. This assessment was repeated in July 1997 after the fitting of a silencer device. The silencer was a bespoke system fitted around the base of the launcher to reduce the noise emission caused by the release of compressed air during firing operations.

5.2.1 Site selection and measurement positions

Figure 1 shows a schematic diagram of the measurement site and the different microphone positions relative to the soil launcher. During the measurements the soil nail firing machine was located on a soft verge alongside a concrete track near the premises where the machine is normally stored. The concrete track was intended to represent the nearside lane of a carriageway. This lane would be closed to traffic if the machine were operating close to the road. This particular site was chosen as it was surrounded by open fields of grassland which were free from objects that might have caused significant acoustic reflections.

The main objective of measurement was to take high quality recordings of the noise at the closest distance from the machine that a vehicle might feasibly pass if the machine were operating alongside the carriageway. Soil Nailing Limited advised that the minimum safety zone between the launcher and the nearside edge of a trafficked lane would be 7 metres. In practice it was not possible to obtain reliable measurements this close to the launcher as the noise level was sufficiently high to cause

the instrumentation to overload. For this reason microphone positions were established in the field behind the track at greater distances from the machine. The actual noise level at 7 metres was calculated later based on the propagation characteristics of the soil nail firing noise determined at the site.

Figure 1 shows that the microphone positions were perpendicular to the line of the soil nail firing machine and were located at 28 and 38 metres from the launcher. A number of noise measurements were made at other positions along the line of travel of a passing vehicle. This was to determine whether drivers might be exposed to higher noise levels when approaching, or having passed the machine at the side of the road. Depending on the directionality characteristics of the source it could not be assumed that the highest noise exposure would occur at the shortest propagation distance (ie perpendicular to the line of the machine). However, these measurements established that there was no preferred directionality to the noise and, as a result, the highest noise levels were found to occur directly alongside the launcher. The height of the microphone positions were set at approximately 1.4 metres above the ground. For a driver of a light vehicle this was thought to represent the average position of the driver's ear above the ground. Although noise measurements were not made at other heights, it was considered that the results would not be significantly different over the range of driver positions as the propagation distances would be similar.

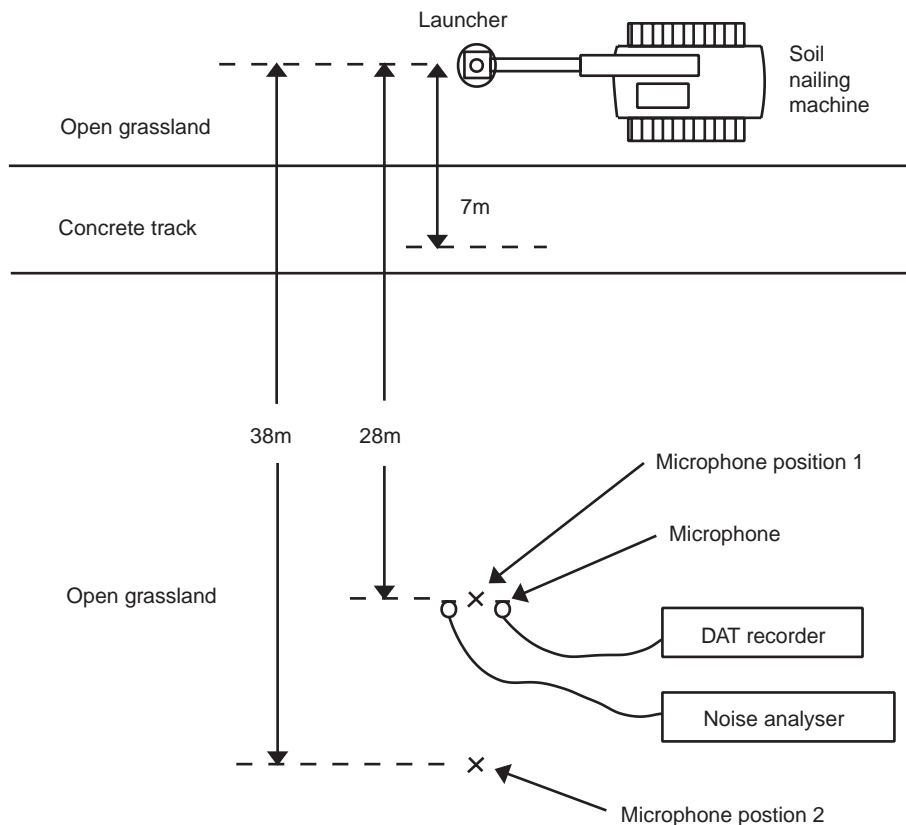


Figure 1 Plan view of measurement site and microphone positions

5.2.2 Instrumentation

Measurements of noise were taken using a CEL 593 type 1 noise analyser capable of measuring peak linear noise level¹. This instrument had recently been checked for conformance with the relevant technical specification for noise measuring instruments (British Standards Institution, 1994). The laboratory carrying out the conformance tests was NAMAS² accredited to perform the necessary tests under precisely controlled conditions. The acoustic calibrator used with the noise analyser was also checked by the same laboratory. The microphone was orientated with the diaphragm in the vertical plane, facing towards the launcher.

To record the sound of the soil nail firing noise a second microphone was set up at the same position and its output connected to a tape recorder. The microphone was a Bruel & Kjaer (B&K) type 4165 measurement microphone connected to a B&K type 2639 preamplifier. This was connected to a SONY TCD D10 PRO DAT recorder via a B&K type 2804 microphone power supply unit.

5.2.3 Measurement procedure

It was suggested by Soil Nailing Limited that representative noise measurements could be made without a soil nail loaded into the launcher as it was thought that the noise level would not be affected. In order to test this suggestion, a comparison of the noise emission was made during firings with and without a soil nail loaded into the launcher. The tests indicated that the noise levels without the nail loaded in the launcher were slightly higher (approximately 1.4 dB) however, bearing in mind the repeatability of the tests, which gave differences of about 3 dB (see also Table 1), it can be concluded that the results with and without the nail were not significantly different.

Consequently, in order to avoid the costs of firing a nail all subsequent repeat tests were carried out without a nail loaded in the launcher.

Before each firing the compressed air pressure was raised to 2500 psi. Soil Nailing Limited advised that this would be a typical operating pressure for the launcher. During most of the noise measurements the launcher was orientated vertically as if firing directly into the ground. To simulate a firing into a vertical bank, other measurements were taken with the launcher orientated horizontally with the direction of firing facing away from the microphone. Typically, two or more measurements were made for each test condition. Recordings of the noise were made during each firing for later analysis and reproduction in the driving simulator.

5.3 Results of the noise measurements

Table 1 gives the results of the peak linear noise levels measured at microphone position 1 at 28 metres from the soil nail launcher (see Figure 1). The results shown were those obtained after the fitting of the silencer.

Although the firing conditions were the same for each test, the noise levels were found to vary over a range of 3.1 dB with a maximum recorded level of 137.4 dB peak

Table 1 Soil nailing noise levels measured at 28m from the source (after fitting of the silencer)

<i>Test number</i>	<i>Noise level (peak linear dB)</i>
1	137.4
2	134.3
3	135.3
4	136.6

linear. To assess the propagation characteristics of the source noise, a further measurement was taken simultaneously at microphone position 2, located 10 metres behind position 1. The difference in noise level recorded at the two positions suggested a propagation characteristic consistent with a point noise source.

To assess the rate at which the sound level changes with distance from the source, a further measurement was made at 38 metres from the launcher (see also figure 1). The results obtained at the two microphone positions were then used to derive an attenuation with distance formula for the ground conditions encountered at the test site.

By applying the measured attenuation rate with distance to the measured levels it was deduced that the maximum sound pressure level at the 7m position would be 149.4 dB. Consequently at this position the peak linear noise level was well in excess of the 200 Pascal (140 dB) sound pressure limit stipulated in the HSE Noise at Work Regulations (HMSO, 1989).

Noise levels measured before the silencer was fitted were, on average, 1.8 dB greater over the range of positions where comparable measurements were taken.

When the soil nail launcher was rotated to a horizontal position, as described in Section 5.1.3, a noise level of 143.0 dB peak linear was recorded at microphone position 1. This measurement was also taken after the fitting of the silencer. As the top of the launcher barrel was pointing directly towards the microphone in this orientation it might be expected that the noise level would be greater. It can be concluded therefore that the peak linear noise level generated by the soil nailing operation is dependant on the angle of the launcher between the vertical and horizontal planes with greater levels occurring as the firing angle increased from the vertical.

Figure 2 gives a typical time history of a sound pressure wave recorded at microphone position 1 (after the fitting of the silencer). The noise from this firing event was recorded with the launcher in the vertical position. The time history was produced by replaying the recorded signal of the noise event into an Ono Sokki type CF-360 digital signal analyser. The resulting time history data was downloaded to a PC and plotted. The figure shows the highly impulsive nature of the pressure wave peaks followed by a short decay.

5.4 Reproduction of the soil nailing noise

Clearly it was not possible to expose driver subjects to soil nail firing noise inside the driving simulator vehicle at levels in excess of the 200 Pascal (140 dB peak linear) sound pressure limit stipulated in the Noise at Work

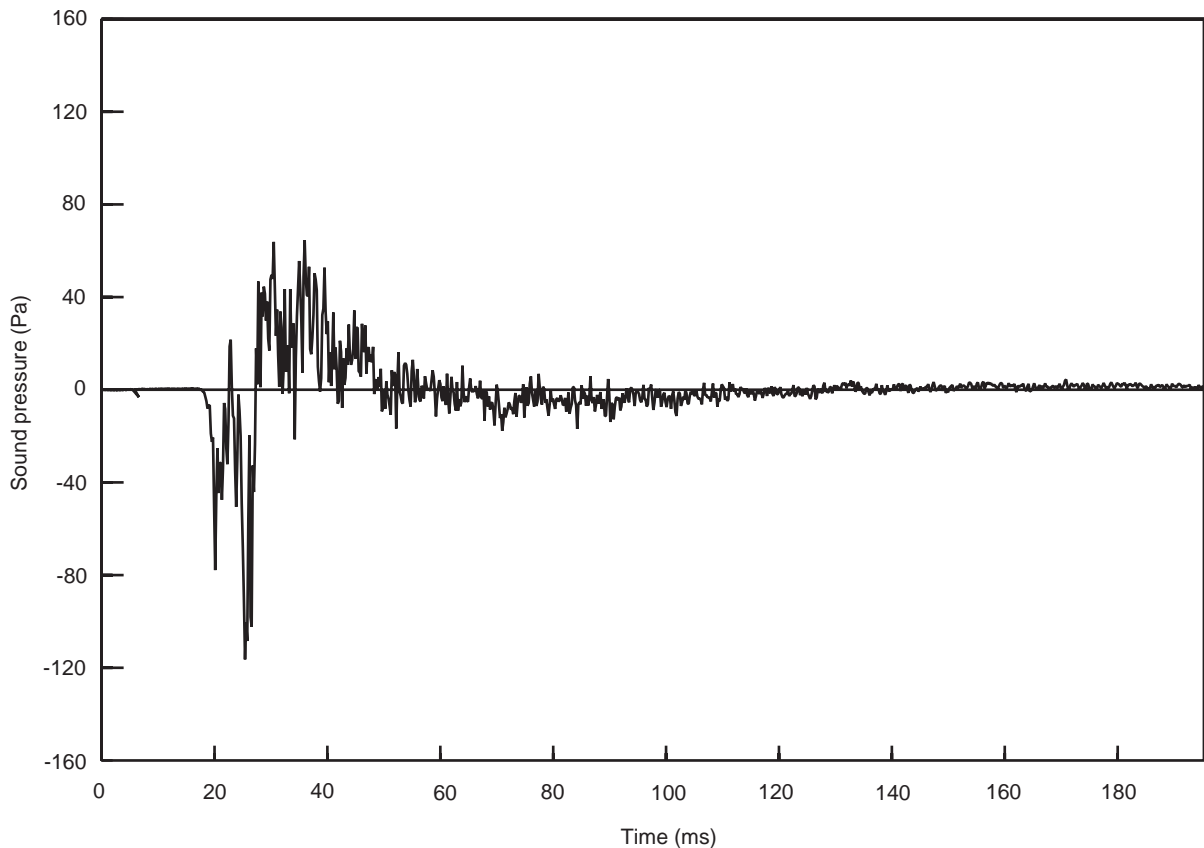


Figure 2 Recorded sound pressure waveform of soil nailing noise (recorded at 28 metres from the soil nail launcher after fitting of the silencer)

Regulations (1989). It was decided, therefore, to test for driver startle reaction at a level of 137 dB peak linear, ie safely below the peak exposure limit of 140 dB.

If no startle response was observed during the subject trial, then it might indicate that 137 dB peak linear would be a satisfactory target noise level. It could then be recommended that the soil nail firing noise should be attenuated to that level or less since there would then be no significant risk of either startle reactions occurring or injurious noise levels being generated. However, if a significant startle reaction was observed, it would clearly be necessary to set a lower target noise level.

5.4.1 Editing of the recorded soil nail firing noise

Recordings of the soil nail firing noise included the sound of a warning alarm which was activated for approximately two seconds prior to each firing operation. To reproduce the noise in the driving simulator, it was necessary to increase the noise level during the approach and diminish the level as the vehicle moved beyond the machine. To simulate worse case conditions it was necessary to trigger the firing noise at the instant that the vehicle was directly alongside the machine. In order to make the adjustments to the soil nail firing noise, the recorded signal was digitally sampled onto a PC. Using proprietary digital audio software, an envelope function was applied to the sample to adjust the noise level before and after the firing event. Based on the soil nailing noise propagation characteristic discussed in Section 5.2, the level of the noise before and

after the firing was adjusted at a rate of 6 dB per doubling of distance assuming a passing speed of 50 mph³. The resulting noise signal was recorded to tape using the SONY TCD D10 PRO DAT recorder which was then later used to replay the signal in the simulator.

5.4.2 Development of the noise reproduction system

To reproduce the soil nail firing noise inside the driving simulator, a powerful, high quality amplifier and loudspeaker system was used. The modified DAT recording of the soil nail firing noise was replayed into the input of a Behringer Super-X frequency crossover connected to a Chameleon 2000D power amplifier. The RMS power output of the amplifier was rated at 1600W. This equipment was located in the simulator control room. The output of the amplifier was connected via low impedance leads to four Sherman CA3 speaker cabinets which were positioned around the simulator vehicle.

During the trials, the replay of the edited soil nail firing noise from the DAT recording was triggered manually by the trial controller. The replay was activated slightly before the driver reached the soil nail firing machine in the simulated scenario. It was timed such that the firing noise would occur at the instant that the vehicle was alongside the machine; preceded by the increasing level of the alarm noise during the approach.

Figure 3 shows the configuration of speakers around the vehicle. In order to produce the soil nail firing noise at a very high level at the driver's ear position, it was necessary

to position the loudspeakers as close as possible to the driver's head. As the figure shows, this was achieved by mounting two speaker cabinets over the open sun-roof, and two next to the open nearside window at the rear of the vehicle. The loudspeaker cabinets did not impinge on the driver's view of the projection screens or the views in the mirrors. Thick black cloths were draped over the cabinets to conceal their shape, and therefore their function.

To measure the noise level at the driver's ear position the CEL 593 noise analyser described in Section 5.1.2 was set up inside the simulator vehicle. The microphone was positioned at the driver's ear position as defined in BS 6086, 'Method of Measurement of Noise Inside Motor Vehicles' (British Standards Institution, 1981). It was found that the noise reproduction system was capable of reproducing the soil nail firing noise at a level of 137 dB peak linear or more at this measurement position. Safeguards were introduced (see Section 5.4.3) to ensure

that subjects were not exposed to noise levels greater than the 137 dB target.

Figure 4 shows a time history of the soil nail firing noise reproduced inside the simulator vehicle at the measurement position. The peak sound pressure of this noise event was equivalent to 137 dB peak linear. For comparison, Figure 5 shows the actual waveform recorded alongside the machine as given in Figure 2. So that the two waveforms can be compared more directly, the original waveform has been amplified slightly so that the maximum pressure peak shown is also equivalent to 137 dB peak linear. It can be seen that the reproduced waveform has a number of negative pressure peaks that are not present in the original waveform. It is possible that this occurred as a result of energy stored in the loudspeaker system from previous excursions of the loudspeaker cones. However, the rapid rise rate and magnitude of the initial pressure peaks was accurately reproduced. Studies have shown that rise rate of

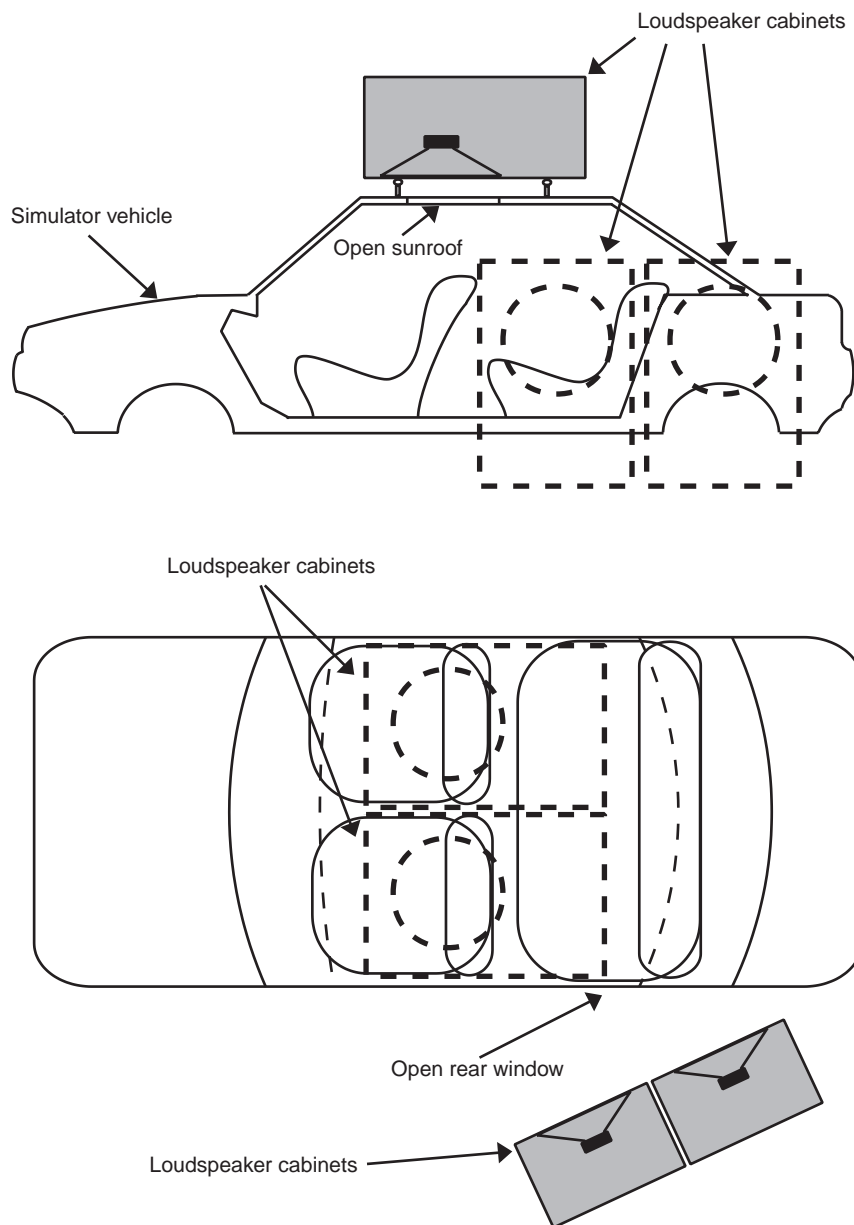


Figure 3 Diagram showing the position of loudspeaker cabinets to reproduce soil nailing noise inside the driving simulator

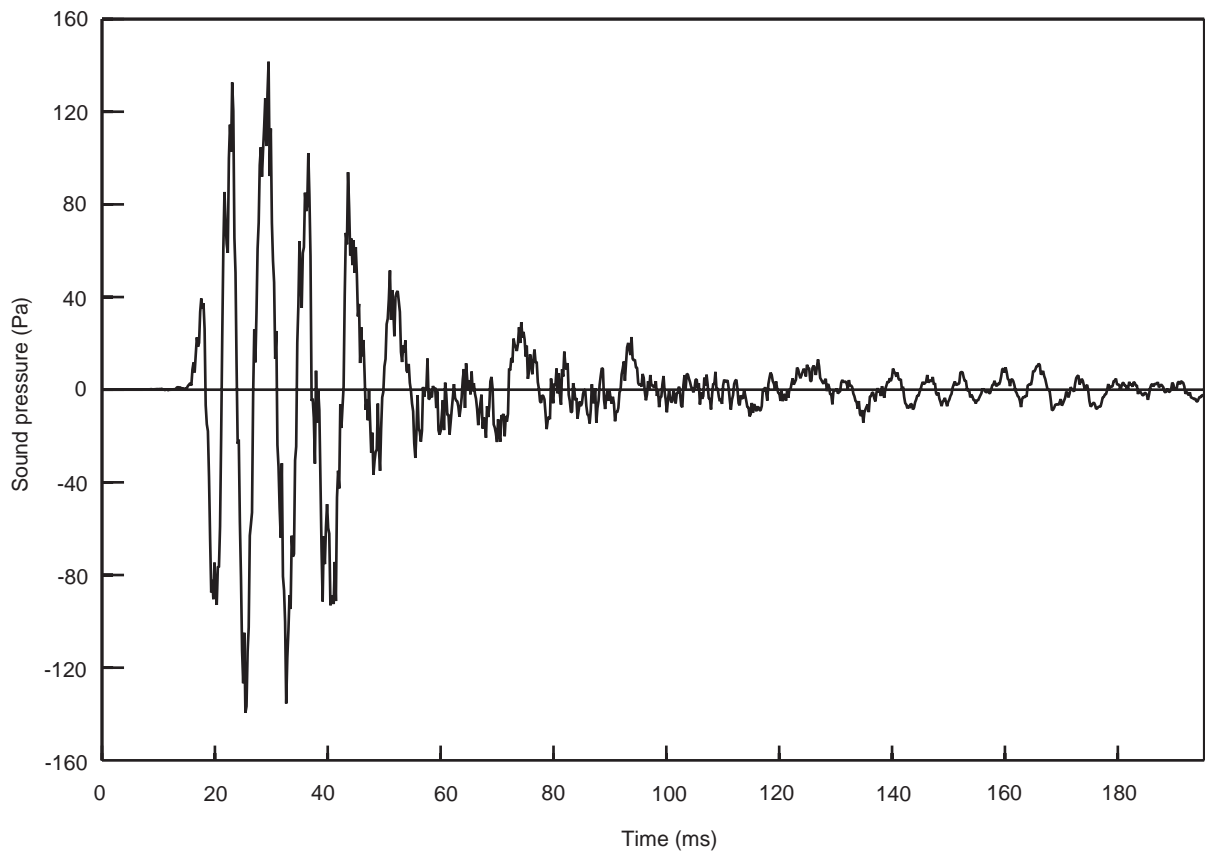


Figure 4 Reproduced sound pressure waveform of soil nailing noise (recorded at driver's ear position inside simulator vehicle)

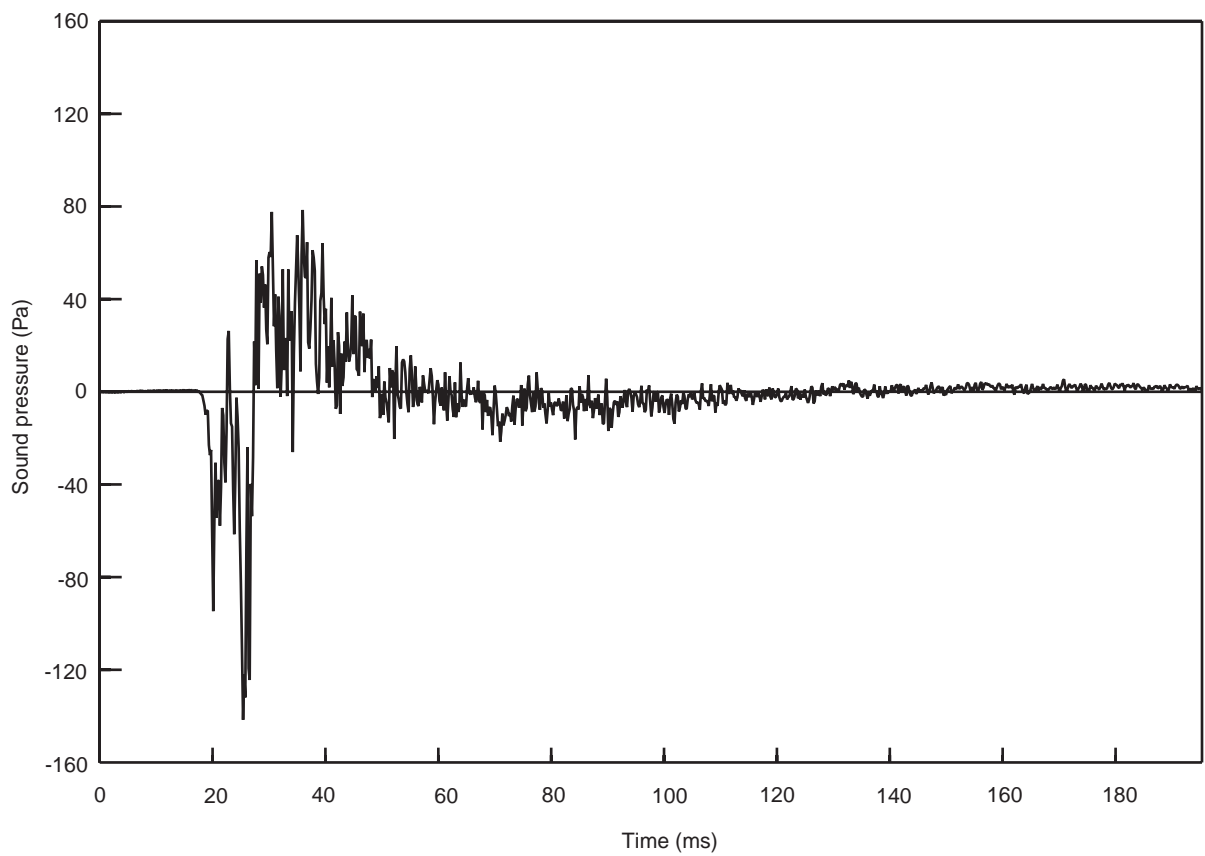


Figure 5 Recorded sound pressure waveform of soil nailing noise (peak level adjusted to 137 dB peak linear for comparison with reproduced waveform)

sound pressure (onset rate) is an important factor in the occurrence of human startle response (Curio, 1993).

Subjective impressions of the reproduced noise were given by those people involved with the study who had heard the soil nail firing operation. It was generally agreed that the level and character of the sound reproduced was a good representation of the soil nail firing noise.

5.4.3 Monitoring of reproduced noise during the trials

To ensure that subjects were exposed to the correct level of soil nail firing noise, the sound reproduction system was calibrated at the beginning and end of each day that trials took place. The measurement of peak linear noise level was carried out as described in Section 5.3.2 using the same NAMAS certified instrument. The noise level before each trial session was adjusted to 137 dB peak linear. The calibration of the sound reproduction system was found to be prone to a small amount of drift during the course of a day. The maximum and minimum levels ever recorded at the end of the measurement sessions were 137.8 and 136.4 dB peak linear respectively which were not thought to affect the accuracy of the measured responses.

The noise levels were also monitored during each replay of the soil nail firing noise throughout the trial. It was not possible to monitor the actual noise level at the driver's ear, as the presence of a microphone would have revealed the nature of the experiment. However, a microphone positioned in a rear footwell was used to detect the noise level of each event. Any significant change in these results would have alerted the controller to excessive drift in the calibration of the noise reproduction system.

5.5 Selection of driving simulator subjects

33 subjects, 16 females and 17 males, with a spread of ages from 18 years to 63 years, were chosen from a register of 900 people maintained at TRL. The volunteers were familiar with the TRL Driving Simulator, having been subjects for other trials, and had not taken part in any trials of a similar nature. When assigned to the trial each subject was asked a series of questions to check that they were in sound health – in particular with no nervous disorders or hearing problems. As it was important that attention was not focused on nervousness and hearing, a variety of questions were asked including questions about eyesight, blood pressure, medication etc.

At the time of booking, subjects were told that the trial concerned 'a study of distractions whilst driving on the motorway'.

5.6 The simulator trial

It is possible to use the simulator to measure the effect of a very wide range of driving conditions. For this study it was decided to limit the road layout to a length of straight motorway built to current standards.

The driving tasks that could be studied range from simple straight line driving with and without traffic to more complex driving manoeuvres involving overtaking which requires a higher degree of concentration. However, in this study it was decided to examine two different but fairly

straightforward driving tasks. The first involved straight line driving in a stream of traffic at a given target speed. The second task involved driving through two sets of road works where remedial work was being carried out on the motorway hard shoulder. In both cases the drivers were required to follow the vehicles in front and not overtake.

The rationale behind the choice of these driving tasks was to examine the effect of soil nail firing on drivers who were presented with a relatively simple driving task, and who may as a result have a relatively low degree of alertness. The overtaking mode requires greater concentration, and the drivers may therefore be more alert to the driving task required, which in turn could influence their reaction to soil nail firing noise.

The simulated drive on this trial was along a 40km section of motorway with roadworks at approximately 16km and 36km from the commencement of the 'journey'. All subjects drove exactly the same route. The first part of the trial was a practice session where the subjects were instructed as follows:

'The vehicle is operating with an automatic gearbox. We will start with a practice session. Please start the car, select first gear, release the hand brake and drive as you would normally. You should start off by driving slowly at first until you have become used to the handling of the vehicle.'

After 10km (approximately 5-7 minutes of driving time) they were told:

'Thank you, that is the end of your practice session. Please stop the vehicle on the hard shoulder, put the handbrake on and switch the engine off. Please wait in the car.'

The simulated scene was reset to the beginning of the route and they were then instructed:

'How do you feel – are you happy to start the trial now?'

When they responded positively, and all drivers did, they were then instructed:

'Please adjust your rear view and side mirror so that you will be able to see the vehicles behind you in the outside lane.'

I would like to remind you that the vehicle is operating with an automatic gearbox. You will be driving along about 30 miles of motorway some of which will be through roadworks. During this time there may be some distractions, but you should continue to drive until asked to stop.'

Please start the car and drive as you would normally for motorway conditions, maintaining normal motorway speeds and overtaking vehicles as you consider appropriate.'

Approximately 16km from the start of the drive the subjects were required to drive past approximately 1km of roadworks being undertaken on the hard shoulder. The motorway, having a rolling landscape, had the nearside

lane coned off requiring drivers to drive in either the middle or outside lane.

At 22km they drove past an embankment on the left-hand side of the motorway resembling an area where roadworks had just been completed, at 27km a similar area was encountered with banks on both sides of the motorway and at 31km on the right-hand side only.

At a point 36km into the trial a second set of roadworks was encountered which was an exact repeat of the first roadworks but this time with embankments on both sides and one soil nail firing machine in addition to the plant in the previous roadworks. At the point of passing the soil nail firing machine the pre-recorded sound was triggered by the controller.

At the point of the soil nail firing sound some of the subjects asked the experimenter what the noise was, others asked whether they should stop. In view of the fact that their original instructions had been 'During this time there may be some distractions, but you should continue to drive until asked to stop' the experimenter ignored all questions and left the subjects to decide what actions to take. Some subjects decided to pull over on to the hard shoulder and were allowed to do so – full observation of their action took place and finally when it was felt that their total reaction had been observed they were asked to continue to the end of the drive.

The subjects drove a further 3km from the point of the soil nail firing before being told:

'Thank you that is the end of the trial. Please slow down and stop the vehicle on the hard shoulder, put the hand brake on and turn the engine off.'

They remained in the car for a short while so that their reactions could be further observed. Finally when they were being escorted from the car the experimenter was careful not to become involved in conversation relating to the trial.

The subjects then completed a questionnaire regarding their experiences.

Finally they were shown the following statement.

'Thank you for taking part in this experiment and for helping us in our research. The maximum noise level experienced in the experiment is well within the safe limit stipulated by law.'

The purpose of the experiment is to investigate the effect on driving performance of sudden loud noises. We are assessing the effect of using certain machinery at motorway roadworks.

It is therefore particularly important that you do NOT divulge this to anyone who is likely to take part in the experiment.'

5.7 Simulator data collected

Data, as listed below, was recorded throughout each subject's trial at a frequency of approximately 15 times per second:

Position on road, denoted by x & y coordinates.

Speed in metres/sec.

Lateral distance in metres from the centre of the road.

Brake pressure (percentage of a maximum pressure which registers at 800 Newtons).

Accelerator pedal (percentage of maximum position available).

Steering wheel position from vertical in radians.

The facial expressions and upper body movements of each subject were videoed during each trial. These videos were analysed by one person for facial response, their driving reactions and any verbal response at the time of the soil nail firing.

6 Results and analysis

As described above, subjects 'drove' along a 40 km route which included two sets of road works, positioned as follows:

1st set – between 16.2 km and 17.2 km

2nd set – between 36.2 km and 37.2 km

The soil nail firing noise was activated at the same point for each subject, at a distance of 36.7 km from the start of the drive ie exactly half-way through the second set of roadworks. Simulator output was produced for each of the 33 subjects, however, only 31 complete records were obtained.

In reviewing the data obtained from the simulator it was clear that the driver behaviour effects that could possibly be attributed to the onset of nail firing noise varied greatly from a very small or nil effect to substantial changes involving lane changing and, in some cases, stopping the car. In consequence it was decided to carry out an analysis of the data in two parts.

In the first part, the whole sample of drivers was considered and statistical comparisons made of driving behaviour before and after the noise. A subset of the data which excluded the motorists who stopped the car were also analysed. These results are presented in section 6.1.

Secondly, the cases that were identified which involved some significant change in driving behaviour were analysed in more detail. For these cases, the responses from the video recording and questionnaire were used to aid the analysis of behaviour. This aspect of the analysis is presented in section 6.2

6.1 Average effect of soil nailing noise on driver reactions

An analysis of speed, acceleration, braking, lateral deviation, and steering wheel movements has been carried out, and a comparison made between the first (control) set of roadworks and the second (experimental) set and, within the second set, between driver behaviour before, and after, the sound of the soil nail firing was heard.

Overall means for the 31 subjects, where complete records were available and for each of the above conditions, have been calculated over the following distances from the start of the trial:

- 1 16.2 km to 18 km (FIRST SET OF ROADWORKS)
- 2 36.2 km to 38 km (SECOND SET OF ROADWORKS)
- 3 36.2 km to 36.7 km (BEFORE NAIL FIRING NOISE)
- 4 36.7 km to 37.2 km (AFTER NAIL FIRING NOISE)

For the comparison of the two set of roadworks, a distance of 0.8 km has been added to the averaging range in order to include the effect of the nail firing noise on driving behaviour immediately after the roadworks finished.

It should be noted that there were two lanes available for subjects to drive in while going through both sets of road works. Consequently, the subjects could change lanes during these periods of the drive. Whether or not this occurred was dependent, to some extent, on the influence of the other traffic using the road. However, since such probabilities of such events occurring were the same for both sets of roadworks it is reasonable to assume that, when taking the sample of drivers as a whole, any influence of lane changing, due to random variations in traffic, would not produce systematic differences in the calculated means.

However, as indicated above, some drivers also moved over to the hard shoulder and stopped the car following the noise event. Consequently, it was felt that by including these gross effects in the overall averaging process they could overpower the more subtle effects that were exhibited by the other drivers. Consequently, a subset (subset A, 24 subjects) was created which excluded the 7 drivers who stopped their cars. Statistical comparisons of the different driving measures for both the full sample and the subset are given in sections 6.1.1 to 6.1.5 below⁴.

6.1.1 Lateral deviation

Lateral deviation was measured in metres from the centre of the middle lane on the motorway. By averaging the position taken by the test vehicle through the distance ranges specified above, a measure of change in lateral deviation was obtained. The results obtained, together with the standard errors of the means, for the whole sample, are given in Table 2.

**Table 2 Mean lateral deviation
(31 subjects, - to right, + to left)**

	<i>First roadworks</i>	<i>Second roadworks</i>	<i>Before noise</i>	<i>After noise</i>
Mean deviation (SE)	-0.62 (0.45)	-0.21 (1.26)	-1.33 (0.94)	0.21 (1.47)

These results indicate that the subjects drove through the second set of roadworks rather more erratically than through the first. It can also be seen that, for the second set of roadworks, the average trajectory driven by the sample of motorists prior to the noise event was 1.33m to the right of the centre line and 0.21m to the left of the centre line after the noise event.

The difference in the mean lateral deviation before and after the nail firing noise was found to be statistically significant at the 5% level.

At this juncture, it is important to point out that the mean lateral deviation was calculated over a 500 metre section of road and, if subjects do react to the noise, it is possible that the main reaction occurs within a relatively short range after the event, say 20-50 metres from the position of the noise source. In such cases, any reaction over this range would only represent 10% at most of the sampled section and the mean would not be expected to be very sensitive to such changes.

The analysis has therefore been repeated using the standard deviation for the lateral position as the metric for all subjects as well as for the subset described above. This metric is more suitable because if subjects do deviate greatly over a short distance then this will have a greater effect on the SD than on the mean.

Table 3 Average SD of lateral position

	<i>Prior to noise</i>	<i>After noise</i>	<i>Differ -ence</i>	<i>Pooled standard error</i>	<i>Signifi -cance of change</i>
All subjects (31)	0.39	1.66	1.26	0.17	99%
Subset A (24)	0.39	1.38	0.99	0.15	99%

It can be seen that in terms of the SD metric there was significantly more variation in lateral position after the noise for all subjects considered as well as the subset which excluded those drivers who stopped the vehicle.

6.1.2 Steering wheel position

The roadworks were on a straight stretch of motorway so in normal circumstances one would not expect the steering wheel to be moved from the vertical by more than a small amount. The results of averaging the steering wheel position for all subjects are given in Table 4.

**Table 4 Average steering wheel position
(31 subjects, - to right, + to left)**

	<i>First road -works</i>	<i>Second road -works</i>	<i>Before noise</i>	<i>After noise</i>
Mean position in degrees from vertical (SE)	0.51 (2.12)	1.31 (7.03)	-0.25 (0.64)	1.87 (9.03)

Differences in mean steering wheel positions for the first and second set of roadworks and before and after the noise were not statistically significant.

As for lateral deviation above, the analysis of steering wheel position has been repeated using the standard deviation as the metric for all subjects and for the subset of drivers who did not stop. These results are given in Table 5.

When all drivers were considered together, variability of steering wheel position increased significantly after the noise event. However, when those drivers who stopped their vehicles were removed from the analysis, there was found to be only a small, non-significant change in average variability.

Table 5 Average SD of steering wheel position

	<i>Prior to noise</i>	<i>After noise</i>	<i>Difference</i>	<i>Pooled standard error</i>	<i>Significance of change</i>
All subjects (31)	4.73	15.92	11.19	4.80	95%
Subset A (24)	4.37	4.41	0.04	0.34	N/S

6.1.3 Acceleration

The results of an analysis of the mean accelerator pedal position for the before and after noise conditions are given in Table 6. In this case there was a significant increase in pedal position following the noise event for both the full sample and the subset.

Table 6 Average use of accelerator pedal (Pedal position as a percentage of maximum depression)

	<i>Prior to noise</i>	<i>After noise</i>	<i>Difference</i>	<i>Pooled standard error</i>	<i>Significance of change</i>
All subjects (31)	9.87	13.59	3.71	0.97	99%
Subset A (24)	10.47	15.01	4.54	1.05	99%

6.1.4 Braking

The data related to brake pedal pressure, for the two sets of roadworks, is summarised in Table 7. There was considerably more use of the brake pedal through the second set of roadworks than through the first, and, during the second set, a notable increase in use following the noise event. The differences were significant at 5% level.

Table 7 Average brake pedal pressure applied (31 drivers)

	<i>First road-works</i>	<i>Second road-works</i>	<i>Before noise</i>	<i>After Noise</i>
Mean brake pedal pressure as % of maximum pressure (SE)	0.03 (0.07)	1.67 (3.91)	0.02 (0.02)	2.11 (4.93)

Further analysis of the results for the second set of roadworks reveals that average brake pedal pressure was considerably affected by the 7 drivers who stopped their vehicle after the noise since when the same analysis was carried out for subset A there was only a very small difference in mean brake pressure before and after the noise.

6.1.5 Speed

There was no significant difference in mean speed, for all subjects, between the first set of roadworks and the second. Mean speeds during the second set of roadworks, before and after the noise, are shown in Table 8.

In this comparison it can be seen that when all drivers are considered the average speed dropped slightly after the noise event although this was not found to be statistically significant. However, when the drivers who stopped were excluded from the analysis the average speed was found to

Table 8 Average speed (m/s)

	<i>Prior to noise</i>	<i>After noise</i>	<i>Difference</i>	<i>Pooled standard error</i>	<i>Significance of change</i>
All subjects (31)	21.98	21.27	-0.72	0.77	NS
Subset A (24)	22.72	24.02	1.30	0.42	99%

increase after the noise event, the increase being statistically significant at the 1% level. Clearly, including the drivers who slowed and stopped the test vehicle had a marked effect on the mean speed after the noise event. This was sufficient in this case to mask the more general increase in speed exhibited by the majority of drivers.

6.1.6 Summary of average effects

Overall it is difficult to draw firm conclusions from the results of this part of the analysis. As might be expected, the inclusion in the sample of drivers who carried out gross manoeuvres following the noise event and pulled over to the hard shoulder did affect the overall statistical analysis for several of the factors examined. However, for the drivers who appeared to drive fairly normally through both sets of roadworks it was found that there were small but systematic changes in driving behaviour after the nail firing noise. The analysis revealed that the trajectories taken by drivers were generally more erratic after the noise event and there was a greater use of the brake and accelerator pedal. Average speeds also increased after the noise event.

6.1.7 Questionnaire

The questions asked after each drive, and a summary of responses given, are listed below.

In general, how realistic did you find the simulator?

Response	No.
Very Good	6
Good	13
Moderate	11
Poor	3
Very Poor	0

In general, how comfortable did you find it to drive the simulator?

Response	No.
Very Good	0
Good	5
Moderate	11
Poor	15
Very Poor	2

Did anything happen that distracted you while you were driving in the simulator?

Response	No.
Simulator Problem	4
Tyre Blowout	9
Loud Bang or Siren	19

How much did this interfere with your driving?

Response	No.
Not at all	11
Somewhat	18
Considerably	4

If you had been driving your own car on a normal road, how likely is it that your driving would be affected?

Response	No.
Not at all	13
Somewhat	18
Considerably	2

Which of the following best describes how you are feeling after the experiment?

Response	No.
Stressed	10
Tired	12
Relaxed	11
Refreshed	–

Is there anything else you would like to say about the simulator, or about any distractions you experienced while driving it?

Principal Response	No.
Signs indistinct or unclear	18
Vehicle handling not realistic, simulator felt strange	7
Other/None	8

6.1.8 Video analysis

Facial expressions, upper body movements, and verbal responses, were noted from the video recordings and overall response was categorised by the analyst as:

- None — carried on driving with no obvious visual or verbal response.
- Slight — jumped slightly or pulled a face.
- Medium — more noticeable visual or verbal response and/or stopped.
- Severe — spoke/asked a question *and* jumped *and* stopped.

Results were as follows:

Table 9 Visible response to noise simulation

Overall response			
None	Slight	Medium	Severe
5	12	13	3

6.2 Case studies of drivers with significant reactions to soil nail firing noise

The previous analysis provides information about changes in certain aspects of the driving function averaged over the driver sample, over the first and second sets of roadworks, and over 0.5 km segments of road immediately preceding and following the noise event. The average changes observed were found, in some cases, to be significant and all drivers noticed the noise, with a high proportion

claiming that it caused or would have caused some effect on their driving.

Although these results give some insight into general driving behaviour changes, they do not provide information on individual driver performance changes. To obtain this more detailed information it was decided to examine a subset of individual driving patterns for those drivers who had exhibited the most significant reactions of the sample studied.

Of the whole sample of 33 runs, three cases were identified where the vehicle deviated from its normal path by a substantial degree, or where sudden changes in vehicle speed or unpredictable manoeuvres took place.

The three cases were:

Subject 16 — a 59 year old woman.

Subject 18 — a 33 year old man.

Subject 20 — a 46 year old man.

These are described in detail in the following sections.

6.2.1 General

For each case study the simulator output is given covering the section of the drive from 0.5 km before the noise event to approximately 1.3 km (1.2 km for case study 1) after the noise event. The simulator outputs include a full record of the speed of the vehicle and the lateral position in the road adopted by the driver (lateral deviation is measured from the centre line of the middle lane on a three lane motorway, - to the right and + to the left, and a lateral deviation of around 3 metres would indicate a change of lane). At the foot of the figure is included summaries of speed, deviation, brake pressure and acceleration for the before and after road segments included in the figure.

6.2.2 Case study 1

This subject was a 59 year old lady. Figure 6 details the simulator output for this subject which shows that on

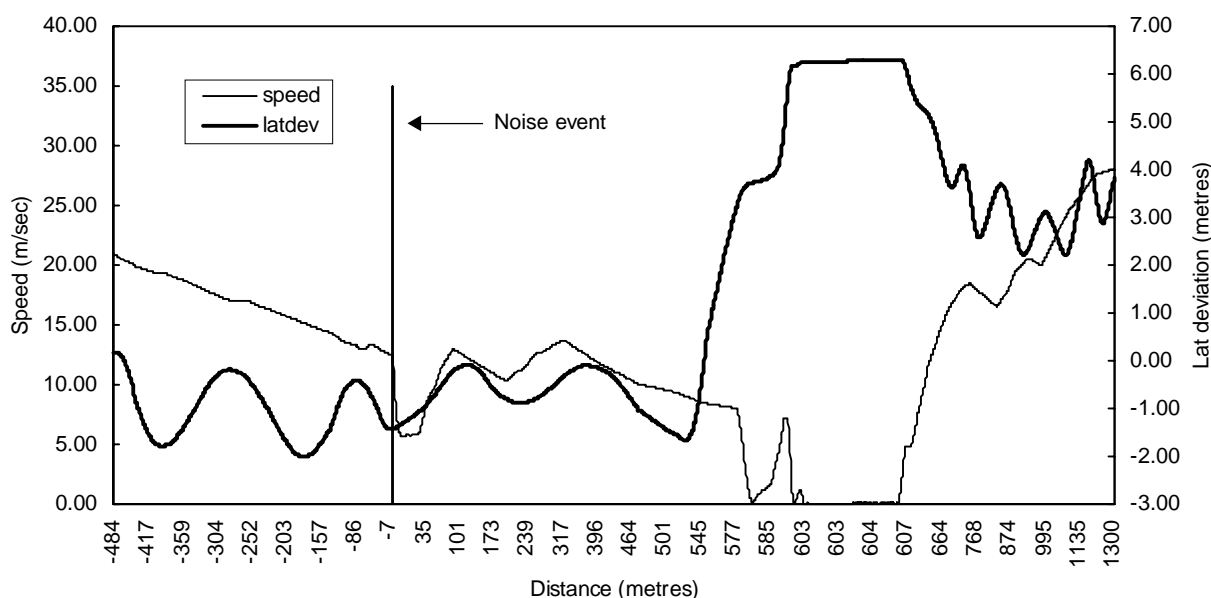


Figure 6 Simulator output for Case Study 1

entering the road works the driver began to decelerate from an entry speed of about 20m/sec, and that by the time the noise event was triggered, was travelling at 13m/sec.

On hearing the noise the driver braked to approx. 5.5m/sec then accelerated to between 10 & 14m/sec before pulling onto the hard shoulder and stopping once the roadworks had been exited.

After asking the simulator operator what to do next the car was restarted and the driver pulled out into the nearside lane although lateral position on the road was erratic as speed increased.

The video record showed that the driver appeared to 'jump' on hearing the noise, and the video analyser gave an overall assessment of reaction to the noise as 'severe'. During the questionnaire the driver said that she thought the loud bang was due to a tyre blowout.

6.2.3 Case study 2

This subject was a male of 33 years of age. The output from the simulator for this subject is shown in Figure 7. It shows that following the noise event the driver decelerated from 21m/sec to a complete stop. The driver drove through a gap in the cones on hearing the sound thinking that a tyre had burst.

The most interesting aspect of the simulator output is that this driver's reaction prior to the incident and subsequent to restarting the vehicle was quite normal, the movement to the right which occurred approximately 1km after the sound merely corresponding to a lane change as the roadworks ended.

No verbal or facial response was noted from the video recording and the overall reaction was rated by the analyst as 'medium'. From the completed questionnaire, however, the driver 'never felt 100%' and stated that the sound of the fired soil nail had a considerable impact on his driving behaviour.

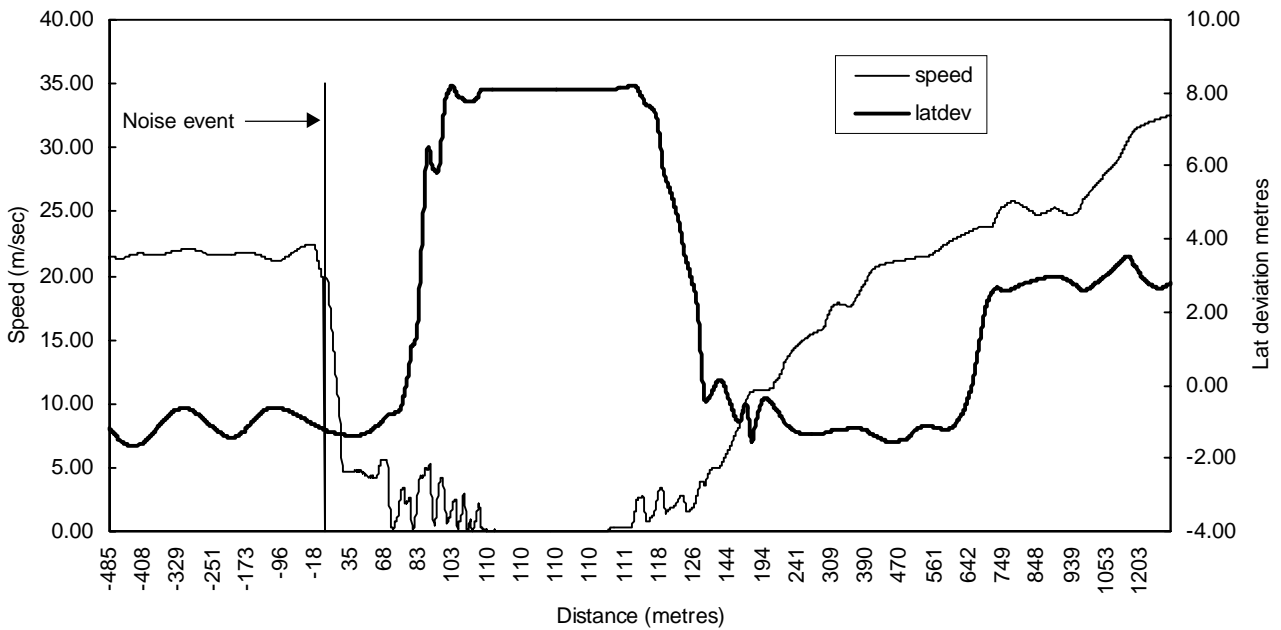


Figure 7 Simulator output for Case Study 2

6.2.4 Case study 3

This subject was a male of 46 years of age. The simulator output is shown in Figure 8. Interestingly this driver increased speed slightly as he progressed through the roadworks. On hearing the nail firing noise he drove through a gap in the cones. The completed questionnaire does not indicate the reason for this behaviour, although, at the time, the driver said he suspected that a tyre blow-out had occurred and asked the operator what he should do next. He then carried on apparently undisturbed and, 0.9km after the end of the roadworks, changed lane and accelerated to overtake another vehicle.

The video record did not show any substantial visual

response and the overall reaction to the noise was described as 'medium' by the analyst. The driver commented, on the questionnaire, that he had increased his speed on approaching the roadworks due to the lack of clarity in signing.

7 Discussion

7.1 General

It is clear from the results of noise measurements taken of nail firing that the peak levels generated can be far in excess of the upper limits specified by the Health and

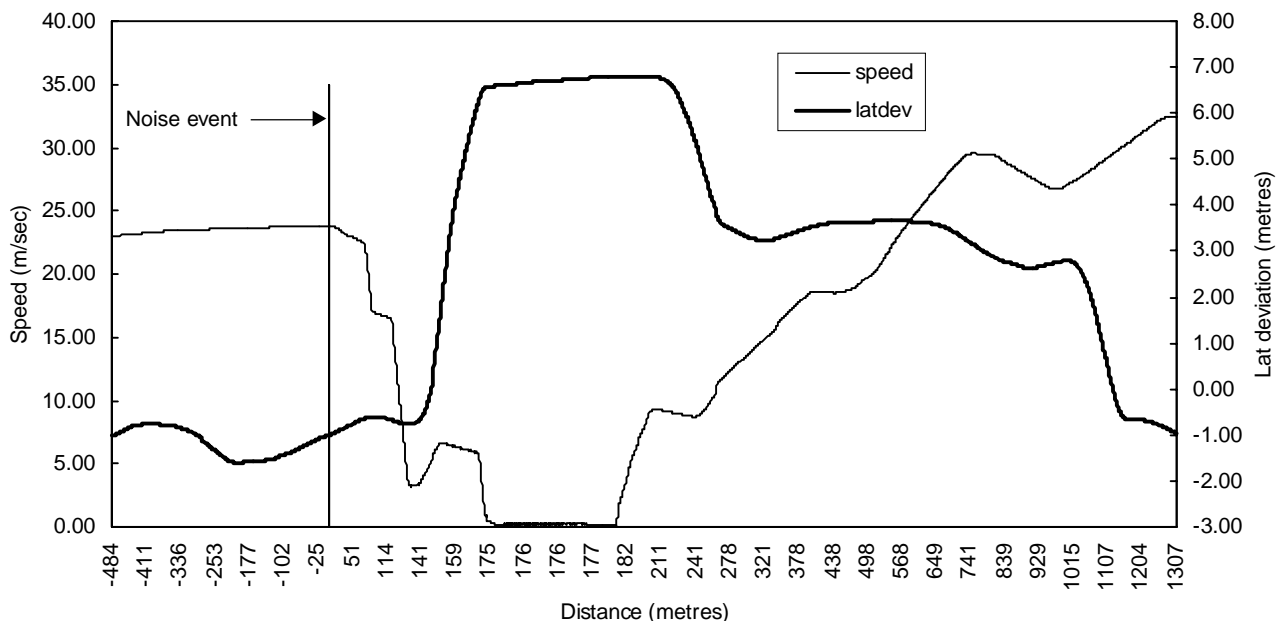


Figure 8 Simulator output for Case Study 3

Safety Executive's Noise at Work Regulations. Clearly the operators of this equipment need to take special precautions to protect their hearing and, in its present configuration, its use alongside trafficked roads should be limited. Fitting a silencer device to the launcher did not produce substantial reductions in noise although a measurable benefit of about 2 dB (A) was noted.

However, the noise level does fall off fairly rapidly with distance at a rate which approximates the inverse square law (ie approximately 6 dB reduction for each doubling of distance) and at approximately 25m from the nail launcher the peak noise should be just below the hearing damage limit. Clearly at further distances then the level would fall progressively below the limit.

In this study the scope suggested that the experimental design required should approximate a near worst case situation. This was taken to be the condition where the nail firing launcher was positioned 7m from a flow of traffic at the nearest point. This was taken to represent the condition where the launcher was operating on a roadside embankment with traffic flowing on the nearside lane.

The noise levels used in the simulation, however, were chosen to be significantly below those recorded from the actual launcher since, at the 7m distance, the actual noise levels were higher than those recommended for safety reasons. Clearly, in practice it would not be possible to operate the launcher with significantly higher exposure levels due to the risks imposed on the general public and so for practical reasons it would not have been sensible to carry out experiments with higher noise exposure levels even if it were conceivably possible to do so.

By exposing subjects to these lower levels the implied rationale adopted was to establish whether there was an adverse reaction at levels close to the legal limit. A positive reaction would indicate that further noise reductions would be needed before the operation could be regarded as safe whereas a negative reaction would indicate an upper limit where the equipment could be safely used.

The results of the study clearly showed that at the levels of exposure studied there were systematic changes to the driver behaviour measures examined and, that for some of the drivers, there were behaviours that could give rise to increased accident risk. The driver that slowed rapidly following the noise event would clearly affect safety if this occurred in real traffic and particularly if this occurred on a high speed road. Additionally drivers who interpreted the noise event as a punctured tyre and subsequently drove through the construction site to park on the hard shoulder were carrying out manoeuvres which unnecessarily raise the level of risk of an accident occurring. This would naturally occur both as a result of the initial manoeuvre and as a result of the vehicle rejoining the traffic stream.

It seems reasonable therefore to conclude that there are safety concerns with exposing drivers to this level of nail firing noise and that significant further reductions in noise would be needed before the equipment could be regarded as safe for roadside use. A further concern could be introduced if the equipment were used with launch angles other than vertical. The measurements showed a

significant increase in noise for the launcher positioned horizontally and pointing at 90 degrees to the line of traffic than when operated vertically.

7.2 Further work indications

i *Noise exposure limits*

Although the results obtained have provided useful insight into the effects of a loud impulsive noise on driver response, it has not been able to indicate what levels would be needed to achieve no significant effects. Clearly, the levels needed would have to be below the 137 dB used in this study but how much lower is still an unanswered question. Further work using different exposure levels would provide the information required.

ii *Signing*

It is possible that some degree of modified behaviour could result if a greater degree of warning were given to motorists approaching the site. Clearly, drivers who are expecting a loud bang would be less likely to interpret the noise event as a puncture or vehicle malfunction. Such warnings could be given by a sign which could be illuminated to increase conspicuity. However, it is known that not all motorists see important signs and so this method of control could not be seen as a complete solution. In addition, it should be noted that the noise event simulated in this study was accompanied by a warning siren which may have had some effect on raising awareness but clearly did not provide a satisfactory solution for all motorists tested.

Further work with the use of signs could show whether they were effective in modifying adverse driver behaviour responses.

iii *Silencing and screening*

It follows that the nail firing equipment in its present form could only be used at some considerable distance from the operating traffic although as mentioned above the precise distance/noise level has yet to be determined. Further work on silencing the device would be needed if the nail firing equipment was to be used at the roadside with traffic operating in the nearside lane. Screening of the noise source may be possible using portable screens positioned around the launcher. Alternatively further treatment to the pressure changes occurring at the exhaust of the firing mechanism might be possible. Again further research could examine different forms of noise control and help determine a cost effective solution.

8 Conclusions

In summary, the results of the study have shown:

- i that the noise levels from the noise firing operation were found to be, on average, 149.4 dB at 7m distance from the unsilenced equipment and 147.6 dB from the same equipment fitted with a silencer;
- ii these noise levels were well in excess of the 200 Pascal (140 dB) limit specified in the Health and Safety Executive Noise at Work Regulations;

- iii that at these levels it would be expected that the driving behaviour of motorists would be affected to an extent which could compromise traffic safety;
- iv substantial additional silencing or screening of the equipment would be needed before it could be used safely at locations positioned alongside a stream of traffic.

9 Acknowledgements

The authors would like to thank Graham Grayson, Gavin Buckle and Barry Sexton for their advice and assistance in the preparation of this report.

10 References

Beranek L L (1988). *Noise and vibration control*. Institute of Noise Control Engineering, Washington DC, USA.

British Standards Institution (1994). *BS EN 60651 : 1994 (IEC 651 : 1979) Specification for Sound Level Meters*. British Standards Institution, London.

British Standards Institution (1981). *BS 6086 Method of measurement of noise inside motor vehicles*. British Standards Institution, London.

Curio I and Michalak R (1993). *Results of a low altitude flight noise study in Germany: acute extra-aural effects*. Shriftner Ver Wasser Boden Lufthyg (Germany), 88 307-21.

Ford J M, Roth W T, Isaaks B G, White P M, Hood S H and Pfefferbaum A (1995). *Elderly men and women are less responsive to startling noise: NI, P3 and blink evidence*. Biol Psycho (Netherlands), Feb 1995, 39 (2-3) 57-80.

Fosse J A, Ison J R, Torre J P Jn. and Wansack S (1989). *The acoustic startle response and disruption of aiming: effect of stimulus repetition, intensity and intensity changes*. Human Factors (USA) June 1998, 31 (3) 307-18.

Health and Safety Executive (1989). *Noise at Work Regulations*. Stationery Office, London.

Thackeray R I, Rylander R and Touchstone R M (1973). *Sonic boom startle effects – report of a field study*. Federal Aviation Administration, Civil Aeromedical Institute, Oklahoma City, USA Report No. FAA-AM-73-11.

Appendix A: A review of noise and startle response research

A review of the literature on startle contains papers on the startle reaction of rats to loud sounds among other stimuli, mostly in journals in the psychological and physiological fields, and work on human startle reaction which appears more generally in relation to sonic booms, gunfire noises from army ranges, the advent of sudden noise from low

flying military jet aircraft and the effect of startle on human behaviour. Much of the reported work on human reaction to impulsive noise is concerned with medical effects related to certain mental or physiological conditions. Some of the more relevant papers concerned with human reaction to impulsive noise are summarised below.

Sonic booms

Much of the work on sonic booms is concerned with the general annoyance caused to neighbouring populations and not specifically with startle response. For example, Fidell and Pearsons (1994) derived dosage-response relationships between C-weighted DayNight Average Sound Level and the prevalence of annoyance with high energy impulsive sounds. However certain studies deal directly with startle response to both real and simulated sonic booms. (Thackeray et al, 1974) reported two studies. The first attempted to determine a sonic boom exposure level below which startle reactions would not occur. Subjects were exposed indoors to six simulated sonic booms having various outside overpressures. In the second study subjects were exposed indoors to a series of 12 simulated booms to assess habituation effects. Automatic and eye-blink responses, as well as ratings of subjective annoyance, were obtained in both studies and the report summarises the expected behavioural, autonomic and subjective effects of exposure to various levels of sonic booms.

Another report (Thackeray et al, 1973) gives the results of a study carried out in Sweden where ten female subjects were tested indoors on each of six days. Two age groups were studied, 20-35 and 50-65 years. Fighter aircraft flying at various heights over the test site produced booms with outdoor overpressures ranging from 60-640 N/sq.m. The number of booms varied from 5 to 13 per day. The subjects performed indoors on a hand-arm steadiness task. The results showed that outdoor overpressures ranging from 70-120 N/sq.m (26-35 N/sq.m indoors) produced reflexive arm-hand movements in about 10 per cent of the subjects. Booms of 300 N/sq.m (67 N/sq.m indoors) and greater produced responses in about 75 per cent of the subjects. Between these extremes of overpressure there was the suggestion of a critical range lying between 150-180 N/sq.m (40-46 N/sq.m indoors) in which an abrupt increase in startle response occurred.

One reference gave a bibliography of 88 citations of research on the effects of sonic booms on humans, animals, birds and fish (NTIS, 1982). Discussions of biophysics, psychoacoustics, stress and auditory tolerances are presented, together with materials on startle responses, disturbance and compression wave reactions.

Impulse noise produced by Army training and operations

A summary of research by the US Army Construction Engineering Research Laboratory (CERL) is given in Schomer and Neathammer (1985). The army had to be able to assess the community reaction to impulsive noise from sources like armour, artillery and demolition. This collection of papers summarises 10 years of work by the CERL in the area of community response to impulsive noise. It is based on laboratory tests using a blast noise simulator, a study of army-wide noise complaints and attitudinal surveys

conducted at Fort Bragg in North Carolina and Fort Lewis in Washington. The major conclusions show that an energy type of model such as the C-weighted day/night average sound level (CDNL) is the best available descriptor for community response. There is no specific reference to startle response to military impulse noise.

Military low altitude flying (MLAF)

A recognised startle effect is that caused by noise produced by military aircraft on low-altitude training flights. Such operations are characterised by infrequent, irregular, sudden, short and loud noise events. The American Air Force supported research to determine whether the current methods of annoyance assessment were applicable to noise from low level flight training operations (Wyle Research Report 1992). The results suggested that in addition to the noise levels of the events, their high onset rate (rate of change of noise with time in dB/sec) played a role in determining human annoyance. Berry (1993) discusses onset rate of noise from military aircraft near military airfields.

A German paper by Curio and Michalak (1993) explored the medical effects of MLAF noise by exposing healthy volunteers via earphones to digitally recorded MLAF noise. The objective was to study the relationship between noise parameters (maximum sound level and sound level rise rate) and specific reactions by the individuals affected. Their reactions were studied on various levels ranging from the subjective experience of negative effects, startle reactions and changes in cardiovascular and endocrine systems.

A main finding was that a high rise rate of sound (onset rate) is the physical parameter which leads to more physical symptoms being cited by the subjects and also to more pronounced myokinetic effects of an objectively measurable nature. Studies of circulation physiology were also conducted to throw light on the haemodynamic mechanism of the startle reaction. The findings suggested that increases in cardiac output in a startled subject with a healthy circulation need not necessarily lead to protracted increases in blood pressure. A counter-regulation occurs by means of vasculomotor responses in the muscle. Should this regulatory system be impaired, as may be the case with elderly people, for example, blood pressure increases of up to 45mm Hg over the initial value may ensue.

A sensitisation was observed after repeated exposure, with the startle reaction intensifying or else being triggered off by lower sound levels. The authors state that the sensitisation of startle reactions is neuro-physiologically associated with unpleasant or fear inducing environmental stimuli. Together with the observed increases in plasma hydrocortisone and changes in magnesium metabolism of a type characteristic of stress, this phenomenon of sensitisation enabled the authors to establish a hypothetical link between specific acute reactions to MLAF noise and long term health effects.

Effect of startle on human performance

Some research work has concentrated on measuring the effect of startle on performance with various tasks. The

papers summarised below describe the effects on a target aiming task and a simulated air traffic control task. No papers were found which dealt with the car driving task.

Fosse et al (1989) carried out three experiments to examine the disruption of perceptual motor performance by intense noise bursts. Subjects aimed a rifle at a fixed target for 15 second periods separated by 15 seconds of rest. This cycle was repeated 30 times in each of two series separated by a 15 minute rest, each series containing five noise bursts. The noise bursts disrupted aiming for 1-2 seconds, an effect that increased with sound pressure level for 110, 120 and 130 dB stimuli. There was no difference between stimuli with energy centred on 250 Hz as compared to 800 Hz. Other subjects received 15 trials with 110 dB then five more trials with 130 dB stimuli; the disruption of aiming by 130 dB was not reduced by prior exposure to 110 dB.

A study by Thackeray and Touchstone (1983) employed auditory startle to simulate the principal components (unexpectedness, fear and physiological arousal) that are common to many types of sudden emergencies. It compared performance recovery following startle with recovery following a non-startling stimulus. The subject's primary task was to monitor a simulated air traffic control radar display. Performance recovery following the emergency – a radar failure signalled by either a loud or low level noise – was assessed in terms of response time and error rate on a secondary information processing (serial reaction) task and also in terms of subsequent performance on the radar monitoring task.

The results showed that while the high intensity noise was clearly startling, subjects exposed to the lower intensity noise showed only a surprise reaction, subsequent performance of the two noise exposure groups differed significantly in only two respects. The variance of initial response times was greater in the startled group, and this group had a higher frequency of incorrect responses on the serial reaction task during the first minute following stimulation.

The authors compared these findings with those of other studies of simulated emergencies and concluded that recovery time for simple perceptual-motor responses during the initial shock phase of an emergency is quite rapid (of the order of 1 to 3 seconds) and this appears to be independent of whether or not the emergency is startling and emotionally arousing or simply surprising and unexpected. If the shock phase evokes heightened emotional-physiological arousal as in the case of startle, information-processing ability may be impaired for approximately 30 to 60 seconds following the stimulus event (see also Thackeray (1973) above).

Clinical studies of startle

Clinical studies of startle are concerned with the pathological, psychological and physiological aspects of startle. A selection is summarised to contribute to the background to the subject.

Two papers deal with hyperekplexia, a syndrome of pathological startle response. Saenz-Lope et al (1984) described three cases of startle disease, or hyperekplexia.

Sudden unexpected noises caused the patients to fall rigidly, often injuring themselves but retaining consciousness. This unusual entity, say the authors, differs from startle epilepsy and cataplexy. The second paper (Brown et al, 1991) reported the startle response to unexpected auditory and somaesthetic stimulation in eight patients with hereditary or symptomatic hyperekplexia. The condition was abnormal in its resistance to habituation and in its exaggerated motor response. Both noise and taps to the face and head elicited a normal early blink response, separate from the subsequent true startle reflex. The authors suggest that both the abnormal startle response in hyperekplexia and the normal startle reflex represent pathological and physiological activity in the same brainstem efferent system.

The relationship between Post Traumatic Stress Disorders (PTSD) and exaggerated startle reflex was studied by Walters and Hening (1992). Tremors in PTSD had not been previously well characterised, say the authors, who cited the case of a 67 year old man who had a 46 year history of a noise induced exaggerated startle reflex followed by large amplitude rest, postural and kinetic tremor that persisted up to three days. The authors postulated a psychogenic origin for the noise induced tremor. The patient also believed the tremor to be psychologically based and to be produced by the fear and anxiety he experiences when he hears loud unexpected noises.

Evidence that elderly men and women are less responsive to startling noises than younger people is given in a paper by Ford et al (1995). The authors had observed in earlier work that the P3 component of the event related brain potential (ERP) elicited by startling noises is reduced in the elderly. In the present work twelve younger men and women (mean 22 years) and twelve older (mean 69 years) listened to three sequences of tones and noises. One type of noise (107 dB) occurred in each sequence. Younger subjects blinked to the noise 4-5 times more often than older subjects and had N1 and P3 amplitudes that were 2-3 times larger, regardless of the noise type. Thus even when noises were narrow band and set relative to the subjects threshold, older subjects were less responsive to startling auditory stimuli than were younger subjects (see also Curio and Michalak (1993) above).

References

Berry B (1993). *Environmental impact of military aircraft noise.* Institute of Acoustics, Acoustics Bulletin, Vol 18, No 4.

Brown P, Rothwell J C, Thompson P D, Britton P C, Day B L and Marsden C D (1991). *The hyperekplexias and their relationship to the normal startle reflex.* Brain (UK), Aug 1991, 114 (Pt 4) 1904-28.

Curio I and Michalak R (1993). *Results of a low altitude flight noise study in Germany: acute extra-aural effects.* Schriftenr Ver Wasser Boden Lufthyg (Germany), 88 307-21.

Fidell S and Pearsons K S (1994). *Comparison of methods of predicting community response to impulsive and non-impulsive noise.* NASA, Ames Research Center, *High-Speed Research: Sonic Boom*, (1), 177-189.

Ford J M, Roth W T, Isaaks B G, White P M, Hood S H and Pfefferbaum A (1995). *Elderly men and women are less responsive to startling noises:N1, P3 and blink evidence.* *Biol Psycho* (Netherlands), Feb 1995, 39 (2-3) 57-80.

Fosse J A, Ison J R, Torre J P Jn. and Wansack S (1989). *The acoustic startle response and disruption of aiming: effect of stimulus repetition, intensity and intensity changes.* *Human Factors* (USA) June 1989, 31 (3) 307-18.

NTIS (1982). *Aircraft sonic boom: biological effects, 1964-1982, citations from the NTIS data base.* PB83 – 800664 NTIS Issue 8300. National Technical Information Service, Springfield, Va, USA.

Saenz-Lope E, Herranz-Tannaro F J, Masdeu J C and Chacon Pena J R (1984). *Hyperekplexia: a syndrome of pathological startle responses.* *Ann Neurol* (USA) Jan 1984, 15(1) 36-41.

Schomer P D and Neathammer R D (1985). *Community reaction to impulse noise.* A final 10 year research summary. Army Construction Engineering Research Laboratory, Champaign, II, USA, Report No. CERL-TR-N-167-REV.

Thackeray R I, Touchstone R M and Bailey J P (1974). *Behavioral, automatic and subjective reactions to low and moderate level simulated sonic booms: a report of two experiments and a general evaluation of sonic boom startle effects.* Federal Aviation Administration, Office of Aviation Medicine, Washington DC, USA, Report No. FAA-AM-74-9.

Thakeray R I, Rylander R and Touchstone R M (1973). *Sonic boom startle effects – report of a field study.* Federal Aviation Administration, Civil Aeromedical Institute, Oklahoma City, USA, Report No. FAA-AM-73-11.

Thackeray R I and Touchstone R M (1983). *Rate of initial recovery and subsequent radar monitoring performance following a simulated emergency involving startle.* Federal Aviation Administration, Office of Aviation Medicine, Washington DC, USA, Report No. FAA-AM-83-13.

Walters A S and Hening W A (1992). *Noise induced psychogenic tremor associated with post traumatic stress disorder.* *Mov Disord* (USA), Oct 1992, 7 (4) 333-8.

Wyle Laboratories (1992). *The effect of onset rate on aircraft noise annoyance.* Research Report WR 92.

Notes

- ¹ Peak linear noise level describes the instantaneous pressure level at the peak of the sound pressure wave. This measure is usually used in the context of assessing hearing damage risk from impulsive noise sources in the work place. The Noise at Work Regulations (HMSO, 1989) state that peak sound pressure in excess of 200 Pascals should not be allowed to reach the unprotected ear. When peak sound pressure level is expressed in decibels 200 Pascals is equivalent to level of 140 dB.
- ² National Accreditation of Measurement and Sampling
- ³ The speed limit in the simulated scenario was 50 mph on the section of carriageway on which the soil nailing machine was located.
- ⁴ In the analysis paired 't' tests have been used to test whether two measures are statistically different. This form of the 't' test eliminates the between subject variability and the tests are therefore more sensitive than grouped 't' tests.

Abstract

This study was commissioned by the Highways Agency to determine whether the noise generated by the firing of soil nails into embankments presents a safety hazard to road users.

Fired soil nails provide a rapid means of stabilising shallow earthwork slips on the trunk road network thereby minimising traffic disruption to road users. However, the process of firing soil nails into the ground involves the generation of a sudden loud noise which may startle passing motorists and thereby present a safety hazard.

TRL has carried out experiments in its driving simulator to determine drivers' reactions to an unannounced simulated nail firing noise and has deduced whether the sudden noise is likely to present a safety hazard to drivers.

The results show that the noise levels generated at 7m from the firing device fitted with a silencer was well in excess of the 200 Pascal (140dB) sound pressure limit stipulated in the Health and Safety Executive Noise at Work Regulations. Noise levels measured before the silencer was fitted were, on average, 1.8dB greater for comparable measurements. The startle effect of the noise was such as to be capable of adversely affecting the driving behaviour of motorists, and thereby make the operation (without further silencing) hazardous for the site layout conditions investigated.

Related publications

TRL332 *Road layout design standards and driver behaviour* by G Maycock, PJ Brocklebank and R D Hall.
1998 (price £35, code H)

TRL198 *In-car equipment to help drivers avoid accidents* by J Broughton and K A Markey.
1996 (price £35, code H)

CT80.1 Driver behaviour update (1995-1997). *Current Topics in Transport: selected abstracts from TRL Library's database* (price £20)

Prices current at January 2000

For further details of these and all other TRL publications, telephone Publication Sales on 01344 770783 or 770784, or visit TRL on the Internet at <http://www.trl.co.uk>.

