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DRIVER BEHAVIOUR IN RESPONSE TO ACTIVELY ILLUMINATED ROAD STUDS: A SIMULATOR STUDY

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Executive summary

Each year across the European Community, around 55,000 people are killed and 1.7m are injured in road accidents at a cost of around €50bn. A disproportionate number of the fatalities occur on roads at night. The study described in this report examines a potential improvement to road safety at night that may be achieved through the introduction of actively illuminated road studs (‘Active’ studs) in place of standard retroreflective studs (‘Passive’ studs). An introduction section examines current and previous research that has been conducted to investigate the effect of using illuminated road studs and sets the scene for this study.

TRL’s full mission driving simulator was used to create a length of rural A-road on which participants’ behaviour was assessed. Thirty six participants were recruited from three age groups: Younger (17-25 years), Middle (26-54 years), and Older (55+ years) to complete the trial. Each participant drove a 37.1km trial route twice. The trial route had lead-in and run-out sections but the test section that was used for comparing across stud conditions comprised six repeats of a basic trial section (three of which were the basic section rotated through 180°). Rotating the basic section reduced participants’ awareness that they were driving through the same corners repeatedly. There were six corners in the basic section where the curve radius fell below 150m. These were the six critical corners used for more detailed analyses.

In each drive, the participant experienced a simulated night-time environment and the road had sections with no studs and sections with studs. In one of their drives, the studded section had active studs; in the other drive it had passive studs. The studs were placed at varying intervals (based on the road characteristics) along the centreline of the road. Additional red studs (in both the active stud and passive stud versions) were placed on the nearside of the four sharpest bends in the repeat section used to create the trial route. The driven vehicle used dipped headlights throughout and no other traffic was present in the simulation. The simulator recorded at 20Hz a variety of information about the way the vehicle was controlled through the trial.

Participants completed a pre-trial questionnaire that recorded their background and driving information before driving the simulator and they also completed a post-trial questionnaire that recorded their subjective feelings towards each of the stud conditions that they had observed (no studs, passive studs, active studs) once they had completed their two drives. Picture cue cards were used to remind participants of the environments that they had seen in the trial.

Results demonstrated that in each age group, participants’ average speed when driving the simulator vehicle was significantly higher (by around 3mph) in both the studded conditions relative to the no stud condition. However, there were no significant differences between the active and passive stud conditions across the age groups in terms of overall speed. Assessment of how participants controlled the lateral position of the vehicle revealed that older participants spent significantly less time with the right edge across the centreline of the road with active studs than they did with passive studs.

More detailed analysis of results focussed on behaviour in each of the critical corners. It was found that in the left turns there was a significant difference between participants’ speed with passive and active studs whereby participants from the younger and older age groups drove around 1-1.5mph faster. However, it was also observed that when the minimum speeds attained by participants through each corner were compared, the significant differences between the passive and active stud conditions disappeared. This suggests that participants’ reduced their speed for the corners to around the same value in both conditions whilst analysis of braking revealed that there were no significant differences in the harshness with which the brakes were applied across the passive and active stud conditions. Analysis of the position at which maximum braking was applied revealed that in right turns, participants in both the Younger and the Older age groups appeared to brake at a more consistent position when the active studs were present than in the passive or the no stud conditions. This suggests that participants were better informed about how they needed to control the vehicle in order to negotiate the bends when the active studs were present.

Analysis of drivers’ lateral position in the corners revealed a marked difference between the passive and active stud conditions in right turns. It was found that drivers kept the right side of their vehicle

significantly further from the centreline in right turns with active studs than they did with either passive studs or no studs. Further analysis looking at the minimum distance to the centreline revealed that, in terms of safety, it was the older drivers that appeared to maximise this advantage. A possible explanation for the advantage shown for active studs in right turns is the increased visibility of nearside studs afforded by right turns relative to left turns. It is therefore suggested that enhanced delineation of the offside road edge may cause similar improvements in drivers' lateral control of their vehicle in left turns as that seen in right turns.

Broughton & Buckle (TRL Report 653, 2006) reported that loss of control was the only precipitating factor in the causation of accidents (of all severities) that had shown a significant increase since 1999. The results from this trial suggest that the Active stud installation that drivers observed in the simulator improved their control, particularly in right turns and for Older drivers. It is therefore possible that the introduction of active road studs may help to reverse this trend.

The questionnaire revealed that participants had highly positive views in relation to active studs. All age groups rated that they felt their experience with active studs was significantly more safe, more confident, more comfortable, and more in control than with either the passive studs or with no studs in place. Participants' even reported that they felt the active studs made the line markings more useful in helping them to guide their vehicle along the rural A-road. Although both passive and active studs were rated as being very useful in helping vehicle guidance, the active studs achieved significantly higher ratings than the passive studs. Active studs appeared to raise participants' confidence levels close to those that they have when driving in the daytime. Participants reported that active studs encouraged them to drive faster than they would normally. However, this is contradicted by the simulator data, which showed that there were only very slight increases in speed with active studs. Participants reported that they believed active studs would be highly beneficial to road transport and road safety.

The STATS19 database is compiled by the Department for Transport (DfT) and is a system for recording data on personal injury road accidents, resulting casualties, and the vehicles involved. Accidents are those which occur on the public highway and which become known to the police within 30 days. Accidents in the years 2000-2004 were analysed to look at the profile of drivers typically involved in accidents on A-roads at night. It was found that the majority of accidents involve the middle age group. However, it is the younger driver population that, relative to the number of journeys they make by car, are over-represented in the accident statistics.

It is concluded that active studs offer a significant safety advantage over standard passive retroreflective studs since they appear to improve lane guidance in right turns without causing drivers to proceed at higher speeds. This benefit appears to affect the older driver population most positively; however, this group is responsible for the fewest accidents on rural A-roads at night, mitigating the benefits that active studs provide. In subjective assessments, participants across all age groups viewed the potential installation of active studs very positively and this could be an important factor in their post-installation acceptance.

1 Introduction

Each year across the European Community, around 55,000 people are killed and 1.7m are injured in road accidents at a cost of around €50bn. A disproportionate number of the fatalities occur on roads at night. Although only 25% of all driving is performed during the hours of darkness, 55% of all road deaths occur in this period. This suggests that the reduction in information available to drivers at lower light levels is a source of increased risk for the driver.

There are three approaches that could be taken to improve driving safety at night. Firstly, one could focus on the specific behaviour of the driver to investigate whether there are particular actions or conditions that increase risk, for example, one could investigate the onset of fatigue. Secondly, one could investigate whether there were safety benefits through the introduction of new technologies to the driven vehicle, such as improved headlight performance. Thirdly, one could examine the driving environment to examine whether changes to the road surface or layout affected safety. The study described in this report examines a potential improvement to road safety at night under this third approach. Using TRL's full mission driving simulator, it examines whether the introduction of actively illuminated road studs on a rural A-road has any effect on drivers' behaviour that may lead to improved road safety.

1.1 The Problem

As traffic levels on the road network grow, developing new methods to ensure the safety of drivers and other road users becomes an increasing concern. Safe progress is more likely if drivers are provided with relevant and intuitive information about the road layout ahead. For many years, this problem has been dealt with through the use of retroreflective road studs ("cat's eyes") embedded in the road surface. These road studs act passively by reflecting some of the light from a vehicle's headlights back to the driver. By placing such studs along the centreline of the road, they mark the direction of the road ahead. These traditional road studs are still prevalent on our roads as they are relatively inexpensive and effective; however they have a number of disadvantages. Since the studs are only illuminated when the headlights are shone on them directly there their ability to delineate effectively a curve in the road is limited. They are almost entirely useless in daylight, and inadequate in the crucial sunset/sunrise periods. They operate best in a dry, clear environment but in wet or foggy conditions, or on busy roads with dipped headlights, visibility can be massively reduced and conventional studs are ineffective (Boys & Green, 1997; Styles, Cairney, Studwick, and Purtill, 2004).

1.2 Internally illuminated Road Studs

Recent years have seen the development of internally illuminated road studs to combat these issues. These actively illuminated road studs ('active' studs) can be solar powered or hard-wired and can be activated automatically in response to a range of environmental conditions, e.g. darkness, fog, rain, pollution. Solar-powered studs are charged during daylight hours and also from vehicle headlights and can store enough energy in a battery for up to a weeks' operation. Active studs are one of the most important factors in creating a safer, more controlled driving environment. The most obvious advantage of active studs is increased visibility – forward illumination can be increased from 100m (with passive retroreflective studs) to approx 900m, irrespective of headlight intensity. 'Preview times' are therefore extended, alerting drivers to potential hazards earlier and leading to a higher level of driving control. ('Preview' is a measure of distance, expressed in time or length, at which the marker must be visible to allow the driver to respond safely. Preview times will depend on sight distance and speed (Mole, 2002)). Active studs can be used where conventional road marking is limited in use, for example, they can provide road layout guidance in daylight hours and in adverse weather conditions. Active studs can detect fading light levels, moisture on the road, fog, icy conditions etc and automatically activate the required level of illumination. Some important benefits (see Mole, 2002) of using these studs are:

- A reduction in accident risk;
- Increased driver visibility, alertness and awareness of potential hazards;
- Avoidance of sudden braking and manoeuvres, i.e. better control;
- Improved delineation, especially in poor weather.

Hard-wired studs can provide higher power lighting (which is of course not dependent on sunlight) and easier synchronisation of strings of studs; however they are more expensive in both installation and maintenance costs than solar-powered studs.

Developed independently but concurrently with the solar-powered and hard-wired active studs, there is a third type of illuminated road stud (Boys & Green, 1997). These are Inductive Power Transfer (IPT) studs and are powered by electricity magnetically coupled to electronics in the stud from wires embedded in the road surface; there is no physical contact between the stud and the cable. It is claimed that this method provides a higher level of reliability and robustness than either solar-powered or hard-wired studs.

Some possible applications of illuminated road studs to improve the safety of our roads are listed below (see Boys & Green, 1997):

- Motorway ramp metering: studs can be sequentially activated to control merging;
- Motorway off-ramps to provide advance warning of exits;
- Vehicle-activated lights at sharp bends or hazards;
- Roundabout control;
- School bus stop-zones activated by time of day and buses;
- Pedestrian crossings emphasised by lanes of studs leading up to the crossing. These studs can change colour and flash where required;
- Tidal flow control in urban areas (i.e. overhead gantries are impractical), illuminated studs (of various colours) can be used to divide the road;
- Advance warning for railway level crossings;
- Replacing some pole-mounted traffic signals.

1.3 Driver behaviour and retroreflectivity

A great deal of research has been done on the retroreflectivity and visibility of pavement (road) markings in general. Zwahlen & Schnell, in particular, have extensively studied the effect of different pavement marking configurations on driver eye-scanning behaviour and visibility distances at night (under headlight illumination). They use visibility models, computer-aided evaluation and field experiments to collect data on driver behaviour (Schnell & Zwahlen, 1999; Zwahlen & Schnell, 1997, 2000).

Schnell & Zwahlen (1999) examines driver preview distances at night as a function of pavement marking retroreflectivities. Visibility models and field experiments indicated that increased pavement marking retroreflectivity results in longer visibility distances and therefore is beneficial to driver safety. They suggest that drivers should have a visibility distance long enough to allow a preview time of 3.65s at a given speed. Also considered was the issue of whether drivers looked far enough ahead on the road to gain the benefit of this increased visibility. Tests were carried out to monitor drivers' longitudinal eye fixation distances when retroreflectivity of the markings was increased. The eye-scanning data showed that drivers adjust their fixation distances and preview times when driving on roads with bright and highly visible pavement markings. These results suggest that brighter markings will increase driver safety and control at night.

1.4 The impact of active studs on road safety

'Before and after' statistics from existing installations abroad show remarkable improvements in safety. Styles, Cairney, Studwick, and Purtill (2003) carried out an observational study in Australia. Their results are summarised below.

The impact of internally illuminated pavement markers (road studs) on driver behaviour was measured using a ‘before and after’ study. Traffic movement observations (video footage) were taken at night along a stretch of road between two bends and data for four hundred vehicles was collected. The variables considered were

- Vehicle speed;
- Brake use;
- High beam headlight use;
- Travel on or over the centreline;
- Lateral placement of vehicle on the road.

Results showed that brake use and headlight beam use were largely unaffected by the installation of the new studs. A favourable finding was that speed through the installation site was reduced due to the new studs. Also there was a reduction in the tendency of drivers to travel on or over the centreline. This is a particularly favourable finding as the risk of head-on collisions will be similarly reduced. Installation of the new studs seemed to encourage drivers to place their vehicle further from the centre of the road in only some circumstances; it is suggested that perhaps in some situations travelling close to a well-defined centre line may be more comfortable than travelling close to a poorly-defined road edge and this may account for the variability.

The study also considered the consistency of pavement markers’ on-off thresholds in fading light, fog and low temperatures. Tests showed that the studs perform as designed but performance can be reduced by their vulnerability to theft and damage (Styles, Cairney, Studwick, and Purtill (2004)).

1.5 Installation Case Studies

Intelligent Road Studs are being increasingly used in the UK; they are installed at one or more locations on more than 85% of the UK’s county and Highways Agency networks. Some specific installation sites are described here.

1.5.1 A24, Surrey

This site was chosen as the road had a particularly high level of darkness-only accidents, a lot involving single vehicles. This implies that a possible cause was the road layout being difficult to read from a distance. The installation proposed (and subsequently installed) by Astucia was designed to minimise disruption to existing road studs and road markings. The main design features were:

- Highlighting the numerous minor roads off the A24; concentrations of red and amber studs on the approach to these junctions for emphasis of the potential hazard.
- Unidirectional green markers to add definition to junctions and gaps in the centre line. These unidirectional studs can be rotated to suit the curve of the road, allowing the driver to be guided round the bend safely.
- For gentle bends the road studs will define the curve from far ahead, giving drivers ample time to assess their approach speed and position and respond appropriately.
- For severe bends with no forward view the road studs will act as a hazard warning with studs placed along the nearside and offside edges of the road at the start of the bend.
- On blind summits stud spacing is reduced to emphasise the hazard and provide drivers with an early warning.

1.5.2 M8, Glasgow

A 3km stretch of motorway has been fitted with Astucia detector studs and (hard-wired) light studs to provide a range of traffic control measures: fog guidance, surface water detection, incident detection, hazard warning. The hard-wired active studs are installed along the road edges to delineate the road in all weather conditions (the studs are visible from up to 1km distance), and are dimmed slightly at night to reduce glare. Detector studs are installed in the centre of lanes which can measure traffic speed, weather conditions, incidents etc. On-site control units can then use this information to relay instructions to the relevant active studs, for example selected strings of studs can be activated to flash a hazard warning upstream of an accident or slow-moving traffic. Sensory units in the studs cause the light intensity to increase in response to reduced visibility. So far, the trial shows that vehicle speeds are reduced when hazard warnings studs are activated, additionally there is an increase in headway and a reduction in lane changing manoeuvres.

1.5.3 A143, Norfolk

Solar-powered active studs were installed by Astucia on a 2km stretch of twisting road prone to high fog levels. Prior to installation the road had a high accident rate (22 accidents in 3 years, 40% at night, 60% in wet conditions) – 95% of which were due to loss of control. Studs were installed along the centreline for delineation of the road at night and fog guidance. Post-installation the accident frequency reduced from 7.3 per year to 2.3 per year (0% at night, 20% in wet conditions) and the severity level of the accidents reduced from 36% (fatal) to 0%.

Active studs are used in many countries around the world in a variety of applications, for example: in the USA and Canada at pedestrian crossings to create a safer sight distance to warn drivers; in Malaysia at traffic light intersections (Mole, 2002) and Astucia currently have trials in the Netherlands, South Africa and Australia as well as various locations around the UK. More trials are planned in the UK in particular at sites with high accident levels.

It is expected that in the future, active studs could be developed to interact with many more aspects of traffic management. Astucia have developed and are trialling a camera stud which can be linked to an Automatic Number-Plate Recognition program, this provides the technology for a range of traffic tracking and information applications. Active stud systems could also identify incidents be recognising reduced speed levels and trigger automated traffic management regimes. Furthermore, active studs could be used to advise on the recommended headway to be left between vehicles in poor visibility or slow-moving traffic.

1.6 Further research

Previous research on the impact of active studs has, through necessity, tended to focus on ‘before and after’ statistics from installation case studies. However, in such studies, there is huge potential for variability in weather conditions, road layout, lights levels, driver behaviour, and many other factors. It is also difficult to identify the how driver behaviour has changed in response to the illuminated road studs to bring about the observed change in accident statistics and to gain any insight into drivers’ subjective feelings about the installation of the active studs. This makes it difficult to assess the benefits of the active studs. A simulator study will enable the impact and effectiveness of active studs to be examined under controlled conditions whilst drivers’ views on their experience can be collected. The various environmental parameters can be controlled precisely and conditions can be repeated exactly where necessary and potentially dangerous driving situations can be studied in safety. More importantly, driving behaviour can be closely and accurately monitored.

By giving drivers more information about the path of the road ahead, active studs have the potential to reduce the risk of vehicle accidents when driving at night. However, there remains the possibility that, rather than take advantage of the reduced risk, drivers will undergo a behavioural adaptation such that they increase their speed until their subjective risk level approximates that which they experience when driving with standard retroreflective road studs.

Wilde (1982, 1988, 1994) described this phenomenon as ‘risk homeostasis’ whereby in response to a change in the road-vehicle-user system, behaviour changes to maintain a target level of risk per unit time. However, Grayson (1996) contended that there has been little evidence to suggest homeostatic processes existed to reduce or nullify safety benefits. A 1990 report by the Organisation for Economic Co-operation and Development (OECD) developed a less prescriptive definition of behavioural adaptations in response to changes in the road-vehicle-user system:

> *"Behavioural adaptations are those behaviours which may occur following the introduction of changes to the road-vehicle-user system and which were not intended by the initiators of the change;*
>
> *Behavioural adaptations occur as road users respond to changes in the road transport system such that their personal needs are achieved as a result; they create a continuum of effects ranging from a positive increase in safety to a decrease in safety."*

However, in seeking a more generalised characterisation of behavioural adaptation, much of the terminology within the OECD definition is open to interpretation. Grayson suggested a more pragmatic approach based on the notion that the introduction of road safety measures may result in adverse behavioural consequences. These cause a reduction in the effectiveness of road safety measures, either by failing to produce the expected benefits in the target population, or by introducing road safety disadvantages to other classes of road user.

Such adverse consequences have been observed with the implementation of vehicle Anti-lock Braking Systems (ABS). Studies have found that vehicles equipped with ABS were over represented in 'at fault' crashes; were more often recorded as braking extremely hard; their drivers were less accurate in their lane-holding behaviour; proceeded at shorter time and distance headways; and had more accidents under slippery driving conditions (see Hertz, Hilton, and Johnston (1996) and Grant and Smiley (1993)).

The simulator studies described in this document were devised to identify whether participants driving along a rural road where active studs have been installed produce an adverse behavioural consequence such that they drove faster than they would on the same road with either passively illuminated studs or with no studs whatsoever, thereby reducing the safety benefit of the technology. They were also designed to discover how the safety benefits that are observed in 'before and after' studies of active stud installations are mediated by closely examining how drivers control their vehicle under such conditions. Simulation offers a practical solution for making such an assessment since participants can be presented with repeatable dangerous situations without risk of physical harm, whilst information about driving performance is recorded accurately by the simulation computers for post-hoc analysis.

Road accidents in which there has been a casualty trigger the police to provide a STATS19 return, which is a brief report detailing the circumstances in which the accident occurred. This is used to create a database of road accidents that is operated by the UK Government's National Statistics department and to which TRL has access. This database was interrogated to establish the potential impact of any differential effects of active studs on night-time driving behaviour observed across the different age groups involved in the trials on the accident statistics, were active studs to be introduced extensively across the UK road network.

2 Method

2.1 Participants

Thirty six participants were recruited to take part in the simulator trials from TRL's dedicated participant database, which comprises over a thousand local members of the public, all of whom have participated in previous trials and are therefore comfortable with driving the driving simulator. The recruitment criteria were such that there were an equal number of participants from three age groups. Consequently, there were twelve participants from:

(i) Younger group: 17-25 years

(ii) Middle group: 26-55 years

(iii) Older group: 56 years and over

This split was chosen to enable the results obtained from the simulator study to be compared to the accident statistics available for similar age groups used in classification of accidents in the STATS19 database. Within each age group, equal numbers of male and female participants were selected.

2.2 Simulator

Driving was completed on TRL's full mission driving simulator. This is based on a Honda Civic cabin, surrounded by projection screens giving 210° forward and 60° rearward fields of view. Full details of the simulator are given in Appendix A.

2.3 Participant handling

Prior to driving the simulator, participants were not informed as to the purpose of the trial in which they were taking part. They were told that they were driving in a night-time environment and that they should drive as they normally would. Each participant stayed at TRL for 2-3 hours when completing trials and was paid £30 for their involvement in the trial.

2.4 Vehicle lighting

The driven vehicle had a headlight distribution based on the isolux distribution of a Peugeot 205 light beam. Parameters of the headlight distribution were adjusted to provide a realistic driving experience on a dark rural A-road. The same lighting distribution was used throughout each drive. Participants were instructed that they were only to use dipped headlights whilst completing trials and a warning signal was given if any other headlight mode were selected. It was decided that participants should not be allowed to use main beam because there will be occasions such as in light traffic conditions when drivers would be reluctant to use their high beam headlights but are still required to negotiate bends and corners. No other traffic was present in the trial.

2.5 Environmental lighting

2.5.1 Ambient lighting

The ambient lighting was adjusted to zero to mimic conditions in a night-time rural setting. Consequently, items within the simulated driving environment, such as passive road studs or the walls/hedges that were adjacent to the driven route, were only visible if they were struck by the vehicle headlights. The only other illuminated objects were the active studs due to their independent light source.

2.5.2 Stud characteristics

The passive studs were created to represent a current top-of-the-range retroreflective road stud. Each stud had a reflection angle of ±15° such that a light source had to be within a 30° sector ahead of the retroreflective element for efficient reflection of the light source.

The active studs used in the simulation were based on the S Series Night Delineation SolarLite Night road studs manufactured by Astucia. This is a solar powered stud with a nickel metal hydride battery that charges under daylight conditions and discharges when the luminance falls below a threshold value, thus causing the light emitting diode (LED) to illuminate.

Both active and passive studs were placed in the same locations throughout the trial route. On the centreline, studs with white reflectors/LEDs were placed at 18m intervals. In bends, the distance interval between studs was reduced to 9m. On the four sharpest bends, the distance interval between studs was reduced to 6m and red studs were placed on the nearside road edge also at 6m intervals. Figure 2.1 shows a photograph of a real stud installation and a comparable bend from the simulated road used in the trial.

Figure 2.1 Real photograph (left panel) and screenshot from the simulated road environment (right panel) each showing centre-line white studs and nearside edge red studs

2.6 Route design

The trial route was based around a generic rural A-road. This was a two-lane carriageway, each lane being 3.7m wide giving a total road width of 7.4m. It was composed of a lead-in section, sections with and without road studs, and a final run-out section. The total length of the simulated route was 37.1km.

2.6.1 Lead-in section

The lead-in section to each drive was an 8.5km section of unchallenging rural road with gentle bends. It was not equipped with any road studs. This section enabled the participant to become familiar with both the handling of the vehicle and driving in the night-time environment before tackling any of the test sections of the route. It also gave each participant time in which their visual system could adapt to the dark environment.

2.6.2 *Test section*

There were six test regions of the trial route. Each region was constructed from a basic 4.6km section. This section contained six critical bends over which participants' driving behaviour would be scrutinised. A plan view of the basic section is shown in figure 2.2. In the basic road section there are six places where the road curves with a radius that is less than 150m. These are the six bends that are used for analysis in the report, numbered in the figure. The corners on which red studs were placed were 1, 3, 4, and 6.

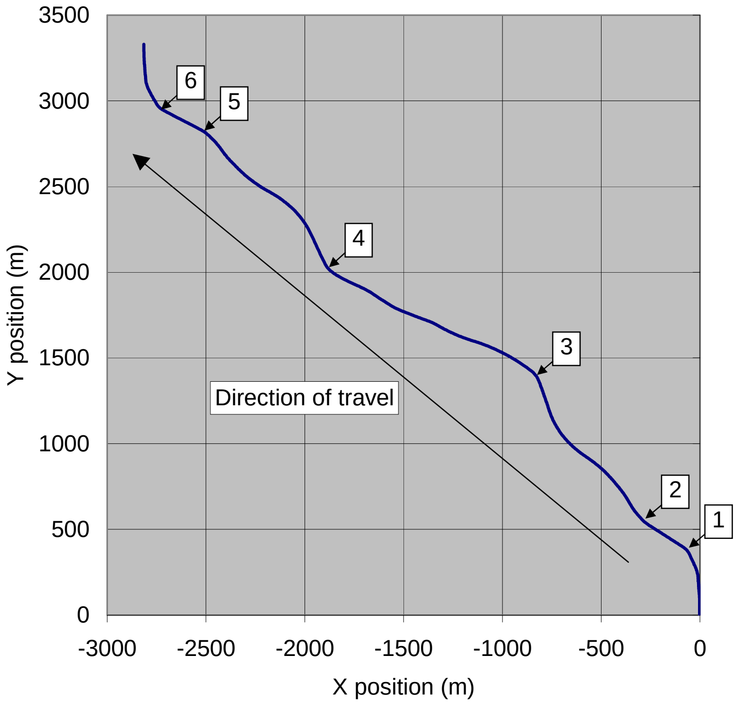

Figure 2.2 Plan view of the basic 4.6km road section

Figure 2.3 shows an exaggerated profile view of the section to highlight the gradients within the route.

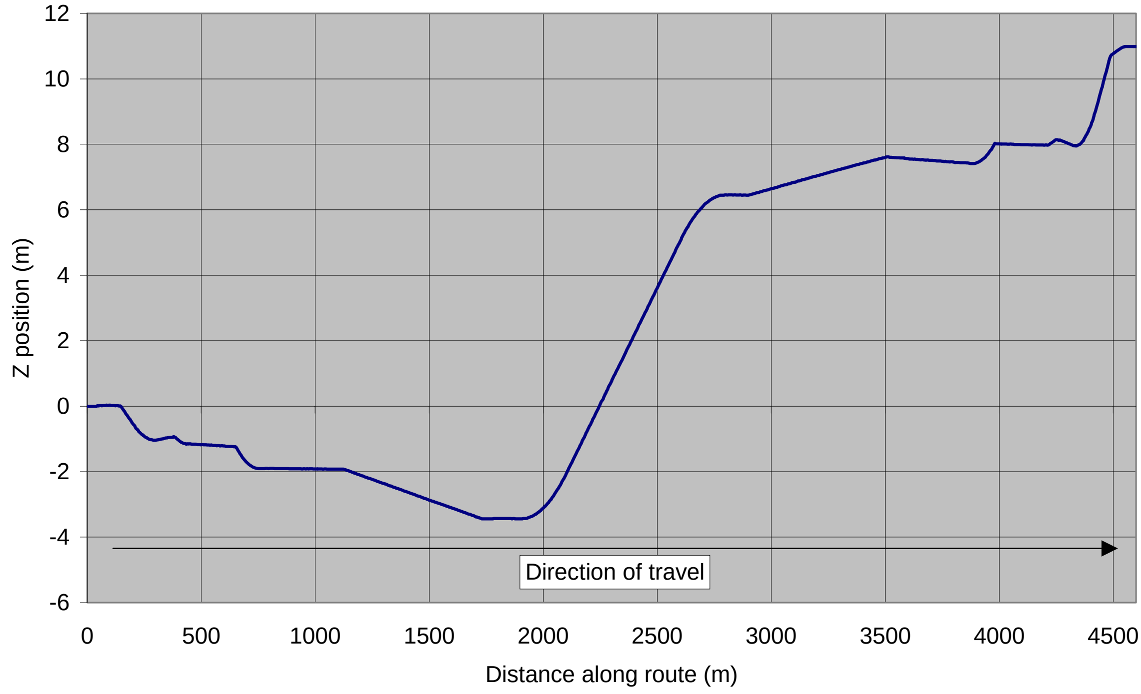

Figure 2.3 Profile view of the basic 4.6km road section (note exaggerated vertical axis)

To reduce the likelihood of participants becoming familiar with the route, the basic 4.6km section was also rotated through 180° to create two different sections with which to build up the trial route type A (the original section) and trial route type B (the rotated section). The order in which the trial sections were encountered was:

Section number	**1**	**2**	**3**	**4**	**5**	**6**
Section type	A	A	B	A	B	B

Since the six critical bends will be encountered in two different directions, there are twelve bends for analysis – 1-6A and 1-6B.

2.6.3 Run-out section

The final run-out section was a straight, 1km section of the rural road and was not equipped with any road studs. It was used to instruct participants that the trial had come to and end and give them an opportunity to bring the vehicle to a safe halt on the road.

2.6.4 Signage

This trial was designed to investigate what might happen if Active studs were installed on a real road. Consequently, appropriate signage was added since without it participants' simulator driving may not be representative of their behaviour when driving on a road that had the correct signage, thereby invalidating the results of the study. Signs were added to the routes in accordance with the DfT Traffic Signs Manual Chapter 4 (Warning Signs) 2004. Chevron signs to indicate sharp turns were also added to each of the critical bends. Although these are not compulsory under the Traffic Signs Manual, it was felt that if Active studs were being considered for installation; other means of indicating to drivers that a hazardous bend lay ahead would have been implemented.

2.6.5 Route composition

In each of the participants' drives, there were five distinct sections, as outlined in table 2.1

<table>
<tr><th>Section</th><th>Sub-section type</th><th>Description</th><th>Length (km)</th><th>Notes</th></tr>
<tr><td>1</td><td>N/A</td><td>Familiarisation</td><td>8.5km</td><td>Undemanding road to allow familiarisation with vehicle and night-time environment</td></tr>
<tr><td>2</td><td>A</td><td>No studs</td><td>4.6km</td><td>Trial section type A with no studs</td></tr>
<tr><td rowspan="4">3</td><td>A</td><td>Studs</td><td>4.6km</td><td rowspan="4">Two instances of each trial section (A and B). All passive or all active studs depending on the drive number</td></tr>
<tr><td>B</td><td>Studs</td><td>4.6km</td></tr>
<tr><td>A</td><td>Studs</td><td>4.6km</td></tr>
<tr><td>B</td><td>Studs</td><td>4.6km</td></tr>
<tr><td>4</td><td>B</td><td>No studs</td><td>4.6km</td><td>Trial section type B with no studs</td></tr>
<tr><td>5</td><td>N/A</td><td>Run out</td><td>1.0km</td><td>Short straight section where the trial is brought to an end</td></tr>
<tr><td colspan="3">Total</td><td>37.1km</td><td></td></tr>
</table>

Table 2.1. Trial sections

2.7 Trial order

Participants completed two drives in the simulator, one in which the studded sections were equipped with passive studs and one in which the studded sections were equipped with active studs. Drivers were likely to feel more comfortable in their second drive when they were more familiar with the task and the simulator. Therefore, to control for this learning effect, equal numbers of participants by sex and age group were assigned to trial order groups (a) and (b). Group (a) drove the route with passive studs first and the route with active studs second, whilst Group (b) drove the route with active studs first and the route with passive studs second.

2.8 Questionnaires

Before driving the simulator participants were required to complete a pre-drive questionnaire. This recorded background information about the participant, information about their typical driving behaviour, and their feelings about driving at night. Having completed their two drives in the simulator, participants also completed a post-drive questionnaire. This questionnaire used picture cue cards to remind participants of the conditions that existed in each drive and asked participants to rate their subjective comfort, control, safety, and confidence across the road stud conditions as well as providing an opportunity for participants to report any general comments they had about the road studs or the trial itself.

Both questionnaires are shown in Appendix B whilst the pictures cue cards are shown in Appendix C.

2.9 Simulator measures

The simulation computers record a vast quantity of data relating to drives completed in the simulator vehicle. For this trial, data recording was locked at 20Hz. A list of the recorded variables is given in Appendix D.

2.10 STATS19 database

The Department for Transport (DfT) compiles data on personal injury road accidents, resulting casualties, and the vehicles involved. Accidents are those which occur on the public highway and which become known to the police within 30 days. There are three main areas in which information is gathered:

(i) Accidents – including the severity of the accident, the number of vehicles and casualties involved, time and location, road class and number, speed limit, weather and road conditions, and carriageway hazards.

(ii) Vehicles – including type, location and manoeuvre at time of accident, and details of the driver (age, sex and breath test results).

(iii) Casualties – age, sex, injury severity, and whether a driver, passenger or pedestrian.

Data are collected monthly from police forces throughout the year and are available for Great Britain and by country region and county. TRL has access to this data and the STATS19 database was sampled to find the number of road users injured in road accidents where there was at least one person killed or seriously injured (KSI). In addition to the number of injuries, the time and date at which the accident occurred and the class of road class on which the accident occurred were extracted from the database. This information was used to examine the differential impact across age groups that the installation of active road studs might have on the frequency of road accident injuries.

2.11 Analysis procedures

Analysis of simulator data was conducted using Microsoft Excel 2002, whilst statistical tests were conducted using the SPSS 14.0 statistical package. A range of tests were used including paired sample t-tests, independent sample t-tests, and the Analysis of Variance (ANOVA) procedure. Comparisons were considered significant if the p-value was less than 0.05. There were three within-participant conditions of Stud type (No studs, Passive studs, and Active studs) and three between-participant conditions of Age group (17-25 years, 26-54 years, 55+ years).

3 Results

3.1 General statistics

3.1.1 Participants

Two participants were unable to complete their simulator drives; one due to simulator sickness and one due to an apparent and inexplicable inability to control the simulator vehicle. Two replacement participants were recruited with profiles matching those of the participants that they replaced.

Age and driving information about the participants who completed trials are shown in table 3.1.

Age group		Age (years)	Years driving (years)	Annual mileage (miles)
Younger (17-25)	N	12	12	10
	Mean	21.5	4.0	11950
	Minimum	18	0.4	4500
	Maximum	25	8	30000
	SD	2.8	2.7	8119
Middle (26-54)	N	12	12	12
	Mean	49.1	29.7	10667
	Minimum	37	19	3500
	Maximum	55	37	18000
	SD	5.1	6.0	4721
Older (55+)	N	12	10	12
	Mean	64.0	42.5	10167
	Minimum	57	34	2000
	Maximum	78	60	24000
	SD	6.4	8.2	6279
Total	N	36	34	34
	Mean	44.9	24.4	10868
	Minimum	18	0	2000
	Maximum	78	60	30000
	SD	18.5	17.1	6253

Table 3.1. Participant information

Table 3.1 shows that participants in the trial are typical of the driving population of the UK. There were equal numbers of male and female participants in each of the Age sub-groups.

3.1.2 Learning effect

The lead-in section of the drive was used to give participants the opportunity to familiarise themselves with driving the simulator in the night-time environment. By comparing participants' average speed over the lead-in section in their first drive with that in their second drive, the learning effect across the two drives can be estimated. Figure 3.1 shows the average speeds for each age group across the two drives.

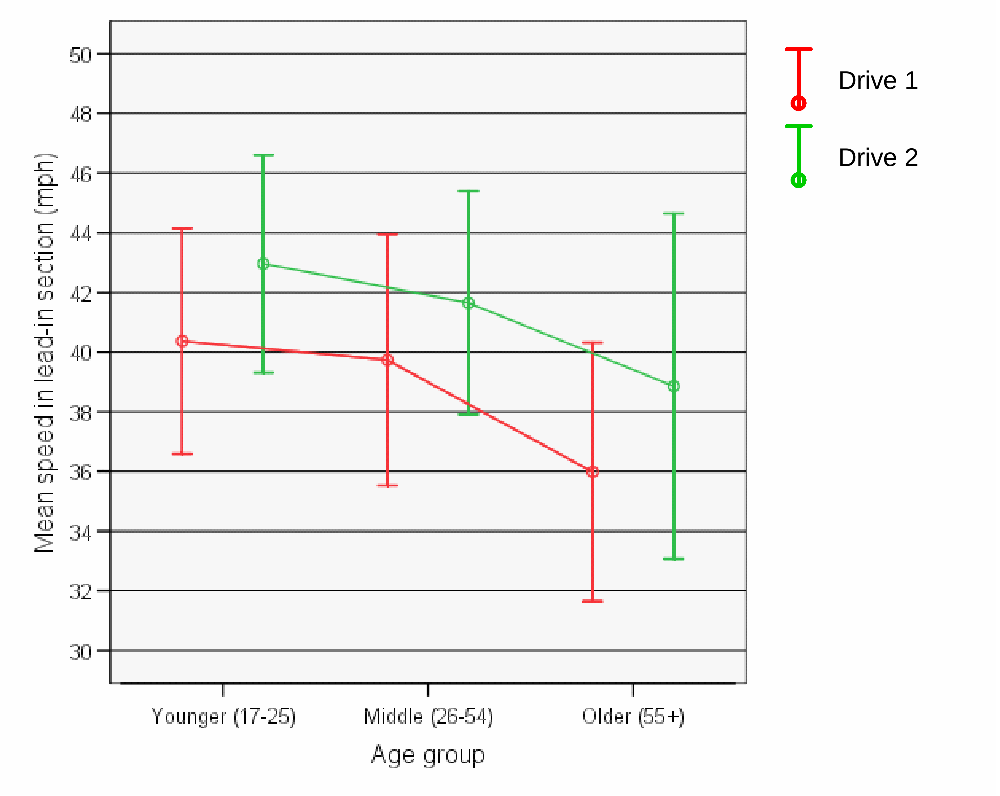

Figure 3.1 Error bar graph to show participants' mean speed in the lead-in section of each drive across Age groups. Error bars show 95% confidence interval on the mean.

It is clear that participants tended to drive 2-3mph faster in their second drive. This difference is significant in a paired samples t-test ($t(35) = -3.68$; $p = 0.001$). This effect was controlled for by making half the participants complete the trial route with passive studs first and the route with the active studs second (participant group (a)) with the other half completing these routes in the opposite order (participant group (b)). To check that this was successful, an independent samples t-test was conducted on participants' average speed in the lead-in section across participant group and this was non-significant in both drive 1 and drive 2 suggesting that the learning effect was successfully controlled for in the trial.

Figure 3.1 also shows that there was greatest variability in the speed of the Older participants and that in each drive the Older participants were slower than the Middle participants, by approximately 3.0mph, with the Younger participants a further 1.0mph faster. These differences, though consistent, fail to reach significance in a one way ANOVA test.

3.1.3 *Overall speed*

For each participant, their average speed over the complete course of each section was determined. This allowed calculation of an average speed in each Stud condition. Figure 3.2 shows participants' average speed across each of the Stud conditions.

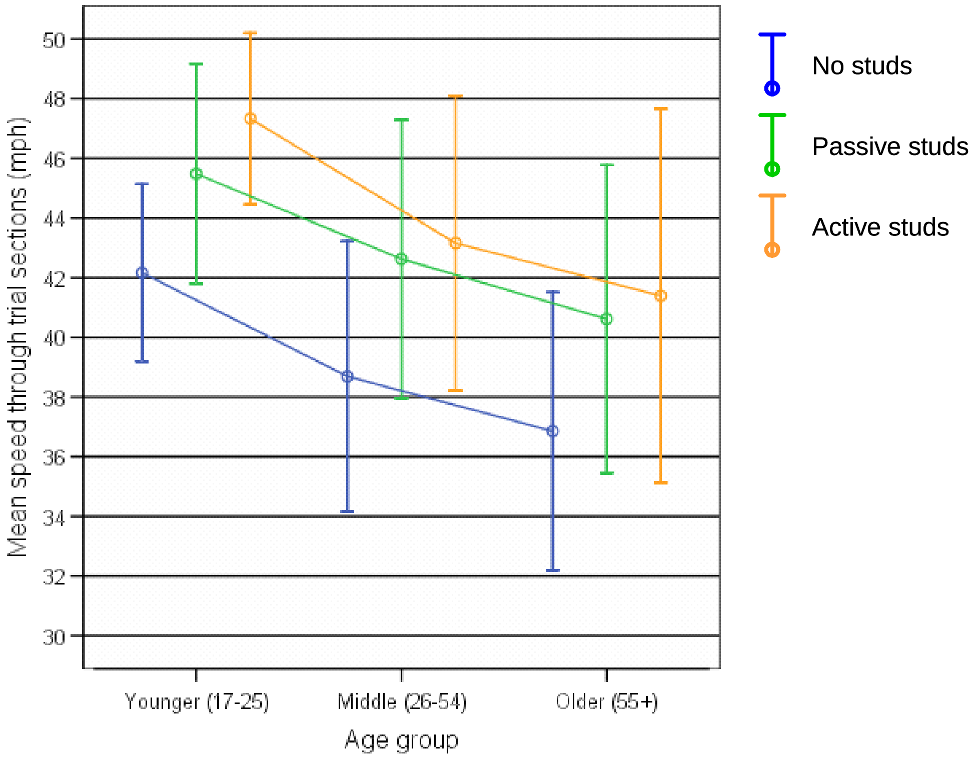

Figure 3.2 Error bar graph to show participants' average speed over the test sections of each drive across the Age groups

There is a near linear relationship between the average speed in each section and age group. Again, Younger participants are the fastest, around 2.5mph faster than Middle participants, who are around 2.5mph faster than Older participants. This relationship is true in each Stud condition. Participants drove slowest in the No stud condition, driving around 3.5mph faster with Passive studs, and a further 1.0mph faster with Active studs. Paired sample t-tests reveal highly significant differences between the No stud and Passive stud conditions ($t(35) = -5.39$; $p < 0.001$) and between the No stud and Active stud conditions ($t(35) = -9.14$; $p < 0.001$). However, there is no significant difference between the Passive and Active stud conditions ($t(35) = -1.37$; p = NS).

3.1.4 *Lateral position*

The lateral position of the simulated centre of the rear axle was recorded throughout each drive in the simulator. This allows the position of the left and right edges of the simulated vehicle to be determined. It was found that participants almost never allowed the left edge of the vehicle either to cross into the verge (there were only seven instances where this happened). However, allowing the right edge of the vehicle to cross the centreline was much more common. This is to be expected since the right edge of the vehicle will cross the centreline if the driver 'cuts' the corner. Figure 3.3 shows the average duration that the right edge of the vehicle was across the centreline across Age groups and Stud conditions.

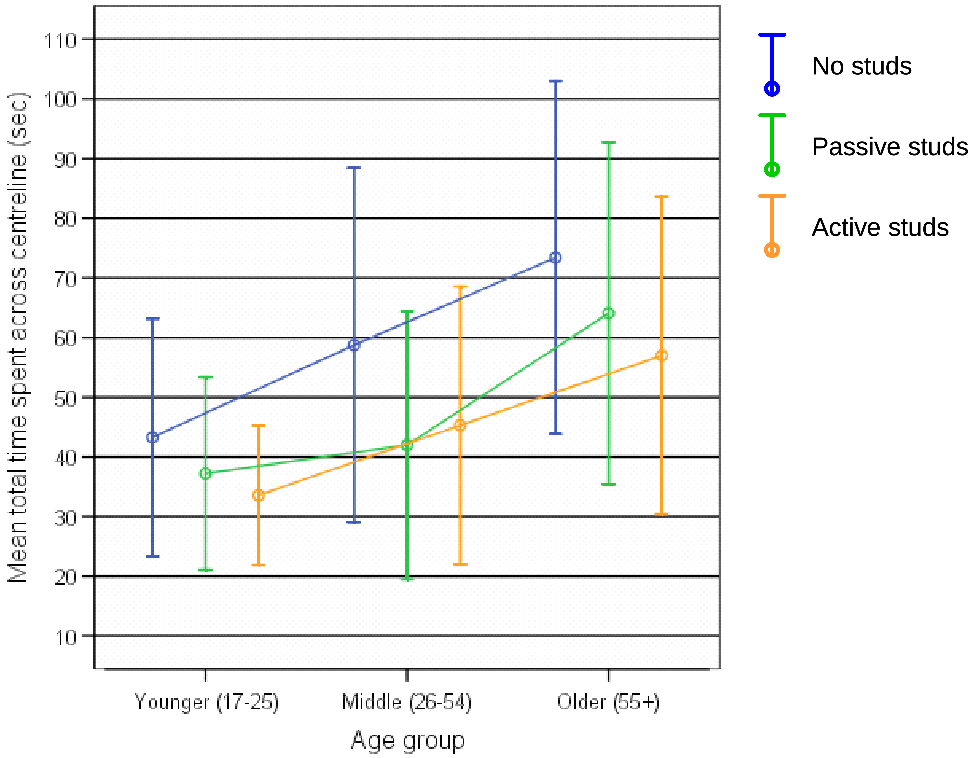

Figure 3.3 Error bar graph to show the mean duration over which participants' allowed the right edge of the vehicle to cross the centreline in test sections across Age groups

Figure 3.3 shows that Younger participants tended to spend the least time with the right edge of the vehicle across the centreline, whilst Middle age group participants spent a little longer crossed, and Older participants spent the most time across the centreline. It is clear that the studded roads made a big difference to each Age group in reducing the time spent across the centreline relative to the No studs condition. This is confirmed by paired samples t-tests that show significant differences between the No studs and the studded conditions (No studs vs. Passive: $t(35) = 3.06$; $p = 0.004$; No studs vs. Active: $t(35) = 4.02$; $p < 0.001$).

There is an interesting discrepancy between the Middle age group participants and the other groups in that the Younger and Older participants both spent less time across the centreline with Active studs compared to Passive studs, whereas the Middle age group participants spent a little less time across the centreline with Passive studs. Investigating further, the time across centreline data was split by Age group and paired samples t-tests were conducted across the Stud conditions. It was found that the only significant difference was for the Older age group in the comparison between No stud and the

Active stud condition ($t(11) = 5.98$; $p < 0.001$). This suggests that the Older age group participants benefited most from the active studs in terms of lane guidance.

3.2 Corner statistics

It is not anticipated that Active road studs would be installed along the entire length of a rural A-road, rather that they would be installed on specific corners where it was expected that drivers would benefit from the additional information that they provide about road direction. Statistics up to this point have focussed on general behaviours over the full length of each trial section. The statistics in this part of the report examine driving behaviour in the twelve critical corners of the two section types only. For analysis, a corner is considered to begin at a driven distance of 150m before the curve radius of the corner fell below 150m and end a further 100m beyond this point.

3.2.1 Corner profiles

Appendix E shows eight of graphs for each of the twelve different corners (1-6A and 1-6B) within the study. They show how different variables changed over the analysis region of each corner across the stud types that were present in that corner. The eight graphs shown are as follows:

(i) X-Y position (m)

(ii) Speed (mph) vs. Distance to corner (m)

(iii) Accelerator pedal depression (0-1) vs. Distance to corner (m)

(iv) Brake pedal depression (0-1)vs. Distance to corner (m)

(v) Time to line crossing – path (sec) vs. Distance to corner (m)

(vi) Left wheel distance to verge (m) vs. Distance to corner (m)

(vii) Right wheel distance to centreline (m) vs. Distance to corner (m)

(viii) Steering input vs. Distance to corner (m)

3.2.2 *Corner speeds*

3.2.2.1 Mean speed

Figure 3.4 shows participants' mean speeds within the critical range of each of the corners, with corners separated by whether they were Left or Right turns.

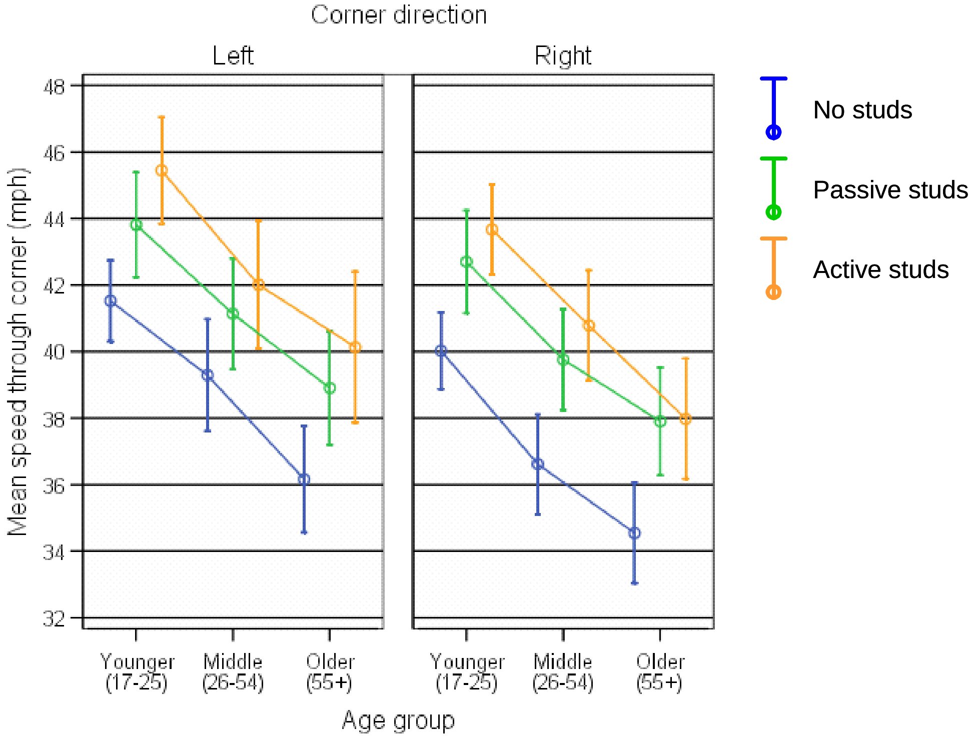

Figure 3.4 Error bar graph to show participants' mean speed through Left and Right turns in each drive across Age groups and Stud conditions

Using data from each corner driven greatly increased the number of data points included in calculations. This has reduced the size of the error bars on the graphs and increased the statistical power of comparisons. Participants appeared to drive faster through the Left turns than the Right runs. This is slightly counterintuitive since the geometry of a Left turn means that it is tighter than the Right turn if that turn is driven in the opposite direction. A possible explanation for this is as follows. If a driver runs wide on a Left run they will drift into the middle of the road. If a driver runs wide on a Right run they will drift towards the verge. Since the vehicle is likely to lose grip and spin if the tyres contact the grass verge, drivers may have felt less assured driving through the Right turns, with a consequent reduction in their speed relative to Left turns.

In either direction, there is a near linear relationship across the age groups, with Younger participants driving about 2-3mph faster than Middle participants, who in turn are 2-3mph faster than Older participants. Comparisons across Stud types show that participants in each age group drove around 2-3mph faster with Passive studs than with No studs. For Left turns with Active studs, participants drove around 1mph faster than Left turns with Passive studs. However, for Right turns, the speed difference is reduced. This is confirmed in paired-sample t-tests. Comparisons of Passive vs. Active studs fail to reach significance for all three age groups in Right turns. The same comparisons for Left turns fail to reach significance for drivers in the Middle age group (All other comparisons of mean speed for No studs vs. mean speed for Passive or Active studs are highly significant ($t(71) < -3.64$; $p < 0.001$ in each cases). All other comparisons across Passive and Active studs are also significant ($t(71) < -2.12$; $p < 0.05$ in each case)).

3.2.2.2 Minimum speed

The mean speed through the corner does not necessarily indicate how well drivers reduced their speed to negotiate the corner. Additional information about how safely corners were negotiated can be derived by looking at the minimum speed drivers achieved each time they drove through a critical corner. Figure 3.5 shows the mean of participants' minimum speeds across Stud types and Age groups for each corner direction.

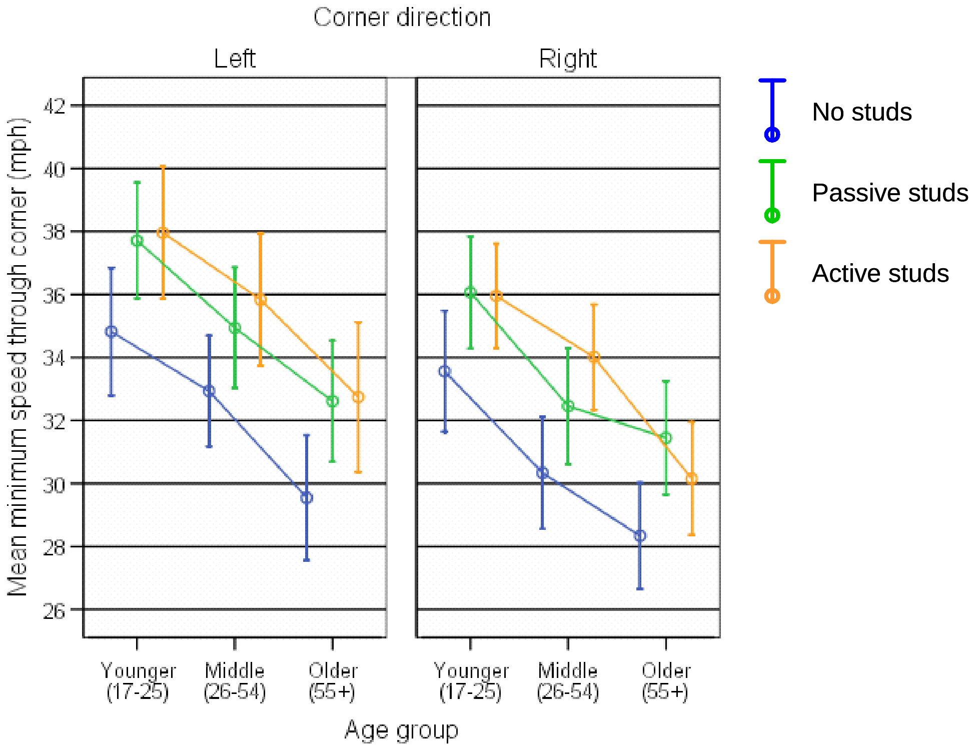

Figure 3.5 Error bar graph to show participants' mean minimum speeds over Left and Right turns in each drive across Age groups and Stud conditions

Figure 3.5 shows that participants' minimum speeds through corners with Passive and Active studs differed less than their mean speeds. The greater minimum speed of participants through corners equipped with studs cause all comparisons with the No studs condition to be significant ($t(72) < -2.35$; $p < 0.05$ in each case). For Left turns, none of the comparisons of minimum speeds between Passive and Active studs reach significance. For Right turns, the Middle group show a significantly faster minimum speed with Active studs ($t(71) = -2.32$; $p = 0.023$) whilst the Older group show a significantly slower minimum speed with Active studs ($t(71) = 2.16$; $p = 0.034$).

3.2.2.3 Maximum brake application

The analysis above suggests that Middle group participants take Right corners faster with Active studs whilst Older participants take Right corners faster with Passive studs. The differences in speed might be considered more dangerous if they were associated with harsher braking since excessive braking can lead to loss of vehicle control. Figure 3.6 shows the mean across participants of the maximum brake application that was observed for each Stud type and Age group.

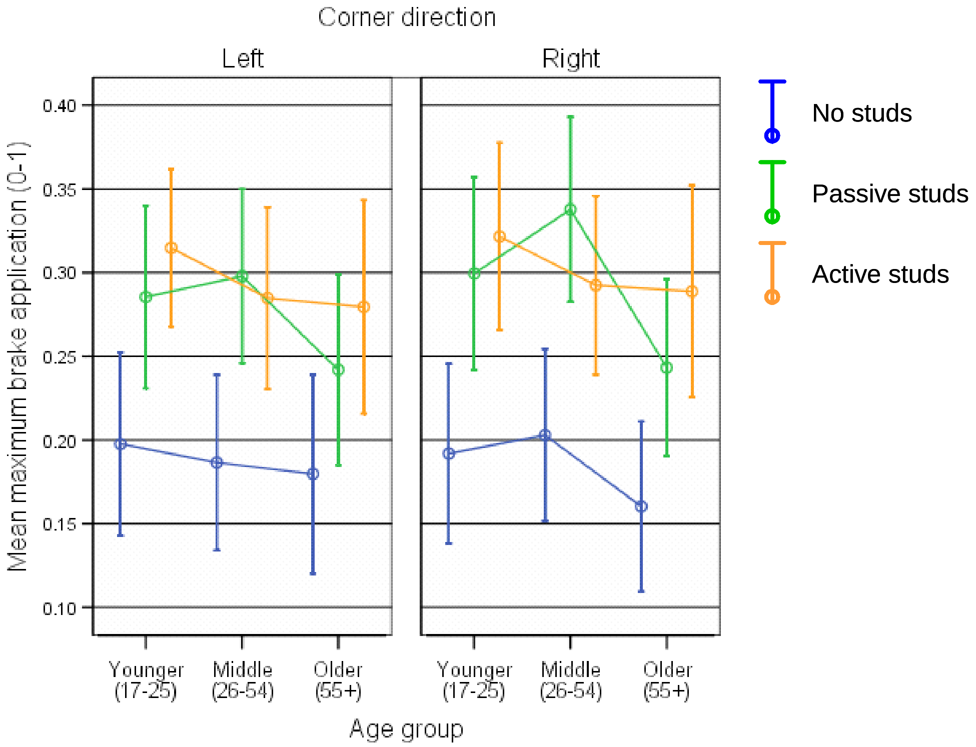

Figure 3.6 Error bar graph to show participants' mean maximum brake application over Left and Right turns in each drive across Age groups and Stud conditions

It is clear that participants brake harder in both the studded conditions. This enables them to achieve a greater reduction in speed from the higher speeds observed when road studs of either variety are present. Paired sample t-tests again show that all comparisons with the No studs condition are significant ($t(71) < -2.84$; $p < 0.01$ in each case). However, none of the comparisons of maximum brake application between corners driven with Passive and Active studs reach significance, suggesting that participants do not brake more harshly in either of the stud conditions.

3.2.2.4 Position at maximum brake application

Road studs give drivers additional information about the direction of the road. This additional information may allow a driver to brake earlier in preparation for a corner. Figure 3.7 shows the mean distance to the corner when maximum brake application was engaged across Stud types and Age groups.

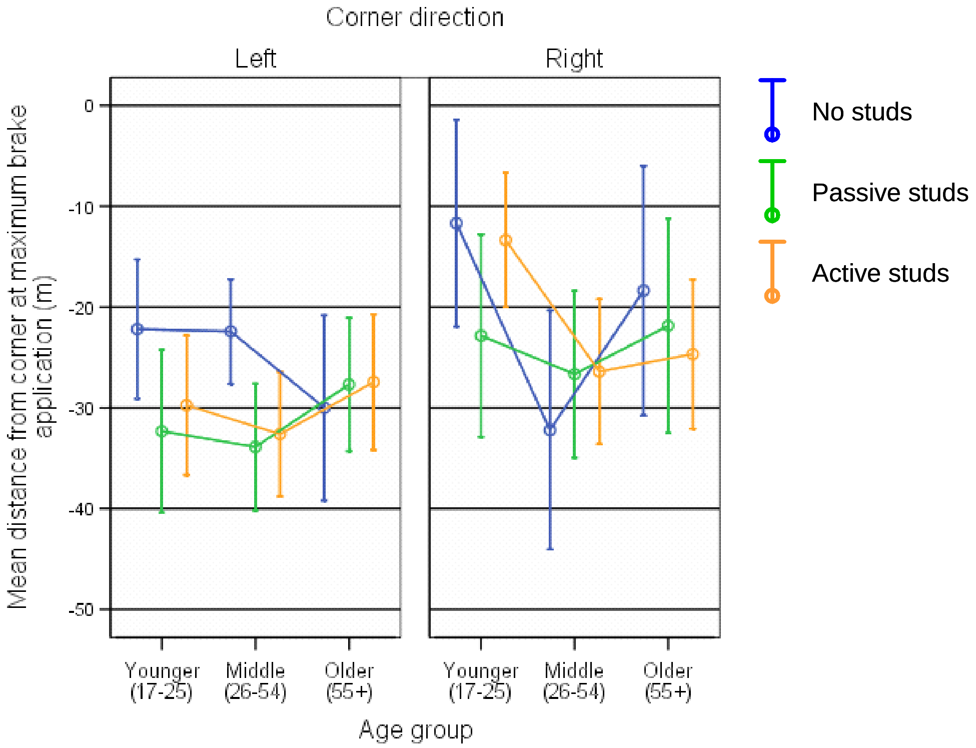

Figure 3.7 Error bar graph to show the mean distance to the corner at which participants achieved maximum brake application over Left and Right turns in each drive across Age groups and Stud conditions

For Left turns, the picture is clear. Younger and Middle age group participants demonstrate maximum braking further from the corner in both the studded conditions whilst Older participants demonstrate maximum braking at about the same distance across all Stud conditions. These differences are confirmed with paired sample t-tests in which comparisons with the No stud condition reach significance for the Younger and Middle age groups ($t(27\text{-}28) > 2.08$; $p < 0.05$ in each case) but not for the Older age group.

For Right turns, differences across the stud conditions are less clear and variation in the distance to the corner at which maximum brake application appears much greater. Only one comparison reaches significance and that is the comparison between No studs and Passive studs for Younger participants ($t(31) = 2.22$; $p = 0.034$). It can be observed from the size of the error bars (that indicate the 95% confidence interval on the mean) that for right turns, the maximum brake application tends to occur at a more consistent position for corners equipped with Active studs than with either No studs or Passive studs. This is particularly true for Younger and Older participants. For the Middle age group the difference is less pronounced. Braking at a more consistent position tends to suggest that participants had a greater awareness of how they needed to control the vehicle in preparation for the approaching bend.

3.2.3 *Lateral position*

Figure 3.8 shows the mean distance from the outside of the right wheel of the vehicle to the centreline of the road (right lateral safety distance) through each corner across Stud type and corner direction.

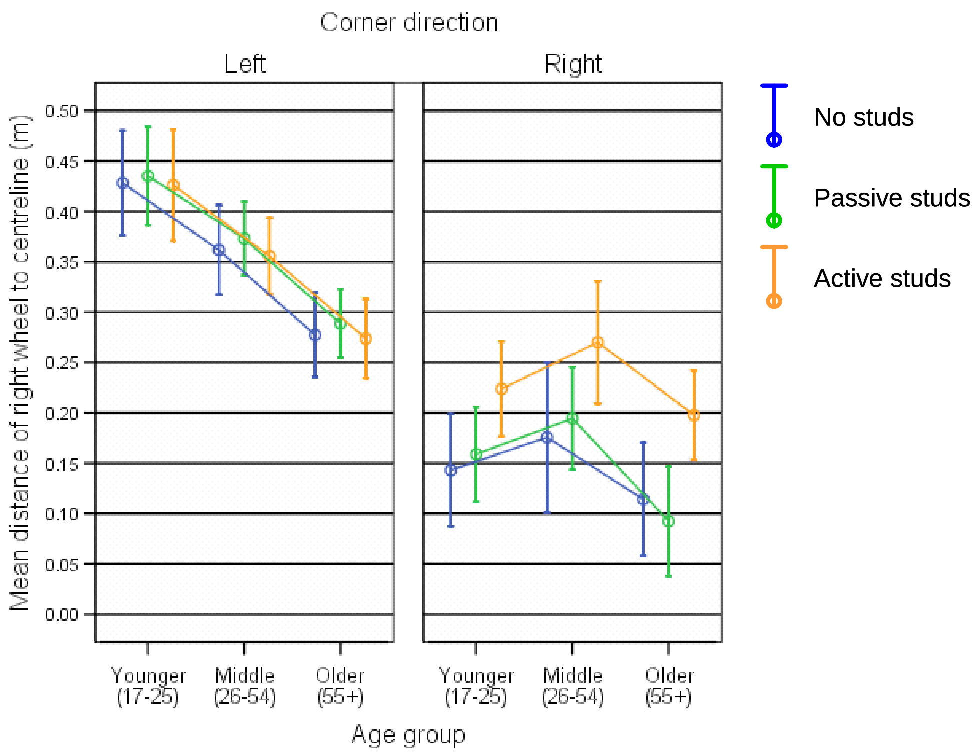

Figure 3.8 Error bar graph to show the mean right lateral safety distance over Left and Right turns in each drive across Age groups and Stud conditions

The first thing to note is that in all conditions the mean right lateral safety distance is less than 0.5m. Since the vehicle is 1.7m wide and the lane is 3.7m wide, participants remain on average 1.5m from the left edge of the road in all corners. The difference in these distances demonstrates that participants prefer to maintain a greater safety clearance to the verge than that to the centreline and supports the observation made in 3.1.4 that participants very rarely cross into the verge. Since the distance to the verge is so large, it is not useful for illustrating any differences across the experimental factors of Stud type or Age group.

Figure 3.8 shows that the distance of the right edge of the vehicle to the centreline in Left turns is remarkably consistent across Stud types. Older participants show the shortest right lateral safety distance with Middle participants keeping about 0.08m further from the centreline. The right lateral safety distance for Younger participants is greatest and is approximately 0.08m further than that for participants in the Middle age group. Differences across stud types do not reach significance.

For Right turns, there is a consistent pattern whereby the right lateral safety distance for the No stud and Passive road stud conditions are similar but the right lateral safety distance in the Active stud condition is between 0.05 and 0.10cm greater. Paired-sample t-tests confirm that the differences in right lateral safety distance between the No stud and Passive stud conditions do not reach significance but all comparisons with the Active stud condition are highly significant ($t(71) < -2.98$; $p < 0.005$ in each case). This supports the findings shown in 3.1.4 and suggests that participants are less likely to cut across the apex of the corner with Active studs.

To further investigate this finding, figure 3.9 shows the mean minimum distance to the centreline that participants achieved across corners.

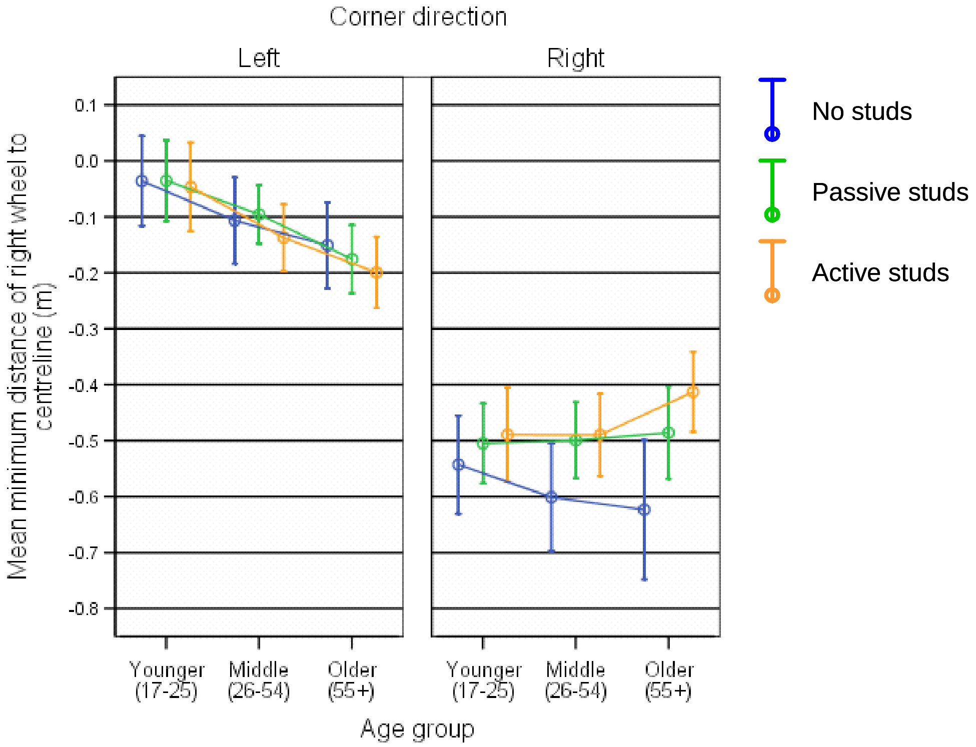

Figure 3.9 Error bar graph to show the mean minimum right lateral safety distance over Left and Right turns in each drive across Age groups and Stud conditions

As with figure 3.8, figure 3.9 shows that in Left turns in the right lateral safety distance is very similar across Stud types. However, for Right turns, figure 3.9 shows that whilst both the studded conditions have shown an improvement over the No studs condition, it is Older participants who have derived the greatest benefit from the Active studs. Paired-samples t-tests show that there are no significant differences across Stud conditions for the Younger age group. For the Middle group, both the studded conditions differ from the No stud condition (No stud vs. Passive: $t(71) = -2.48$; $p = 0.015$; No stud vs. Active: $t(71) = -2.70$; $p = 0.008$). For the Older group, all comparisons across Stud type reach significance (No stud vs. Passive: $t(71) = -2.27$; $p = 0.026$; No stud vs. Active: $t(71) = -3.45$; $p = 0.001$; Passive vs. Active: $t(71) = -2.33$; $p < 0.023$).

3.3 Questionnaire

Pre- and post-trial questionnaires were used to investigate participants' subjective feelings about the trial (see Appendix B). Picture cue cards were used to remind participants of the conditions that the experienced in the two drives (see Appendix C).

3.3.1 Safety

Participants were asked to give their subjective ratings of Safety under the conditions shown in each picture. Results are shown in figure 3.10

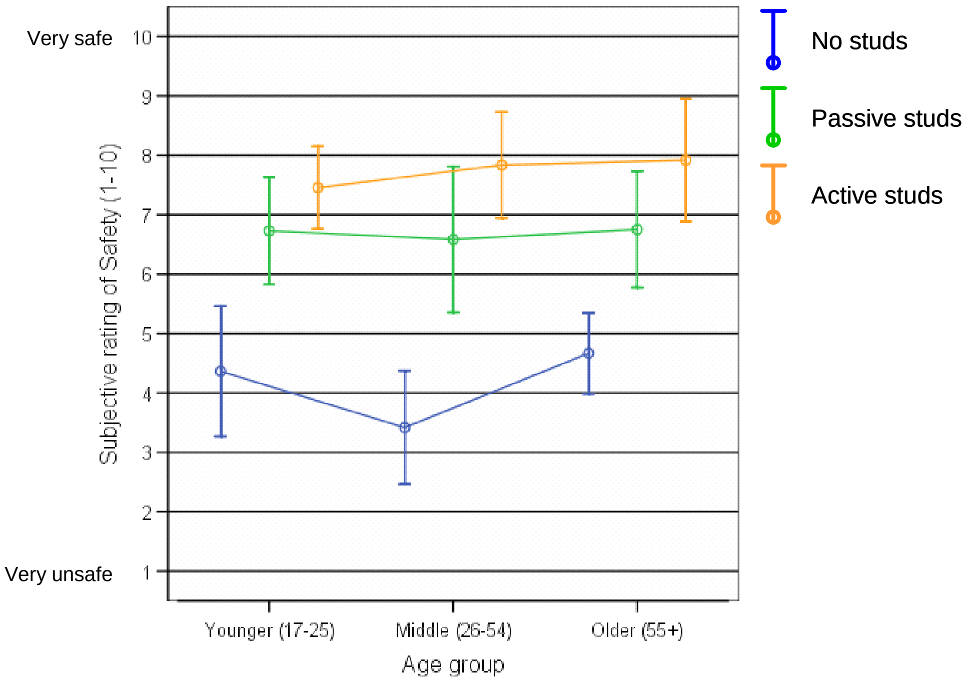

Figure 3.10 Error bar graph to show participants' mean subjective ratings of Safety across Stud type and Age group

Figure 3.10 shows that participants felt least safe in with No studs, more safe with Passive studs, and most safe with Active studs in each Age group. Comparisons across Stud type show that these differences are highly significant ($t(34) < -6.27$; $p < 0.001$ in each case). Looking at each Age group, we find that all comparisons across Stud conditions remain significant ($t(10\text{-}11) < -3.06$; $p < 0.02$ in each case).

3.3.2 Confidence

Participants were asked to give their subjective ratings of Confidence under the conditions shown in each picture. Results are shown in figure 3.11.

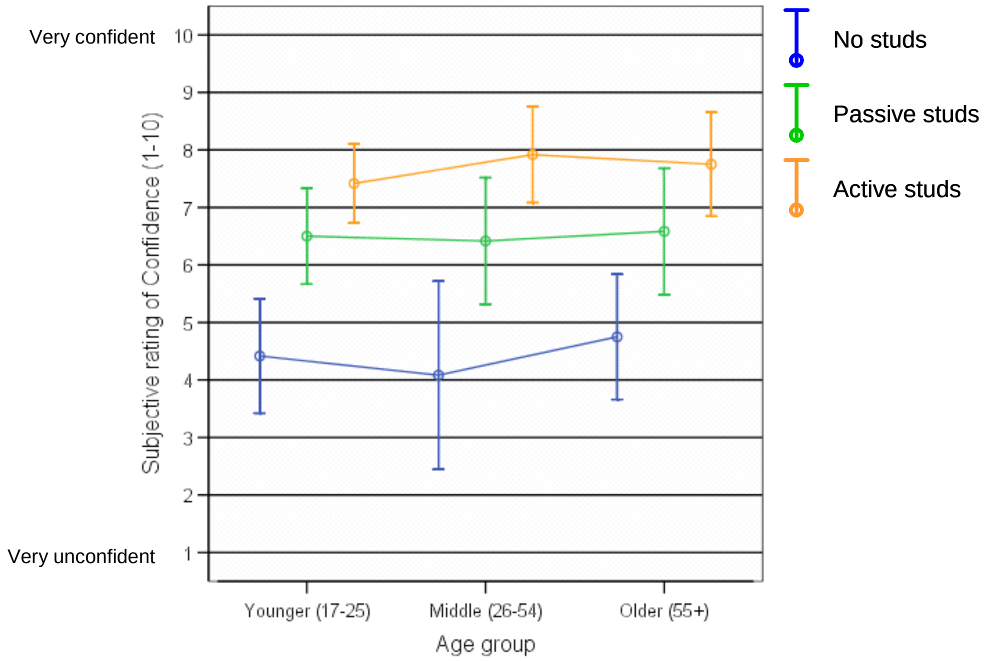

Figure 3.11 Error bar graph to show participants' mean subjective ratings of Confidence across Stud type and Age group

Unsurprisingly, figure 3.11 shows a similar to pattern to that shown for Safety. Participants felt least confident with No studs, more confident with Passive studs, and most confident with Active studs in each Age group. Comparisons across Stud type show that these differences are highly significant ($t(35) < -6.41$; $p < 0.001$ in each case). Looking at each Age group, we find that all comparisons across Stud conditions remain significant ($t(11) < -3.34$; $p < 0.01$ in each case).

3.3.3 Comfort

Participants were asked to give their subjective ratings of Comfort under the conditions shown in each picture. Results are shown in figure 3.12

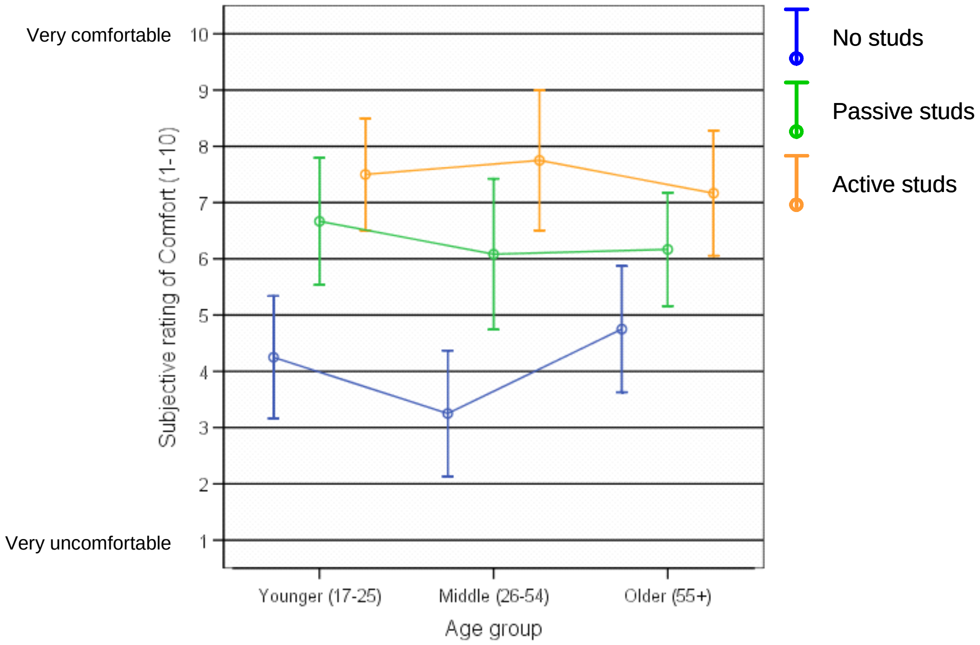

Figure 3.12 Error bar graph to show participants' mean subjective ratings of Comfort across Stud type and Age group

Figure 3.12 shows the consistent pattern. Participants felt least comfortable with No studs, more comfortable with Passive studs, and most comfortable with Active studs in each Age group. Comparisons across Stud type show that these differences are highly significant ($t(35) < -5.30$; $p < 0.001$ in each case). Looking at each Age group, we find that all comparisons across Stud conditions remain significant ($t(11) < -3.07$; $p < 0.02$ in each case), with the exception of the comparison between No studs and Passive studs for the Older group.

3.3.4 Control

Participants were asked to give their subjective ratings of confidence under the conditions shown in each picture. Results are shown in figure 3.13.

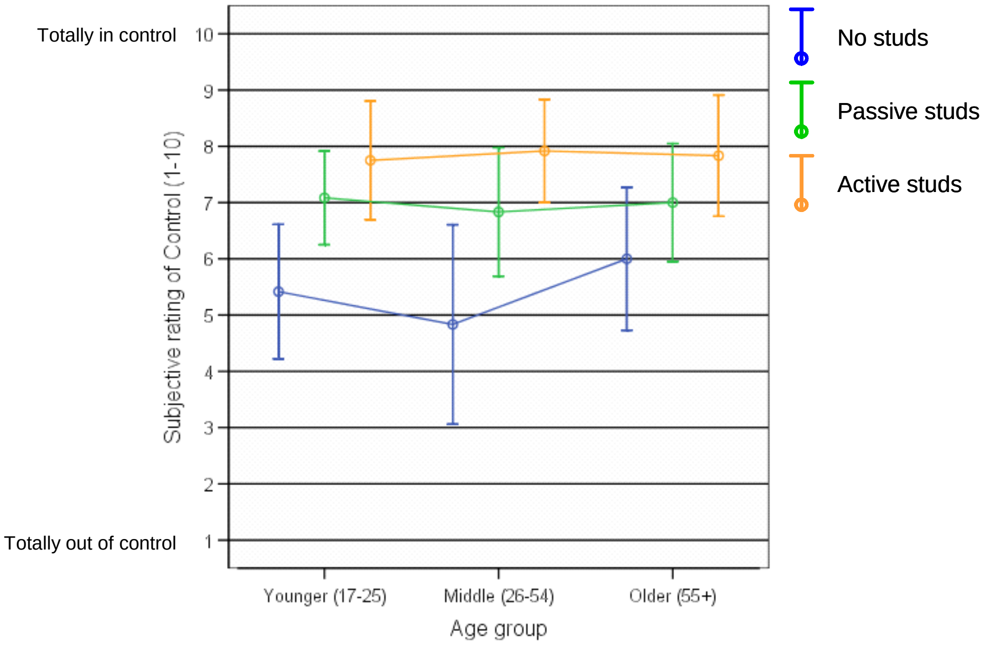

Figure 3.13 Error bar graph to show participants' mean subjective ratings of Confidence across Stud type and Age group

Figure 3.13 shows the same pattern as that shown for Safety, Confidence, and Control. Participants felt least in control with No studs, more in control with Passive studs, and most in control with Active studs in each Age group. Comparisons across Stud type show that these differences are highly significant ($t(35) < -5.37$; $p < 0.001$ in each case). Looking at each Age group, we find that all comparisons across Stud conditions remain significant ($t(11) < -2.60$; $p < 0.03$ in each case), again with the exception of the comparison between No studs and Passive studs for the Older group.

3.3.5 Usefulness

Participants were asked to rate how useful they felt different elements of the road scene were in helping them guide the vehicle along the road.

3.3.5.1 Line markings

Figure 3.14 shows participants' mean subjective ratings of the Usefulness of Line markings in helping them to guide the vehicle along the road.

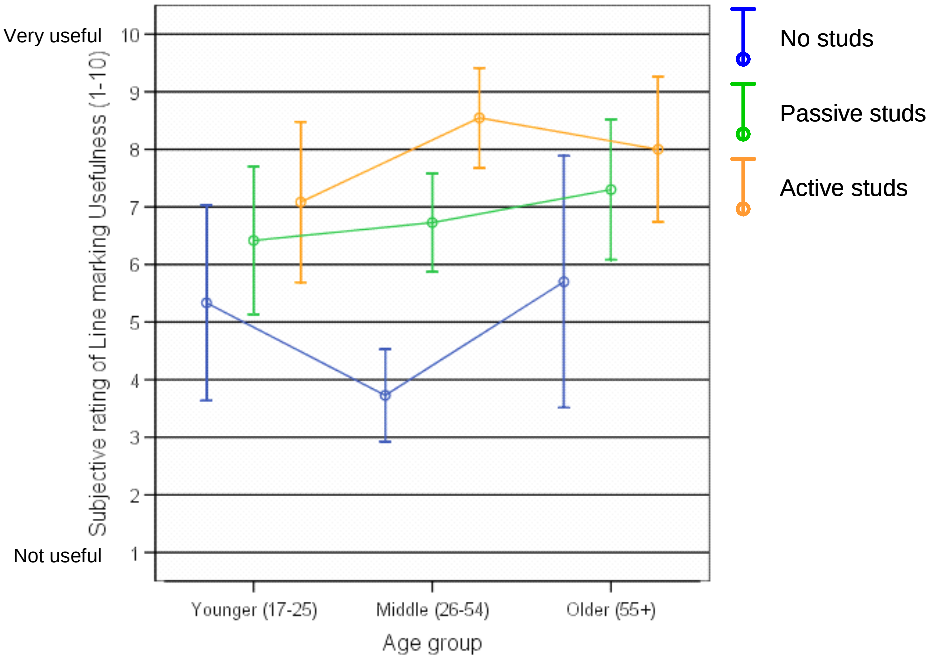

Figure 3.14 Error bar graph to show participants' mean subjective ratings of the Usefulness of Line markings across Stud type and Age group

Figure 3.14 shows a similar pattern to that observed previously. Participants rate line markings most useful with Active studs, less useful with Passive studs, and least useful with No studs. It was anticipated that participants would rate the line markings more useful in the No studs condition since in the absence of any road studs, the line markings would become more important in helping the driver to guide the vehicle. However, participants' ratings in this question suggest that the extra delineation provided by studs increased the usefulness of line markings. The differences across Stud types are all highly significant ($t(32) < -4.04$; $p < 0.001$ in each case). Breaking down the results by Age group, we find that no comparisons reach significance for the Younger age group. However, all comparisons are highly significant for the Middle age group ($t(10) < -3.92$; $p < 0.005$). For the Older participants, only the comparisons involving the Active studs reach significance ($t(9) < -2.32$; $p < 0.05$ in each case).

3.3.5.2 Road signs

Figure 3.15 shows participants' mean subjective ratings of the Usefulness of Road signs in helping them to guide the vehicle along the road.

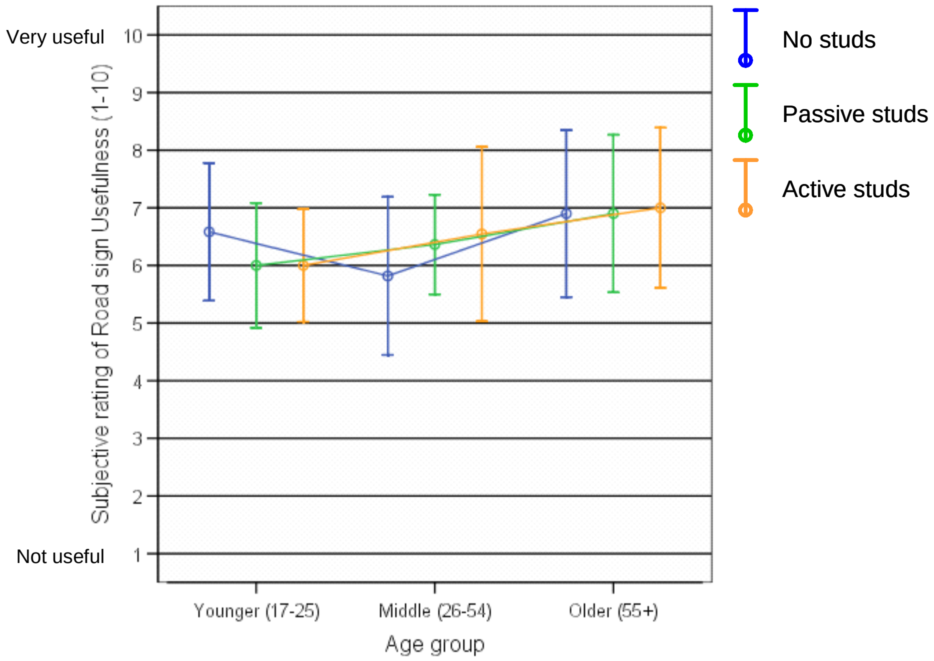

Figure 3.15 Error bar graph to show participants' mean subjective ratings of the Usefulness of Road signs across Stud type and Age group

Figure 3.15 shows that there are essentially no differences across either Age groups or Stud types in participants' ratings of the Usefulness of the Road signs in helping them to guide the vehicle along the road. This is confirmed by non-significant paired-samples t-tests.

3.3.5.3 Road studs

Figure 3.16 shows participants' mean subjective ratings of the Usefulness of the Road studs in helping them to guide the vehicle along the road.

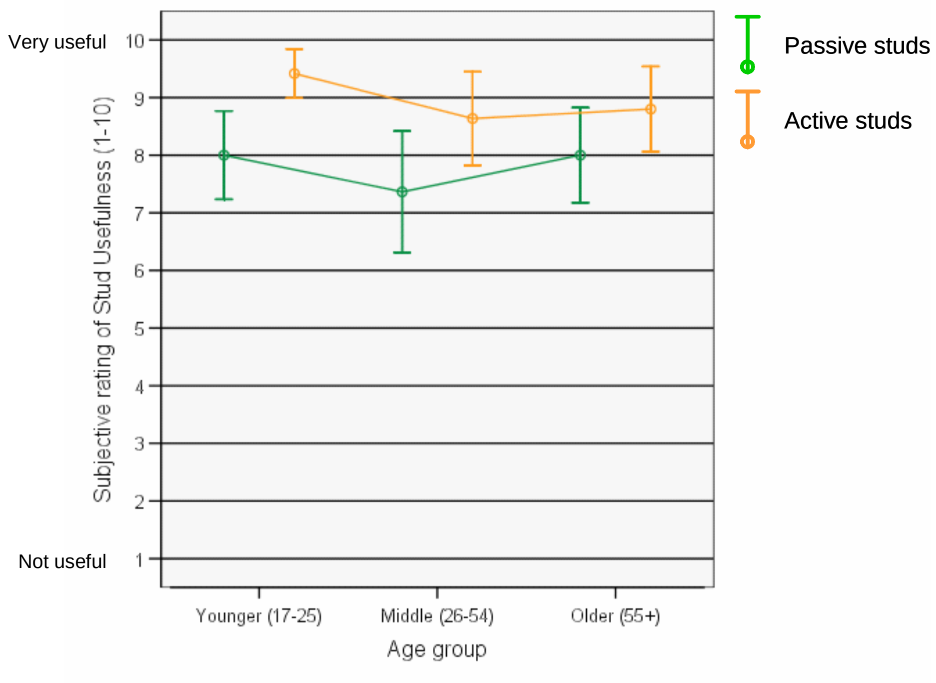

Figure 3.16 Error bar graph to show participants' mean subjective ratings of the Usefulness of Line markings across Stud type and Age group

Figure 3.16 shows that participants find both Passive and Active studs very useful in vehicle guidance – mean ratings are consistently above seven. However, the comparison of the ratings for Passive and Active studs is highly significant ($t(32) = -6.16$; $p < 0.001$). Looking at each Age group, we find that all comparisons remain significant ($t(9\text{-}11) < 2.97$; $p < 0.02$).

3.3.6 *Confidence Day/Night/Active studs*

Participants were asked in the pre-trial questionnaire to rate their confidence when driving and their confidence when driving at night. In the post-trial questionnaire they were asked to rate how confident they would feel when driving on a real road equipped with Active studs. The results are shown in Figure 3.17.

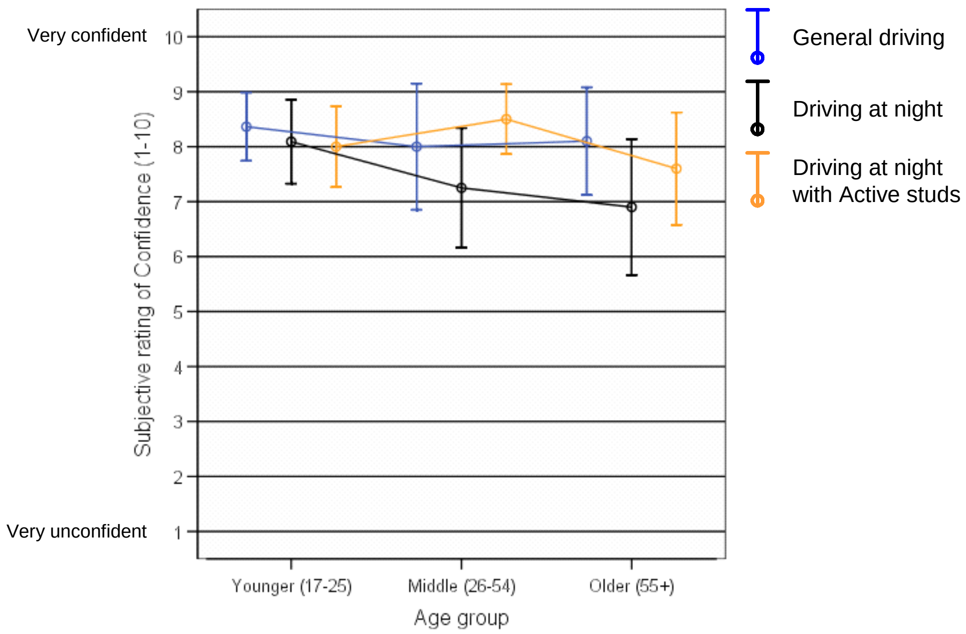

Figure 3.17 Error bar graph to show participants' mean subjective ratings of Confidence in general driving, driving at night, and driving at night with Active studs across Age group

Figure 3.17 shows that Younger participants show similarly high confidence ratings across all conditions. Middle age group participants report the highest confidence when driving at night on roads equipped with Active studs – even exceeding their reported confidence for general driving. Older participants report least confidence when driving at night, greater confidence when driving at night on roads equipped with Active studs, and most confidence in general driving.

Ignoring the Age groups, comparisons across these confidence ratings shows that although there is a highly significant difference between confidence ratings in general driving and driving at night ($t(34) = 5.95$); $p < 0.001$). However, there is no significant difference between participants' confidence in general driving and driving at night on a road equipped with Active studs. Breaking the results down by Age group we find that there are no significant differences for the Younger participants. For the Middle age group participants, we find that the comparison between confidence ratings for general and night driving is significant ($t(11) = 3.45$; $p = 0.005$) whilst the greater confidence shown driving at night with Road studs means that the comparison between that and driving at night also reaches significance ($t(11) = -2.32$; $p = 0.040$). Consequently, the comparison between general driving confidence and confidence when driving on a road equipped with Active studs fails to reach significance. For Older participants, only the comparison between general driving and driving at night reaches significance ($t(11) = 5.61$; $p < 0.001$).

3.3.7 *Relative speed*

Participants were asked three questions about the speed with which they thought they drove through the trial with Active studs. The first asked whether they thought they drove faster with Active studs. The results are shown in figure 3.18.

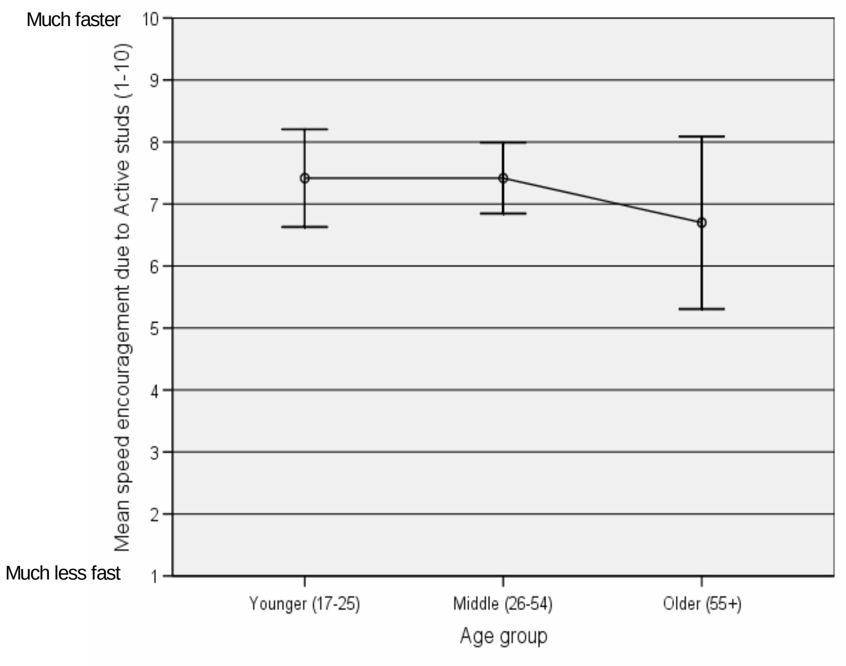

Figure 3.18 Error bar graph to show participants' mean subjective ratings of how much faster they thought they drove with Active studs

The results suggest that the majority of participants believed that they drove significantly faster with Active studs. Older participants did not rate their speed quite so highly with Active studs. Ratings did not differ significantly across Age groups.

3.3.8 *Benefits to Travel/Safety*

Participants were asked to rate on a ten-point scale what difference the introduction of active studs would have to road Travel and to road Safety. The results are shown in figure 3.19.

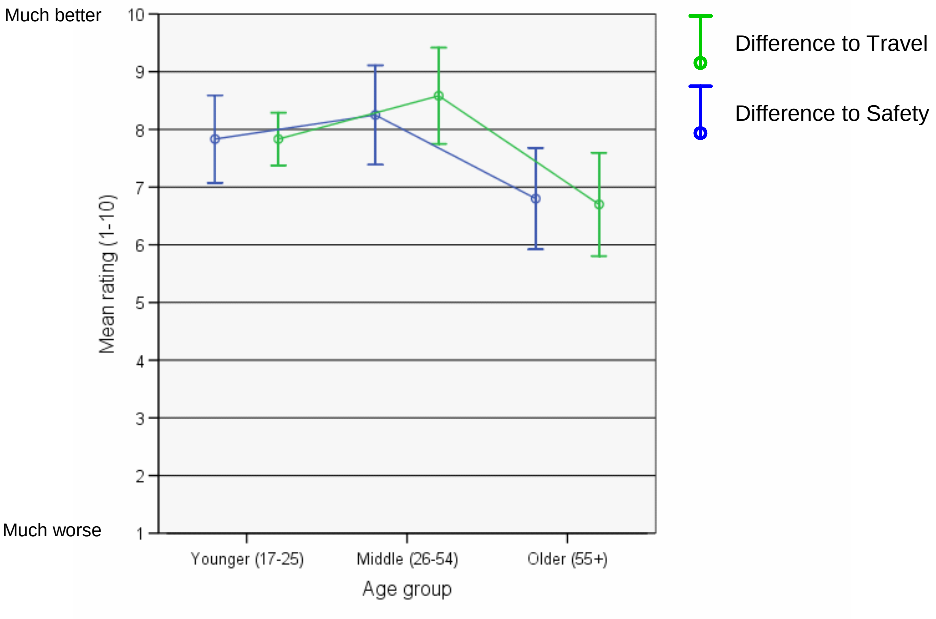

Figure 3.19 Error bar graph to show participants' mean subjective ratings of the difference Active studs would have on road Travel and road Safety

Figure 3.19 shows that participants were very positive about how beneficial the introduction of Active studs would be. A one-way ANOVA was used to compare ratings across Age groups and found that ratings for both Travel ($F(31) = 3.73$; $p = 0.035$) and Safety ($F(31) = 7.79$; $p = 0.002$) differed significantly, whilst Tukey pairwise comparisons revealed that these differences lay between the Middle and Older age groups.

3.3.9 Awareness of Active studs

The final question in the questionnaire asked participants whether they were aware of active studs before participating in the trial at TRL. The results are shown in table 3.2.

Had heard of Active studs	Younger (17-25 years)	Middle (26-54 years)	Older (55+ years)	Total
Yes	2	5	0	7
No	10	6	12	28
Total responses	12	11	12	35

Table 3.2 Frequency of responses as to whether the participant had heard of Active studs before participating in the trial

Table 3.2 shows that just under half of participants in the Middle age group had heard of Active studs whereas awareness of this technology was limited in the other Age groups.

3.3.10 Participant comments

Participants were able to give any general comments they had about the trial and/or active studs at the end of the questionnaire. Given participants' positive ratings for the active studs in previous sections, it was unsurprising to find the majority of participants gave positive comments about the use of active studs. There were 30/36 participants that gave a comment, comprising 9/12 Younger participants, 10/12 Middle participants, and 11/12 Older participants. Of the 30 comments made, 23/30 could be regarded as positive towards the use of active studs (7/9 for the Younger group, 9/10 for the Middle group, 7/11 for the Older group). Some examples of positive comments are as follows:

(i) *They made a huge difference in guiding me along the road*

(ii) *The ability to "read" the road is much better. You can see so much further ahead and so be aware of possible dangers. You can allow more of your concentration to go to you peripheral vision and possible dangers there might be. When the studs disappear there might be a dip in the road so any overtaking would be unwise. The red and white on bends make you more aware of the corners and guide you better than just a white line. The whole driving experience is more enjoyable and stress free, this especially if using an unknown or unfamiliar route. Also very useful in fog/mist not just night time.*

(iii) *I felt much safer and able to judge the road ahead. I felt less "strained" and tense. I also felt it caused less eye strain. When trying to follow poorly marked roads like picture 3 you tended to concentrate on visualising and following the trail looking in front less whereas the road studs drew your vision up and gave you a better feeling of vision. This increased the feeling of being in control.*

(iv) *Actively illumination made driving much easier & more predictable which in my opinion made it much easier, less tiring & therefore much safer. If these are not already in use I would definitely like to see their introduction in particular on unpredictable roads with a lot of curves.*

There were only three comments that could be construed as negative towards the use of active studs, one from each of the age groups. They were:

(i) *The bright red on the left in a left hand bend threw me as white and red studs converged and I felt the road was disappearing.*

(ii) *I think that the road studs could mesmerize drivers and make them sleepy. I had difficulty concentrating.*

(iii) *When I saw the illuminated road studs I knew where I was going so I drove faster which is probably not a good thing.*

It is likely that comment (ii) was due more to the soporific effect of driving the simulator in a night-time environment for an extended period rather than as a consequence of driving with active studs.

There were 6/30 comments that suggested active studs could encourage drivers to increase their speed (3 from the Younger group, 3 from the Older group). An example is as follows:

(i) *Actively illuminated road studs will make a difference for the driver & passengers but might encourage drivers to drive faster. On the whole a good idea.*

3.4 Interrogation of the STATS19 database

Broughton & Buckle (TRL Report 653, 2006) reported that loss of control has been an increasingly common cause of car accidents of all severities since 1999. Indeed, Broughton & Buckle report that no other factors responsible for precipitating accidents had increased in incidence over the same period and in fact most had decreased. To investigate the breakdown of accident data across the factors of road type, age group, and light conditions, information was extracted from the STATS19 database relating to the number of injured people there were in accidents in which there was at least one person killed or seriously injured. Analysis of this data revealed that accidents were most frequent on A-roads. The breakdown is shown in table 3.3.

Road class	Injuries (18-25yrs)	Injuries (35-50yrs)	Injuries (60-99yrs)	Total injuries
Motorway	1545	2961	828	4083
A (M)	81	153	52	223
A	17083	21702	10210	28998
B	6412	8105	3448	13198
C	4187	5155	2030	8851
Unclassified	10299	11844	5128	19027
Total	39607	49920	21696	74380

Table 3.3 Numbers of injuries by class of road in the years 2000-2004

For each accident, the date and time were recorded. Since data relating to the exact location of the accident was not available, this information was cross-referenced to the sunrise and sunset times for a central position in the UK (Birmingham). This enabled accident times to be classified into three groups according to the approximate light level that existed when the accident occurred. If the accident occurred within ±90 minutes of sunrise/sunset, the accident was classed as having occurred in low-light conditions. Outside of these times, accidents were classified as Day or Night accordingly. Figure 3.18 shows the total number of injuries on A-roads, broken down by the light level in which the accident occurred and the Age group of the injured parties.

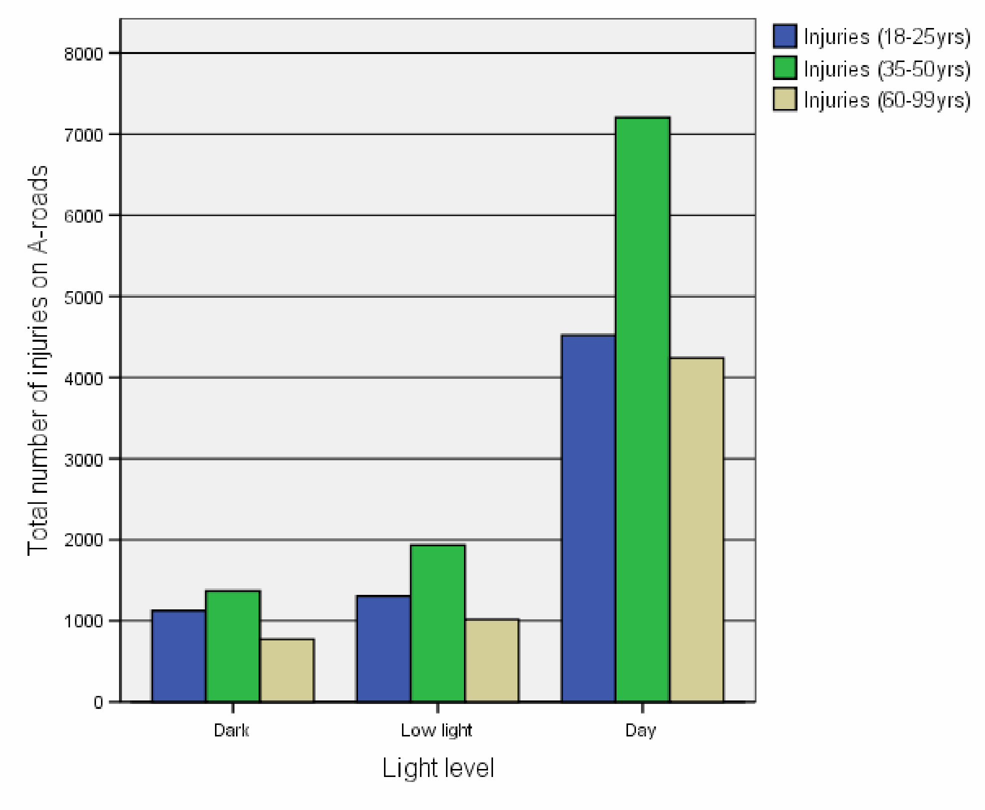

Figure 3.18 Bar graph to show the number of injuries sustained in road accidents on A-roads across the different light levels

Figure 3.18 shows that in Dark and Low light conditions, it is the middle age group that suffers the most injuries. However, this may be due to over-representation of this age group on the roads. Data from the DfT on the number of car journeys completed in 2004 per person per year by age group were used to normalise the number of injuries by the proportion of road users that are likely to be present on the roads within that age group[1]. This data is shown in figure 3.19.

[1] No information is available about the number of journeys that may be completed at night by drivers from each age group. This may give slightly different proportions.

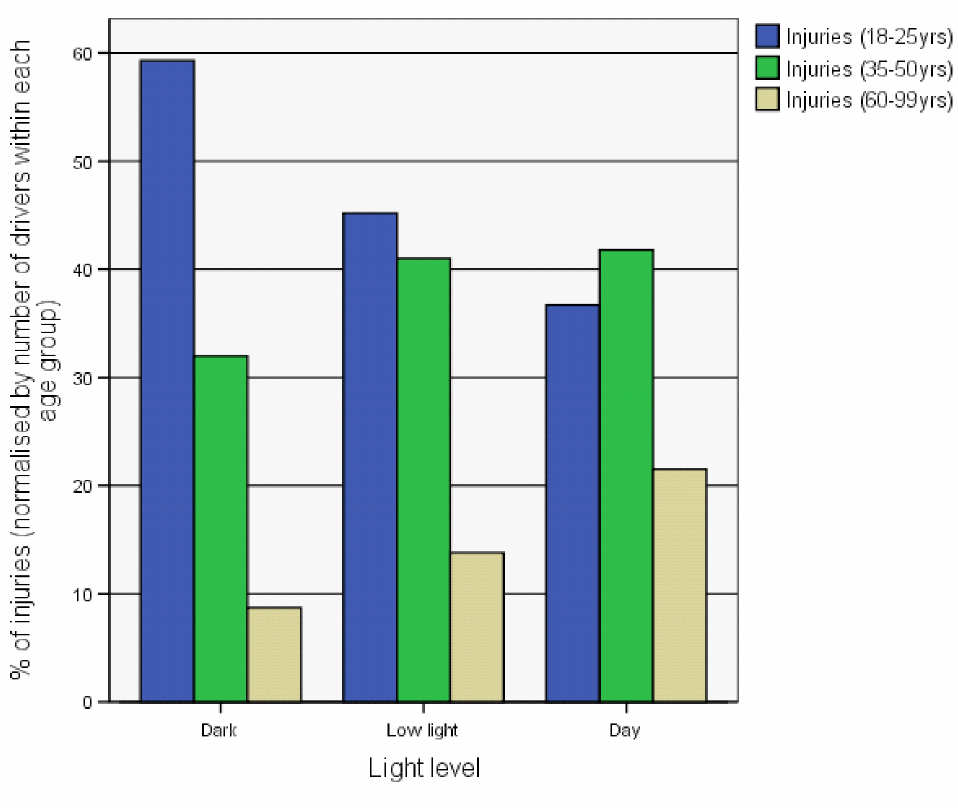

Figure 3.19 Bar graph to show the percentage of injuries sustained in road accidents on A-roads across the different light levels within each age group, normalised by the proportion of users in that age group.

Figure 3.19 shows a markedly different picture to that in the previous figure. It shows that young drivers are greatly over-represented in injuries in dark conditions, relative to the number of trips completed by Younger drivers. Older drivers are the least likely to be injured in a road accident at night in all Light levels. Under Low light and Day light levels, Younger and Middle age group drivers comprise a similar percentage of injuries.

4 Conclusions and Discussion

The first conclusion of this study relates to the hypothesis raised in the Introduction that participants would undergo behavioural adaptation in response to the introduction of active studs, taking advantage of the additional visual information that they provide about the direction of the road to drive faster along the simulated route. The overall speed pattern shows that although participants drove significantly faster with Passive studs and Active studs relative to the No stud condition, they did not drive significantly faster in the Active stud condition relative to their speed in the Passive stud condition. More detailed analysis showed that when the analysis was focussed on the bends, a significant difference was observed between Passive and Active studs for Younger and Older drivers' mean speeds in Left turns (but not for drivers in the Middle Age group) whereby participants maintained a higher average speed through Left turns with the Active studs. This result was investigated further by examining the minimum speed achieved by participants as they negotiated each corner. The results showed that where there were significant comparisons between the Passive and Active stud conditions for mean speed, the comparisons failed to reach significance when minimum speed was considered. This suggests that participants are still slowing to the same speed with Active studs for each bend as they do with Passive studs. It should also be noted that Older participants appeared to drive significantly slower through right turns with Active studs than they do with Passive studs. In terms of speed, the conclusion is that participants do not appear to take bends that are equipped with Active studs at an increased speed that would compromise their safety relative to the speed that they achieve with Passive studs. It is also important to note that participants did not brake any more harshly with Active studs relative to their braking with Passive studs. Furthermore, analysis of the position at which maximum braking was applied revealed participants in both the Younger and the Older age groups appeared to brake at a more consistent position when the Active studs in right turns. This suggests that participants were better informed about how they needed to control the vehicle in order to negotiate the bends when the Active studs were present. A further point in relation to speed is that in the questionnaire participants believed that they drove significantly faster with Active studs. The data suggests that this is not the case and so active studs appear to make people *believe* that they drove faster, possibly by providing additional visual motion cues. This greater speed awareness has positive safety implications since drivers maybe more inclined to reduce their speed if they perceive any hazards in the road.

The duration that participants spent with the right edge of the simulator vehicle across the centreline of the road whilst driving the complete route was assessed across the Stud conditions. It was found that both studded conditions caused significant reductions in the time spent across the centreline. Comparisons for each Age group failed to discriminate across the Passive and Active studs for Younger and Middle age group participants. However, it was found that for the Older age group, Active studs caused participants to spend significantly less time across the centreline than with Passive studs. This result bolsters the safety case for Active studs for drivers in the Older age group. Drivers' ability to guide the vehicle relative to the centreline was further investigated by looking at behaviour in critical corners. It was found that there was a clear advantage for the Active studs over both No stud and Passive stud conditions in right turns suggesting that they reduce drivers' tendency to cut across the centreline in such bends. By examining the data more closely, it was found that this benefit appears to be particularly important for Older drivers since the typical distance that they cross the centreline is significantly reduced with Active studs. Broughton & Buckle (TRL Report 653, 2006) reported that loss of control was the only precipitating factor in the causation of accidents (of all severities) that had shown a significant increase since 1999. The results from this trial suggest that Active studs improve control, particularly in right turns and for Older drivers. It is therefore possible that the introduction of Active road studs may help to reverse this trend.

The failure to find a similar improved lateral control of the vehicle and improved consistency in the position of maximum braking effort for left turns is perhaps due to the layout of the corners. In two of the right turns, the participant would have been able to see red studs on the nearside edge of the road, extending around the corner and, together with the white studs in the centreline, would have provided the driver with additional information about the position and curvature of the bend. For an equivalent left turn, a driver's view of the red studs curving around the nearside edge of the road would have been obstructed by the hedge/wall on the roadside. The driver would therefore have to rely only upon the white studs on the centreline, giving reduced information about the curvature and direction of the bend. This asymmetry in the information available to drivers in left and right turns could be balanced by increasing the conspicuity of delineation cues on the offside road edge. One possible technique could be the use of offside illuminated studs, as shown in figure 4.1.

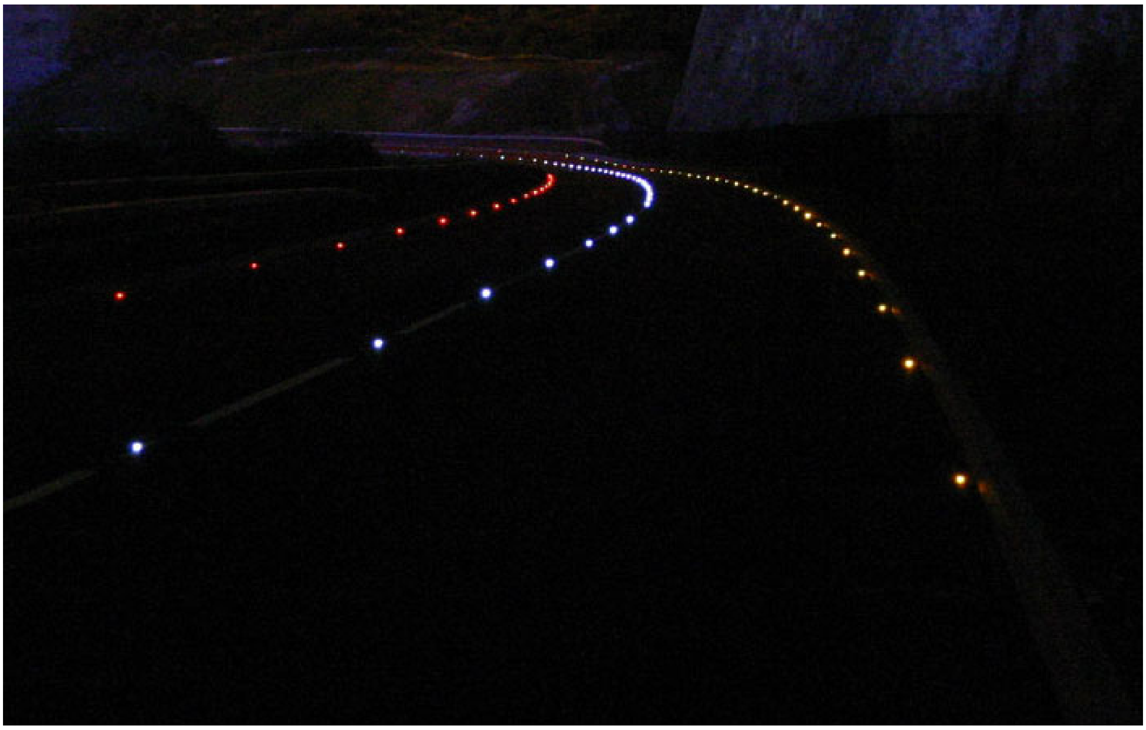

Figure 4.1 Example installation of actively illuminated road studs with nearside red studs, centre-line white studs, and offside amber studs.

Figure 4.1 shows that in a left turn, where visibility of the red studs is restricted beyond the apex of the bend, the addition of the amber studs enhances the information available to the driver about the curvature of the road. With additional cues to highlight the offside road edge, such as those provided by the amber studs in figure 4.1, the simulator results for left turns may have been more similar to those found for right turns. A further simulator study could identify whether enhanced offside delineation would cause similar improvements in lateral control for left turns and what system is most effective and intuitive to drivers e.g. offside red active studs; yellow studs; delineation etc.

The post-trial questionnaire results revealed that participants held very positive feelings towards the Active stud installation that they experienced in the simulator trials. Participants' ratings of their Safety, Comfort, Control, and Confidence with Active studs significantly exceeded those for the No stud or Passive stud conditions. It was also found that participants in the Middle and Older age groups found that Active studs improved the usefulness of line marking in their control of the vehicle. When asked how useful participants found Passive and Active studs, both rated highly. However, Active studs had a significant advantage over the Passive studs. When looking at confidence levels when driving, driving at night, and when driving at night with Active studs, it was found that the Active studs improved drivers' confidence such that it did not differ significantly from their confidence when driving during the day. Participants were very positive about how beneficial the introduction of Active studs would be in terms of differences to road safety and road travel. This is unsurprising given participants' positive ratings for Active studs in terms of Safety, Confidence, Comfort, and Control. However, what is perhaps more surprising is that it was participants from the Younger and Middle age group who give Active studs the most positive ratings whereas the ratings from Older drivers, though still high, are significantly lower. The driving data suggests that it is Older drivers who experience the greatest benefit. This result may be due to Older drivers treating the introduction of any new technologies with a degree of circumspection.

Analysis of the STATS19 database found that the majority of accidents that result in injuries occur on A-roads and that drivers from the Middle age group are the most frequently injured. However, when the data is normalised to reflect the typical age profile of drivers on UK roads, we find that it is the Younger drivers who are the most likely to be involved in an accident on an A-road during the hours of darkness. This represents the main drawback in regards to the benefits of Active studs. However, there were more than four thousand injuries to the over-60 age group between the year 2000 and 2004. Active studs may help to make inroads towards reducing this number, whilst younger populations may also derive some benefit.

The installation of Active road studs in preference to Passive studs represents a significant commitment to a technology that has benefits that are currently more anecdotal than scientific. This study has helped to elucidate where such benefits may lie. It seems that Active studs do not cause drivers to undergo significant behavioural adaptation such that they drive faster with Active studs. This is an important finding since a possible criticism of Active studs is that drivers may proceed faster using the additional information about road direction provided by the Active studs. This sort of adaptation has been observed in drivers using vehicles equipped with ABS brakes. However, very few significant differences were observed between Passive and Active studs in terms of speed and even these disappeared when the drivers' minimum speeds through curves were measured.

The failure to find significant differences in speed between Active and Passive studs, whilst addressing a potential criticism of Active studs, does not present a hugely persuasive argument in their favour. However, the improved vehicle guidance that was observed in right turns is a much more positive result. If drivers are nearer the verge through a right turn, they are less likely to collide or interfere with any oncoming traffic that might be present in the turn, reducing the likelihood of an accident.

Whilst this study has been useful in examining driver behaviour in response to Active studs, it really represents a starting point for determining the implications of their installation. Firstly, it would be of interest to discover whether there were differential benefits of Active studs in poor weather conditions. Secondly, this trial is likely to have been the first occasion on which participants would have driven on a road equipped with actively illuminated road studs. It is possible that the novelty effect of seeing the Active studs affected participants' behaviour in the simulator. A longitudinal study would help to identify whether drivers behave differently when they become accustomed to the benefits that Active studs provide. Thirdly, as mentioned previously, this study revealed that Active studs appeared to assist drivers in maintaining a safe lateral road position in right turns but it was suggested that the asymmetric distribution of nearside (red) and centreline (white) studs may have been responsible for the failure to find an effect in left turns. A further study using enhanced offside delineation such as offside road studs would help to establish whether this was the case. Furthermore, this trial only touched on the possible uses that Active studs may have. Flashing Active studs could be used to warn drivers of an upcoming hazard or congestion, animated Active studs could be used to help drivers to choose an appropriate speed through roadworks or a roundabout, Active studs could be used to implement dynamic lane markings – these are a few of the possible applications of this technology. However, each must be tested to evaluate its potential benefit and to assess whether drivers would undergo behavioural adaptations of the type described above.

In summation, actively illuminated road studs appear to offer a safety benefits over and above that offered by high specification passively illuminated road studs without any associated increase in speed. The advantages of Active studs appear to be felt most keenly by drivers in the older population through improving vehicle guidance in right turns. This finding must tempered against the slight speed increase observed with Active studs through left turns. It is also unfortunate that the biggest safety benefit appears to be for the older driver population who are least likely to be involved in an accident on a rural A-road at night. Drivers across the age range of participants were overwhelmingly positive in their subjective feelings on their experience of Active studs and on the potential benefits that their introduction might have and this may be an important factor as their installation is likely to be viewed similarly positively by real road users.

Acknowledgements

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Appendix A. TRL Driving Simulator

A.1 TRL Driving Simulator

TRL has successfully operated a driving simulator for 15 years and in that time the simulator has seen a number of different incarnations over time to keep pace with improvements in vehicle, projection, computing, and simulation technologies and as such is the most advanced simulator in the UK. The latest iteration uses a Honda Civic family hatchback (Figure A1). Its engine and major mechanical systems have been replaced by a sophisticated electric motion system that drives rams attached to the axles underneath each wheel. These impart limited motion in three axes (heave, pitch, and roll) and provide the driver with an impression of the acceleration forces and vibrations that would be experienced when driving a real vehicle. This significantly enhances the realism with which drivers approach the driving task and reduces the incidence of simulator sickness (a condition with symptoms similar to those of motion sickness) among participants. All control interfaces have a realistic feel and the manual gearbox can be used in the normal manner (automatic gears can be simulated).

Figure A1 – TRL Driving Simulator

Surrounding the simulator vehicle are large display screens onto which are projected the graphic images that represent the external environment to the driver. The level of environmental detail includes photo-realistic images of buildings, vehicles, signing, and markings, with terrain accurate to the camber and texture of the road surface. We have also recently added the capability to simulate night-time driving scenarios. The driving environment is projected at resolution of 1280×1024 onto three forward screens give the driver a 210º horizontal forward field of view. The presence of the two flat side screens adjacent to the driver gives a very strong impression of other vehicles travelling alongside of the vehicle. A rear screen provides a 60º rearward field of view, thus enabling normal use of all mirrors.

Surveillance video cameras are mounted in the car and participants can be recorded during their drive. There is also an intercom facility for communication between the vehicle and the control room. An in-car colour LCD display can also be used to give instructions or provide other task-related information.

Figure A2 – TRL Driving Simulator: Control Room

More than fifty autonomous traffic vehicles can be programmed to participate in the simulation. TRL has a library of different vehicle types to choose from including cars, trucks, buses, emergency vehicles, bicycles, and pedestrians. Each obeys specific driving rules to behave in a normal manner with respect to other traffic vehicles. However, these can be overridden causing them to perform specific manoeuvres e.g. emergency stop, sudden lane change etc. The autonomous vehicles also have dynamic properties of their own – they appear to pitch realistically under acceleration and braking, and vehicle graphics include body tilt and roll under braking, acceleration and turning; speed dependent rotating wheels and fully working brake, indicator, fog and head lights. These provide additional cues to the driver and greatly enhance the realism of a scene. To generate scenarios with a heavy traffic load (> 1700 vehicles per lane per hour) we can generate a vehicle 'swarm'. The swarm function allows us to define a region around the driver where vehicles will be placed and controlled. A vehicle moving out of the visible range of the driver is replaced by a new vehicle positioned to maintain the desired traffic density. This gives the impression of very high volume of traffic while maintaining the performance of the simulator.

A stereo sound system with speakers inside and outside the vehicle generates realistic engine, road, and traffic sounds to complete the representation of the driving environment. The software used to implement the simulation is called SCANeR II and was created by OKTAL to provide a flexible and powerful simulation with a highly advanced traffic model. It is employed by more than twenty research institutes across the globe and TRL leads the user group with access to OKTAL expertise for trial set-up and integration, if required.

The dynamics of the vehicle are modelled using a validated vehicle model that is used for product development by Renault. The model interprets the driver's control inputs, relates them to the current vehicle status and computes a prediction of how a real vehicle would behave in the given circumstances. The system then responds to present to the driver its optimal representation of how this behaviour would be perceived through the visual, sound, and motion sub-systems. This entire process is repeated at 60Hz so that the driver perceives a seemingly continuous driving experience. Data is then recorded relating to all control inputs made by the driver, including steering, pedals, gear, indicators; vehicle parameters such as speed, RPM; and parameters to assess behaviour in relation to other vehicles such as distance and time headways.

Participants for trials are recruited from a dedicated database of over 1300 members of the public. This comprises drivers from a wide range of ages and backgrounds, all of whom are familiar to TRL such that participants from particular demographic bands or driving experience/ability ratings can be selected to suit the trial requirements. The simulator facilities include a medical room for taking any physiological measures and trials management staff are trained in Good Clinical Practice. There is an interview room for questionnaire completion and debriefing and an information room for conducting simple computer tests. Data management procedures are well established and compliant with the Data Protection Act 1998 to ensure security, confidentiality, and integrity of all records.

Appendix B. Questionnaires

This appendix shows the pre- and post-drive questionnaires used in the trial.

B.1 Pre-drive questionnaire

To be completed by TRL Participant Number: ________________		Date of Trial: _____/_____/_________	
Driving Simulator Study: Night-time driving			
SECTION A DRIVER PROFILE			
Note: • All information on this form is confidential. • It will be stored securely at TRL. • No information will be used by other projects at TRL. • No individuals will be identified.			
A1. Name			
A2. What was your age at your last birthday?			
A3. Are you Male or Female (tick)?			
Male		*Female*	
A4. How many years have you held a full driving licence?			
A5. Approximately how many miles have you driven in the last year?			
A6. What type of vehicle(s) do you drive (tick all those that apply)?			
		Motorcycle	
		Car	
		Light Goods Vehicle	
		Heavy Goods Vehicle	

SECTION B YOUR DRIVING									
(Please circle the number that you feel is most appropriate)									
B1. In general, do you enjoy driving?									
Completely dislike driving									*Thoroughly enjoy driving*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
B2. On how many days do you drive in a typical week?									
	Never							*Everyday*	
	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	
B3. How confident do you feel when driving?									
Very unsure									*Very confident*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
B4. How confident do you feel when driving at night?									
Very unsure									*Very confident*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
B5. How often do you break the speed limit in these three environments?									
(a) In TOWN?									
Very infrequently									*Very frequently*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
(b) On COUNTRY ROADS?									
Very infrequently									*Very frequently*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
(c) On MOTORWAYS?									
Very infrequently									*Very frequently*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*

End of Pre-drive questionnaire

B.2 Post-drive questionnaire

To be completed by TRL

Participant Number: ________________ Date of Trial: _____/_____/_________

Driving Simulator Study: Night-time driving

SECTION C

DRIVING CONDITIONS

PLEASE REFER TO THE PICTURES PROVIDED

Each picture shows a screenshot of a section of the road that you have driven

C1. How ***safe*** did you feel when driving along the road as shown in:

(a) PICTURE 1?

Very unsafe									*Very safe*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*

(b) PICTURE 2?

Very unsafe									*Very safe*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*

(c) PICTURE 3?

Very unsafe									*Very safe*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*

C2. How ***confident*** did you feel when driving along the road as shown in:

(a) PICTURE 1?

Very unconfident									*Very confident*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*

(b) PICTURE 2?

Very unconfident									*Very confident*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*

(c) PICTURE 3?

Very unconfident									*Very confident*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*

C3. How ***useful*** were the line markings in helping you to guide the car along the country road in:									
(a) PICTURE 1?									
Not useful									*Very useful*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
(b) PICTURE 2?									
Not useful									*Very useful*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
(c) PICTURE 3?									
Not useful									*Very useful*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
C4. How ***useful*** were the road signs in helping you to guide the car along the country road?									
(a) PICTURE 1?									
Not useful									*Very useful*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
(b) PICTURE 2?									
Not useful									*Very useful*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
(c) PICTURE 3?									
Not useful									*Very useful*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
C4. How ***useful*** were the road studs (‘*cat’s eyes*’) in helping you to guide the car along the country road?									
(a) PICTURE 1?									
Not useful									*Very useful*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
(b) PICTURE 2?									
Not useful									*Very useful*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*

C5. How ***comfortable*** did you feel when driving along the road as shown in:									
(a) PICTURE 1?									
Very uncomfortable									*Very comfortable*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
(b) PICTURE 2?									
Very uncomfortable									*Very comfortable*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
(c) PICTURE 3?									
Very uncomfortable									*Very comfortable*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
C6. How much ***control*** did you feel you had over the car when driving along the road as shown in:									
(a) PICTURE 1?									
Totally out of control									*Totally in control*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
(b) PICTURE 2?									
Totally out of control									*Totally in control*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
(c) PICTURE 3?									
Totally out of control									*Totally in control*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*

SECTION D FINAL OPINIONS									
QUESTIONS IN THIS SECTION REFER TO ACTIVELY ILLUMINATED ROAD STUDS (LIKE THOSE SHOWN IN PICTURE 2)									
D1. How **confident** would you feel about driving at night on roads equipped with actively illuminated road studs?									
Very unsure									*Very confident*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
D2. Do you feel that the actively illuminated road studs encouraged to you to drive:									
Much less fast				*No change*					*Much faster*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
D3. What difference to **travel** do you think use of the actively illuminated road studs might have?									
Much worse				*No change*					*Much better*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
D4. What difference to **safety** do you think use of the actively illuminated road studs might have?									
Much worse				*No change*					*Much better*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
D5. In the driving task, what effect do you feel that the actively illuminated road studs had on your speed? Compare relative to sections of road where there were:									
(a) PASSIVELY ILLUMINATED ROAD STUDS (Picture 1)									
Much less fast				*No change*					*Much faster*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
(b) NO ROAD STUDS (Picture 3)									
Much less fast				*No change*					*Much faster*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*

Continued over the page…

D6.	Prior to today's driving task, had you seen or heard any information about actively illuminated road studs (like those shown in picture 2)?			
	Yes		*No*	
D7.	Do you have any other comments about today's driving task or the use of actively illuminated road studs?			

End of Questionnaire

Thank you very much for your participation in this study.

Appendix C. Pictures used in association with post-drive questionnaire

The pictures shown below are those used in association with the post-trial questionnaire. They were used to remind participants of the road stud conditions that they experienced in the two drives. The position of the vehicle was chosen so that a bend warning sign and lane markings were visible

Figure C1. Picture 1 showed the road with Passive road studs in place.

Figure C2. Picture 2 showed the road with Active road studs in place.

Figure C3. Picture 3 showed the road with no road studs.

Appendix D. Recorded simulator data

The table below lists the variables recorded at 20Hz within each drive completed in the simulator.

Recorded variable	Unit	Description
Frame	-	Frame number of data file
Time	s	Time since start of data recording
X	m	X position of driven vehicle
Y	m	Y position of driven vehicle
Z	m	Z position of driven vehicle
Speed	km/h	Current driven vehicle speed
PK	m	Distance travelled along trial route
Lane	-	Lane number of driven vehicle
Lateral position	m	Lateral position of driven vehicle relative to road centre-point
Headlights	-	Driven vehicle headlight state
Indicators	-	Driven vehicle indicator state
Accelerator	(0-1)	Accelerator pedal depression
Brake	(0-1)	Brake pedal depression
Steer	(-1 to +1)	Current steering angle
Gearbox	-	Current gear (1-5; neutral = 0)
Acceleration in X	ms^{-2}	Lateral acceleration of the driven vehicle
Acceleration in Y	ms^{-2}	Longitudinal acceleration of the driven vehicle
Acceleration in Z	ms^{-2}	Vertical acceleration of the driven vehicle
Heading	°	Current compass heading of the driven vehicle
Pitch	°	Pitch angle of vehicle
Roll	°	Roll angle of vehicle
TLC(Heading)	s	Time to line crossing based on current forward velocity
TLC(Lat)	s	Time to line crossing based on current lateral velocity
TLC(Path)	s	Time to line crossing based on current path and speed
Road curvature		Inverse of road radius (sign of value gives direction of curvature)
Road radius		Radius of curvature of road at current driven vehicle position
Road slope	°	Slope angle of road
Correct Lights		Value to check correct headlight mode is engaged
Section		Section number in which the driven vehicle is currently situated (0-7)

Table D1. Recorded simulator data

Appendix E. Corner profiles

This section shows eight graphs for each of the twelve corners (1-6A and 1-6B) in the study. The graphs show the mean values recorded across all instances of that corner for each stud type. Since each unique corner was driven twice by each of the thirty-six participants for each stud type, the mean values were calculated across seventy-two values. Error bars, where shown, represent the 95% confidence interval on the mean.

The eight graphs shown are as follows:

(ix) X-Y position (m)

(x) Speed (mph) vs. Distance to corner (m)

(xi) Accelerator pedal depression (0-1) vs. Distance to corner (m)

(xii) Brake pedal depression (0-1)vs. Distance to corner (m)

(xiii) Time to line crossing – path (sec) vs. Distance to corner (m)

(xiv) Left wheel distance to verge (m) vs. Distance to corner (m)

(xv) Right wheel distance to centreline (m) vs. Distance to corner (m)

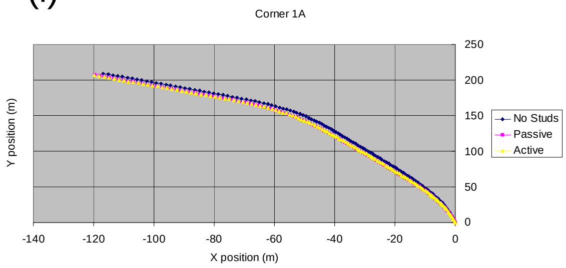
(xvi) Steering input vs. Distance to corner (m)

Data was recorded at 20Hz but in order to calculate a genuine average across participants, values from fixed distances need to be taken. To achieve this, the data points were interpolated to find data values every two metres. The zero point of each corner is taken as the first point at which the curve radius falls below 150m. Curve direction, length, and minimum radius are shown in the table below:

Corner	Direction	Length (m)	Minimum radius (m)	Red studs on nearside
1A	Left	50	80	Yes
2A	Right	50	110	No
3A	Left	90	110	No
4A	Right	70	110	No
5A	Left	40	110	No
6A	Right	50	80	Yes
1B	Left	50	80	Yes
2B	Right	40	110	No
3B	Left	70	110	No
4B	Right	90	110	No
5B	Left	50	110	No
6B	Right	50	80	Yes

Corner 1A

(i)



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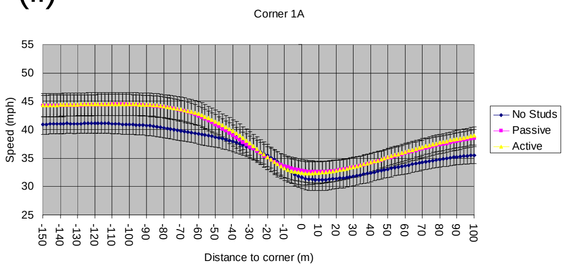

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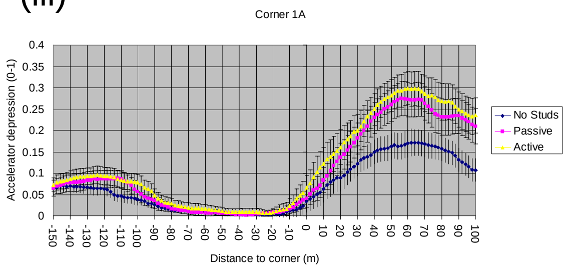

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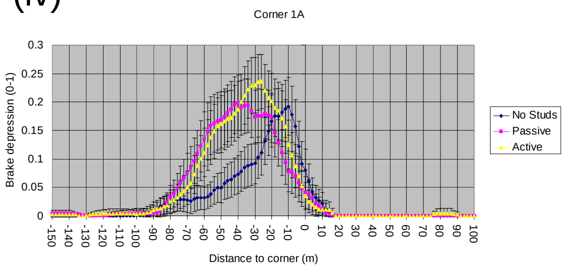

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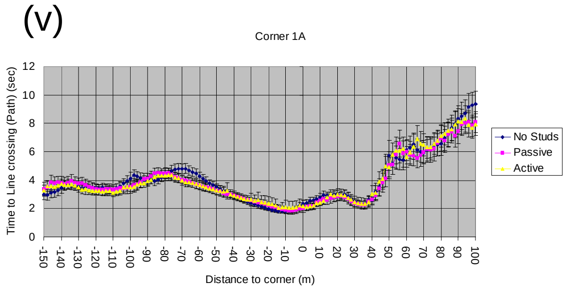
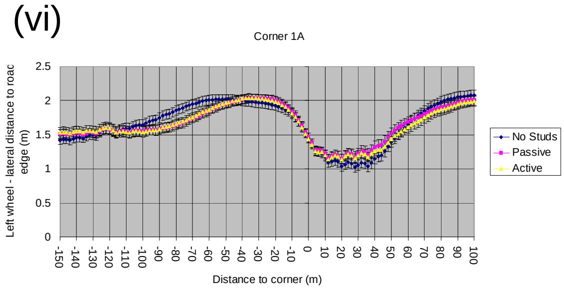
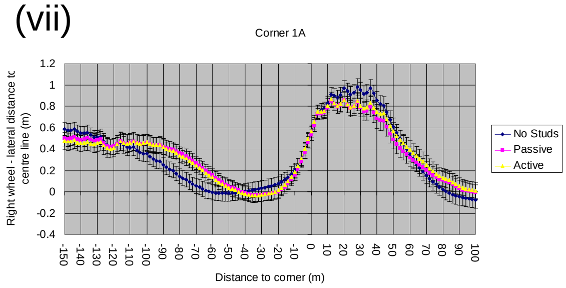


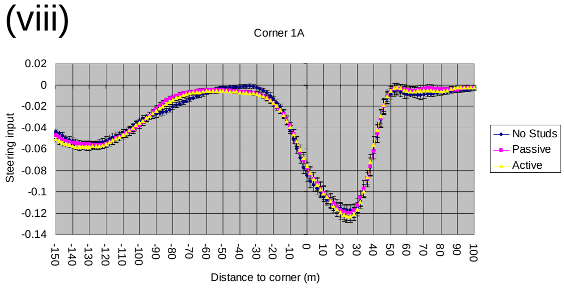
(vi)



(vii)



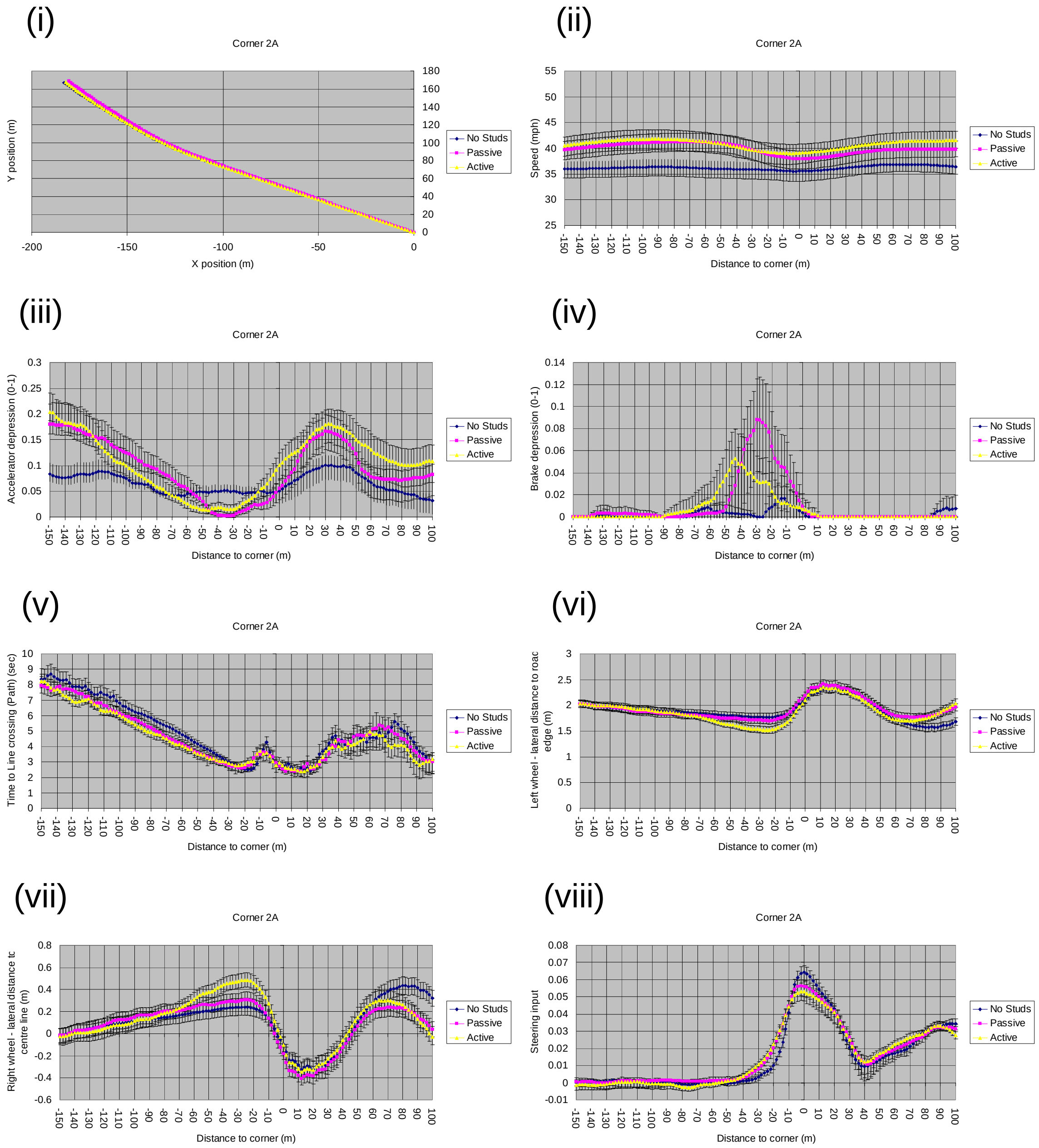
(viii)



<u>Key to charts:</u>

(i)	X-Y position (m)	(ii)	Speed (mph)
(iii)	Accelerator pedal depression (0-1)	(iv)	Brake pedal depression (0-1)
(v)	Time to line crossing - path (sec)	(vi)	Left wheel distance to verge (m)
(vii)	Right wheel distance to centreline (m)	(viii)	Steering input

Corner 2A

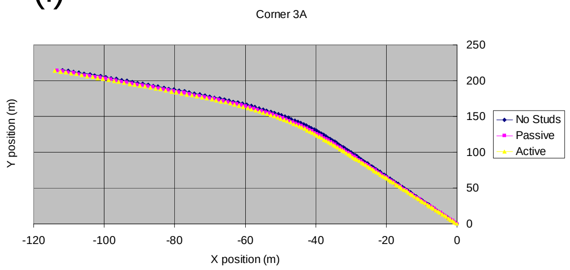


Key to charts:

(i)	X-Y position (m)	(ii)	Speed (mph)
(iii)	Accelerator pedal depression (0-1)	(iv)	Brake pedal depression (0-1)
(v)	Time to line crossing - path (sec)	(vi)	Left wheel distance to verge (m)
(vii)	Right wheel distance to centreline (m)	(viii)	Steering input

Corner 3A

(i)



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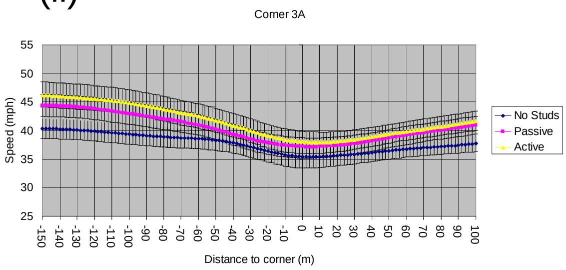

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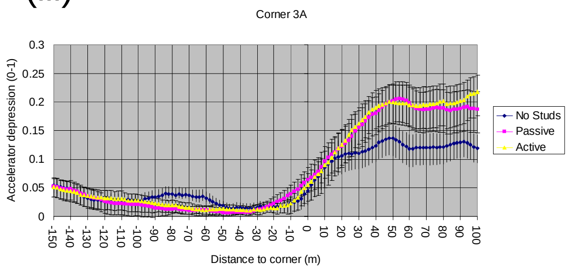

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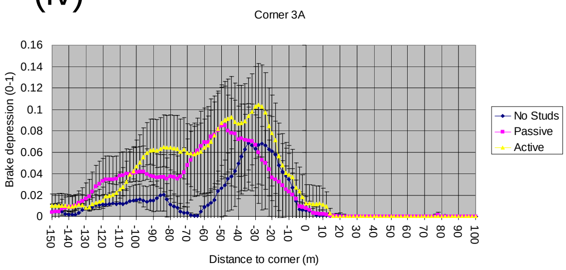

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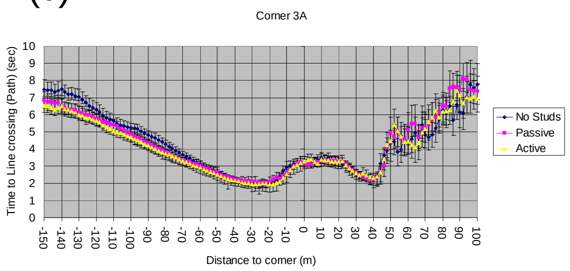

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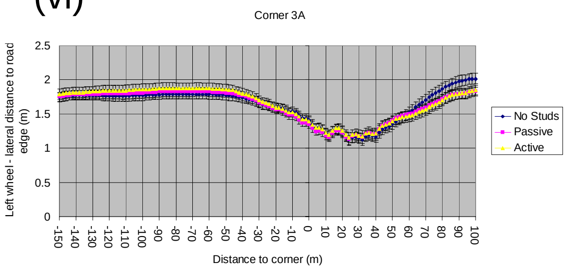

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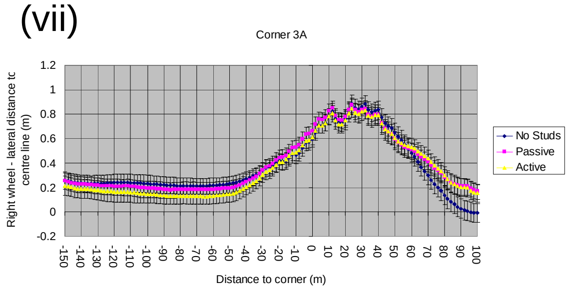

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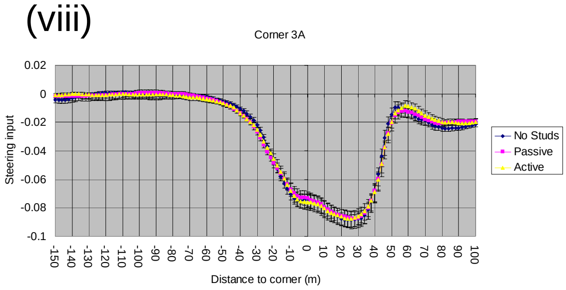
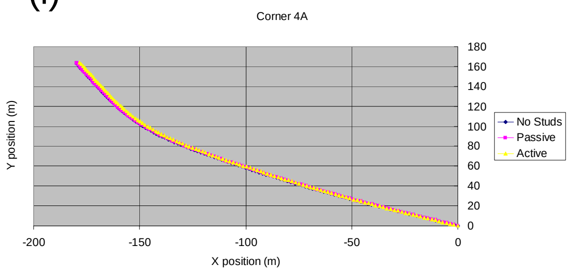


Key to charts:

(i)	X-Y position (m)	(ii)	Speed (mph)
(iii)	Accelerator pedal depression (0-1)	(iv)	Brake pedal depression (0-1)
(v)	Time to line crossing - path (sec)	(vi)	Left wheel distance to verge (m)
(vii)	Right wheel distance to centreline (m)	(viii)	Steering input

Corner 4A

(i)



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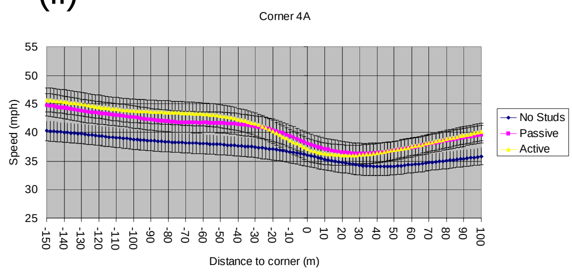

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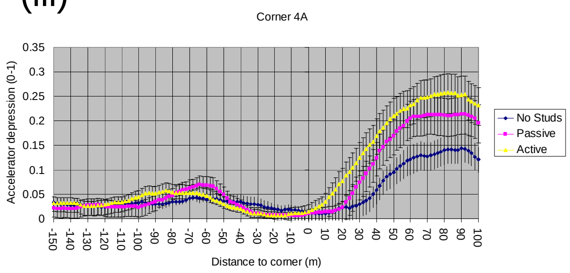

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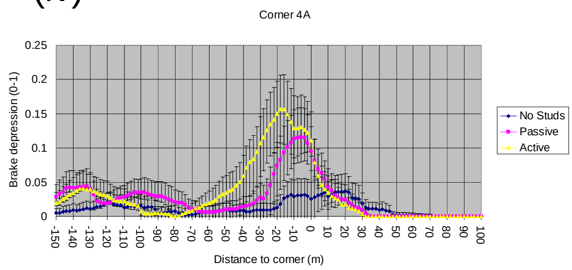

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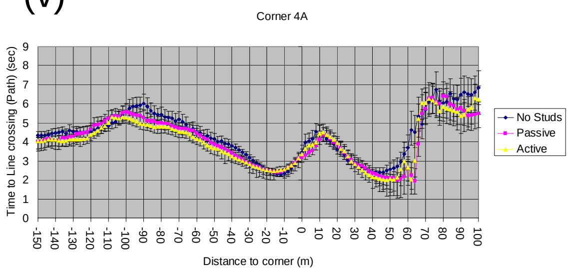

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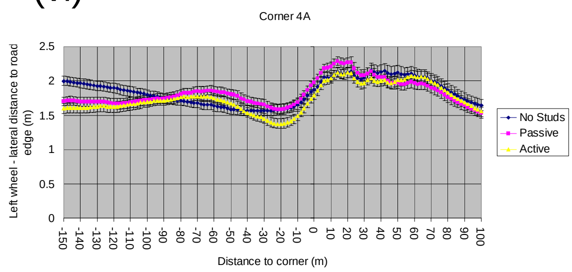

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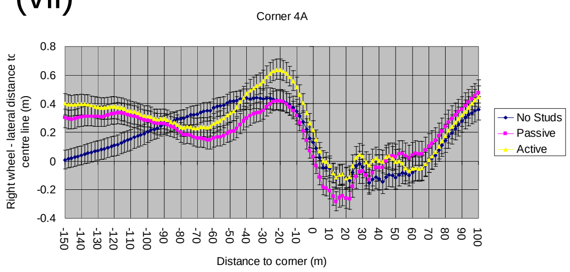

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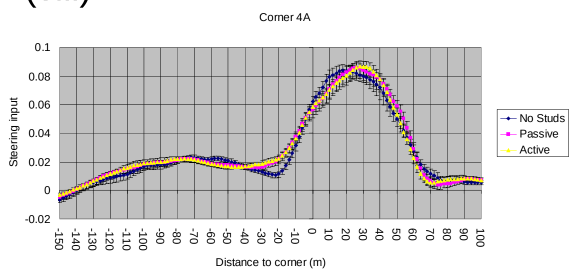
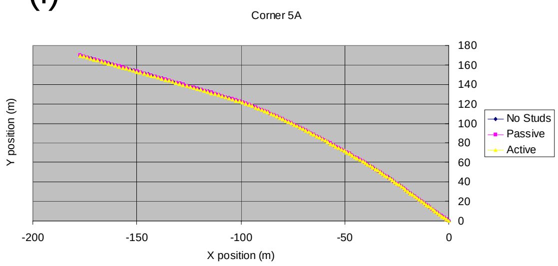


Key to charts:

(i)	X-Y position (m)	(ii)	Speed (mph)
(iii)	Accelerator pedal depression (0-1)	(iv)	Brake pedal depression (0-1)
(v)	Time to line crossing - path (sec)	(vi)	Left wheel distance to verge (m)
(vii)	Right wheel distance to centreline (m)	(viii)	Steering input

Corner 5A

(i)



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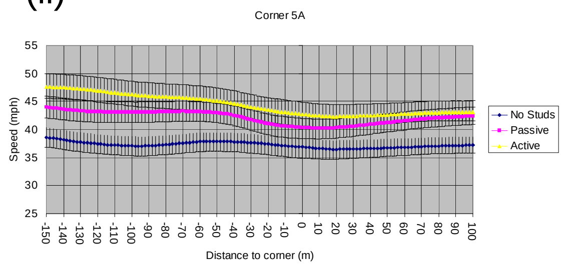

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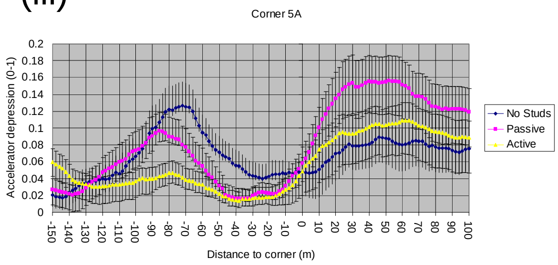

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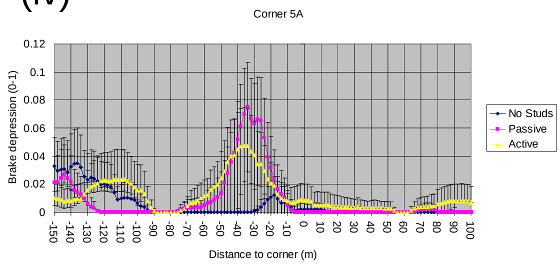

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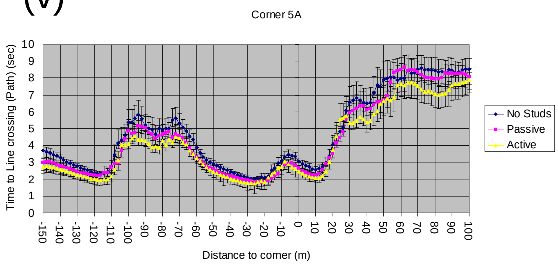
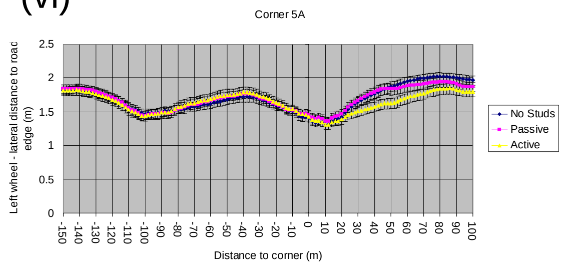


(vi)



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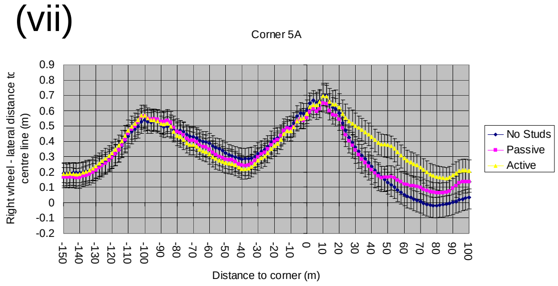

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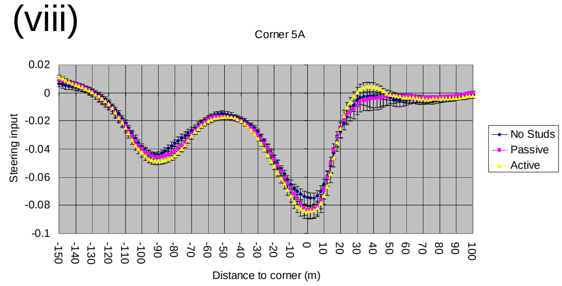
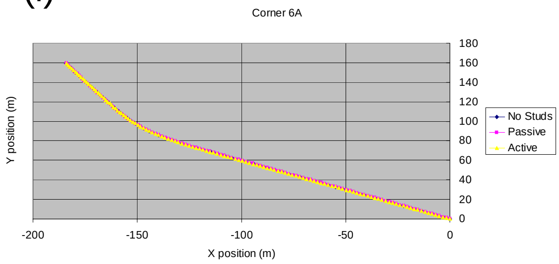


<u>Key to charts:</u>

(i)	X-Y position (m)	(ii)	Speed (mph)
(iii)	Accelerator pedal depression (0-1)	(iv)	Brake pedal depression (0-1)
(v)	Time to line crossing - path (sec)	(vi)	Left wheel distance to verge (m)
(vii)	Right wheel distance to centreline (m)	(viii)	Steering input

Corner 6A

(i)



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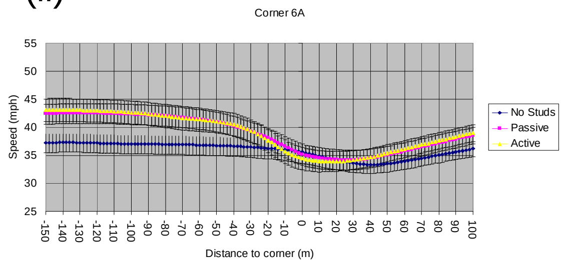

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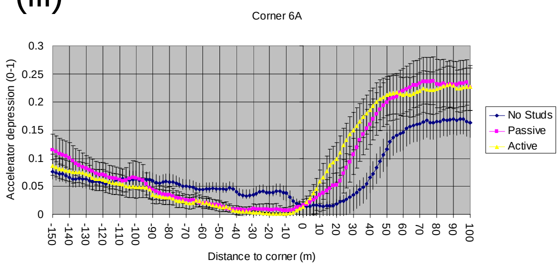

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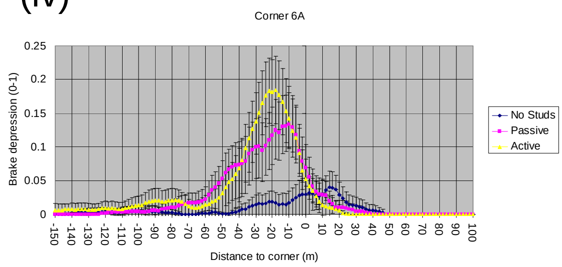
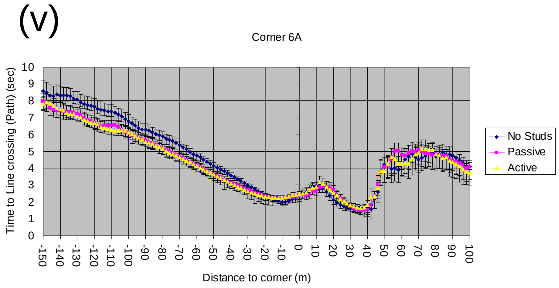
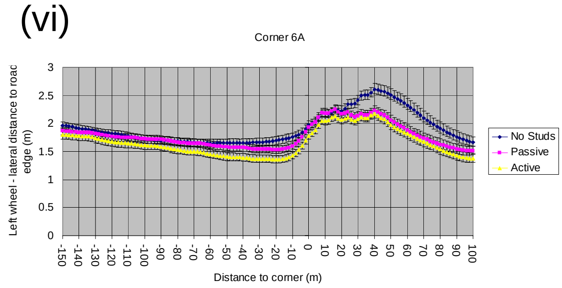


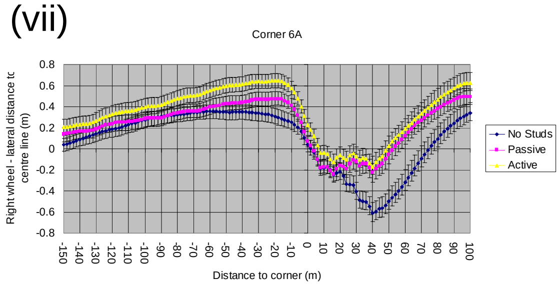
(v)



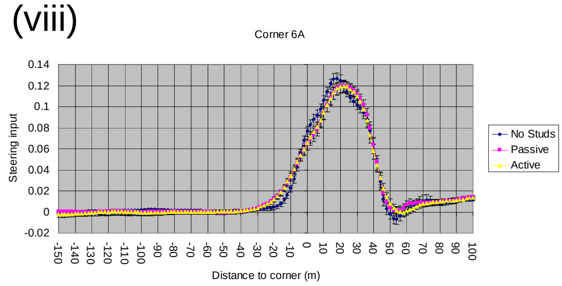
(vi)



(vii)



(viii)

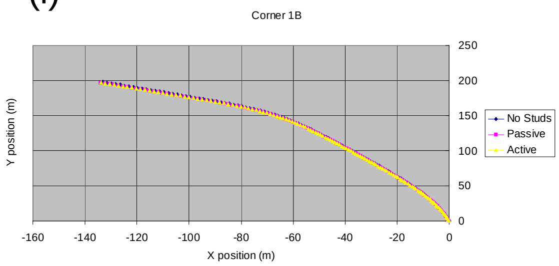


<u>Key to charts:</u>

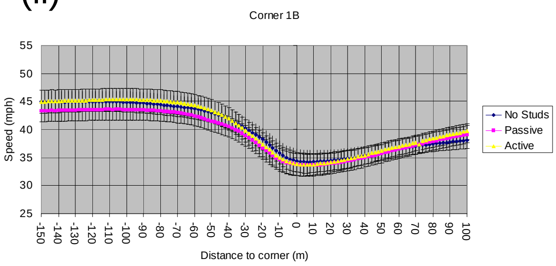
(i)	X-Y position (m)	(ii)	Speed (mph)
(iii)	Accelerator pedal depression (0-1)	(iv)	Brake pedal depression (0-1)
(v)	Time to line crossing - path (sec)	(vi)	Left wheel distance to verge (m)
(vii)	Right wheel distance to centreline (m)	(viii)	Steering input

Corner 1B

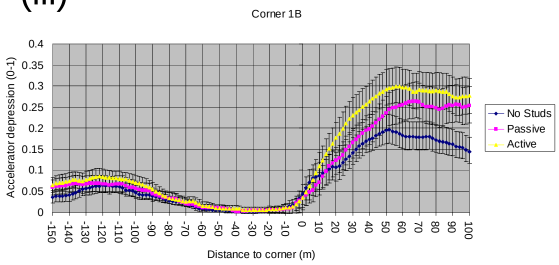
(i)



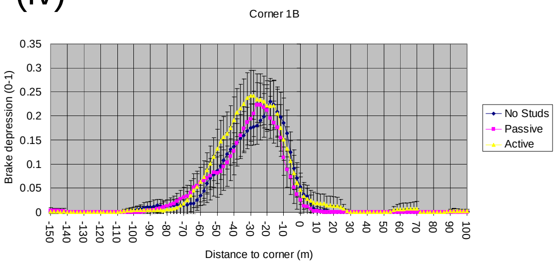
(ii)



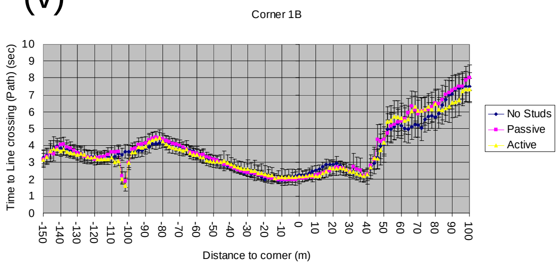
(iii)



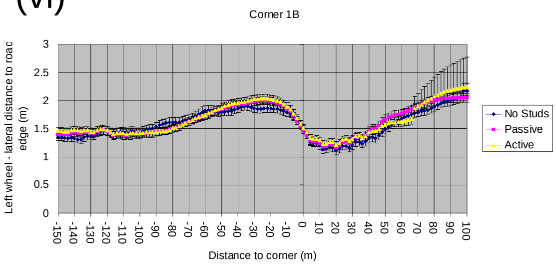
(iv)



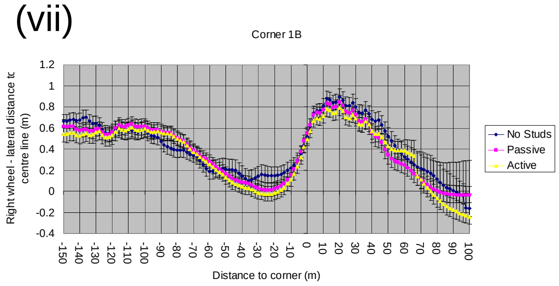
(v)



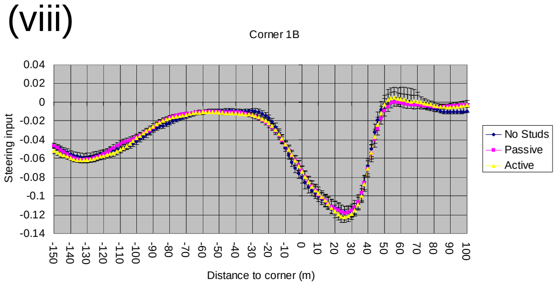
(vi)



(vii)



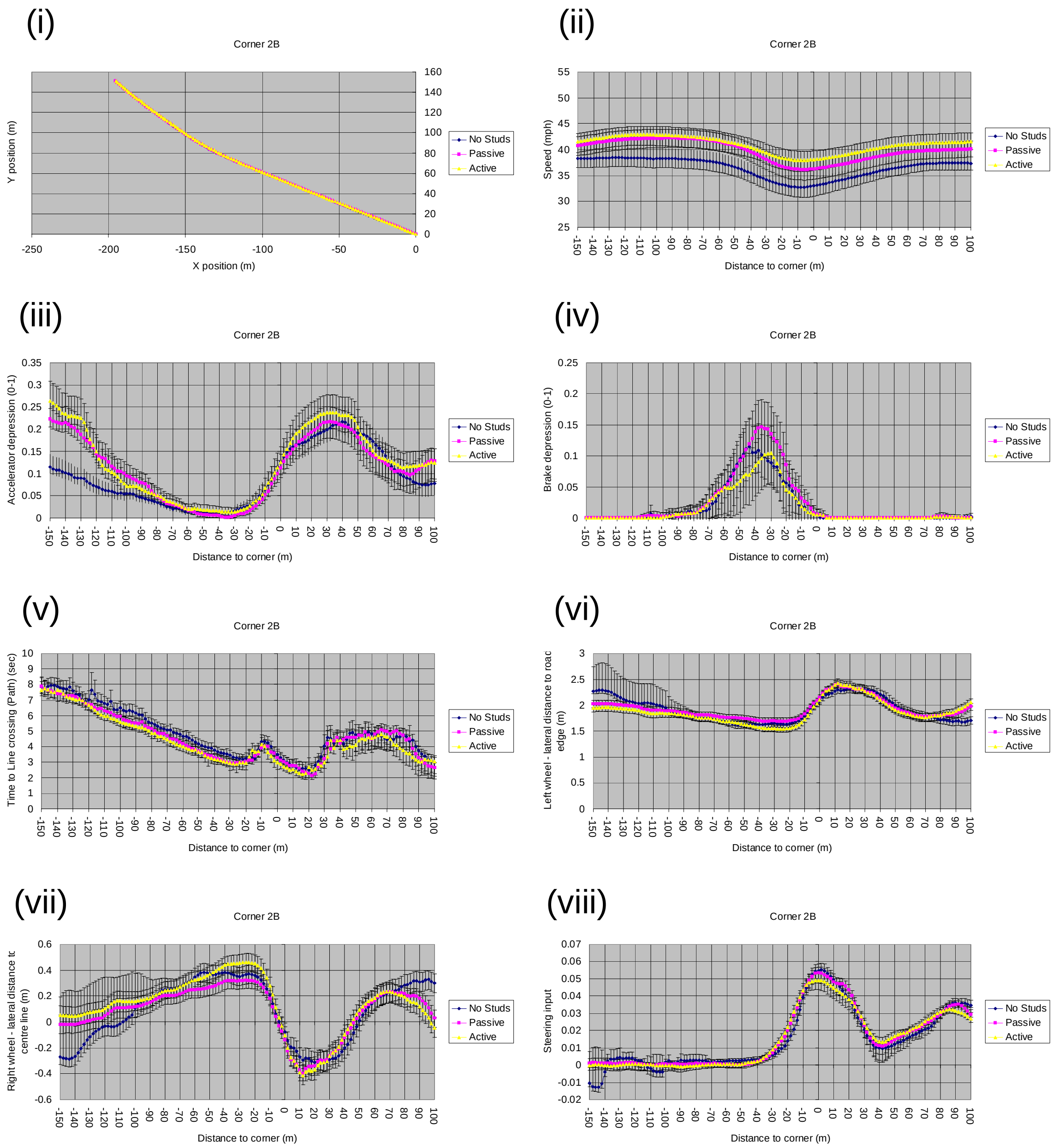
(viii)



Key to charts:

(i)	X-Y position (m)	(ii)	Speed (mph)
(iii)	Accelerator pedal depression (0-1)	(iv)	Brake pedal depression (0-1)
(v)	Time to line crossing - path (sec)	(vi)	Left wheel distance to verge (m)
(vii)	Right wheel distance to centreline (m)	(viii)	Steering input

Corner 2B

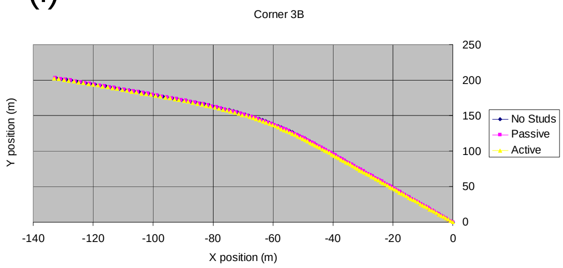


Key to charts:

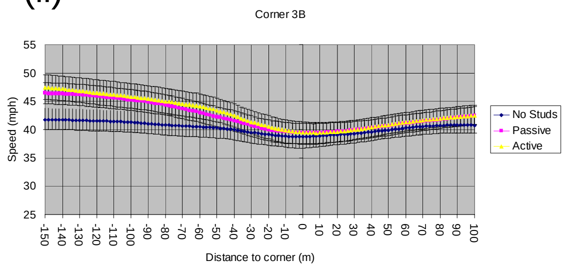
(i)	X-Y position (m)	(ii)	Speed (mph)
(iii)	Accelerator pedal depression (0-1)	(iv)	Brake pedal depression (0-1)
(v)	Time to line crossing - path (sec)	(vi)	Left wheel distance to verge (m)
(vii)	Right wheel distance to centreline (m)	(viii)	Steering input

Corner 3B

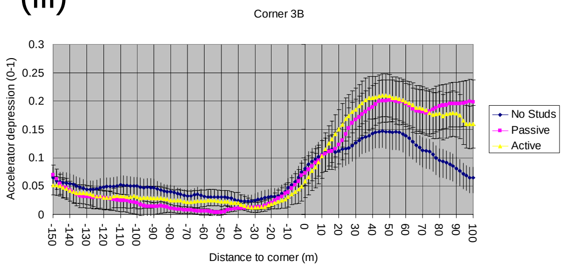
(i)



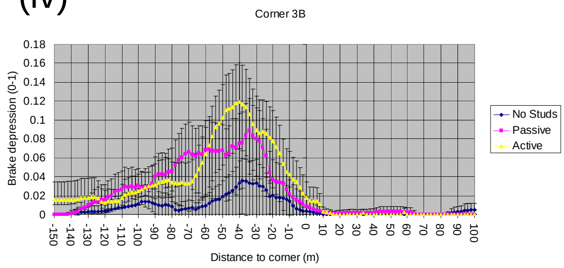
(ii)



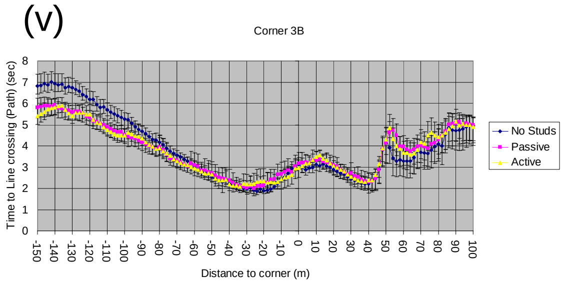
(iii)



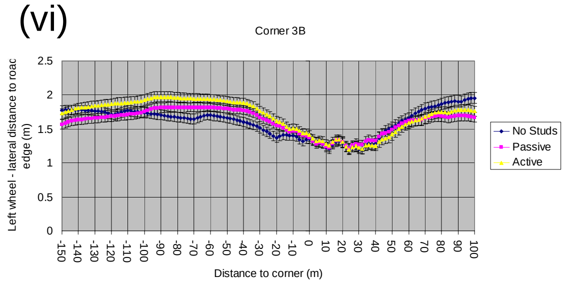
(iv)



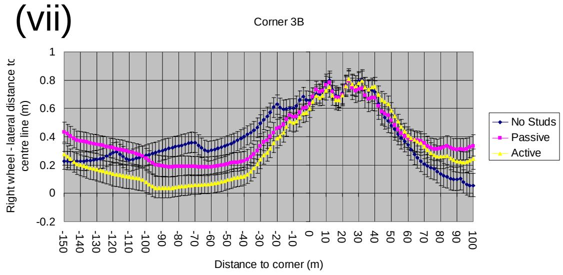
(v)



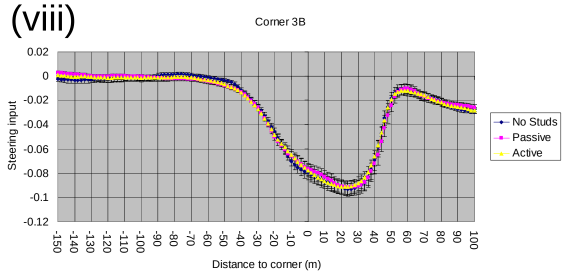
(vi)



(vii)



(viii)

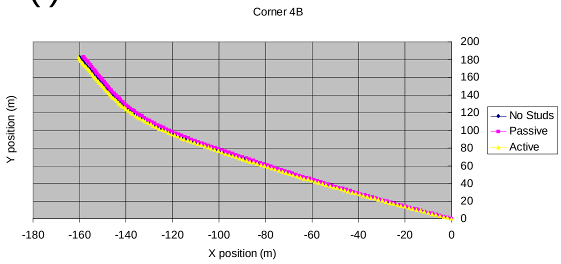


<u>Key to charts:</u>

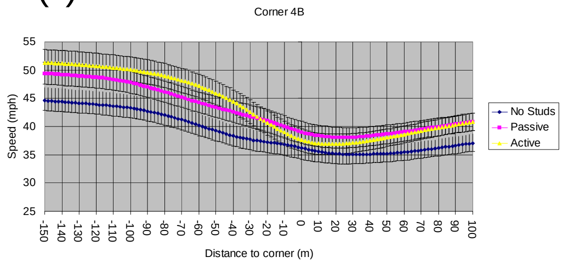
(i)	X-Y position (m)	(ii)	Speed (mph)
(iii)	Accelerator pedal depression (0-1)	(iv)	Brake pedal depression (0-1)
(v)	Time to line crossing - path (sec)	(vi)	Left wheel distance to verge (m)
(vii)	Right wheel distance to centreline (m)	(viii)	Steering input

Corner 4B

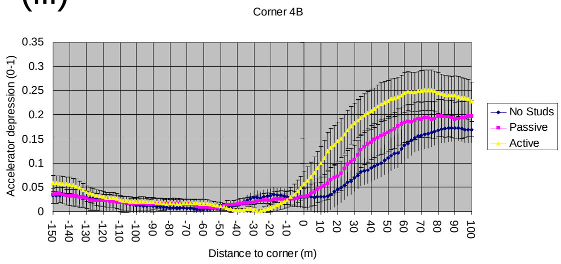
(i)



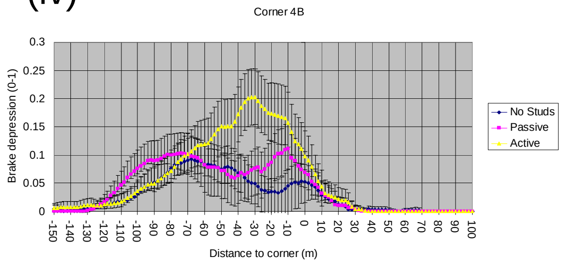
(ii)



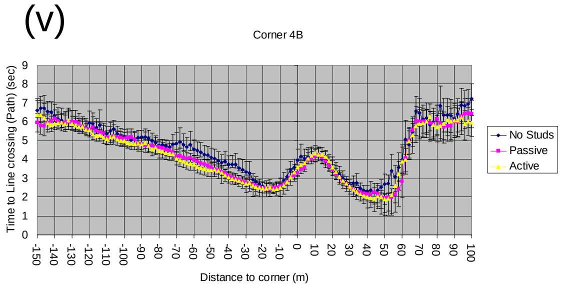
(iii)



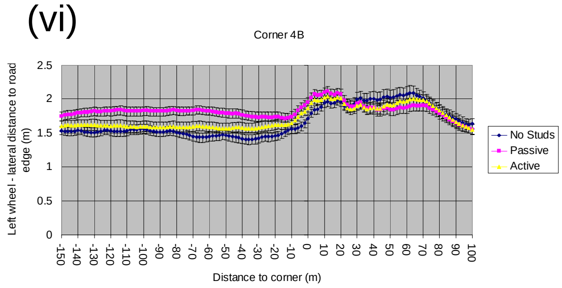
(iv)



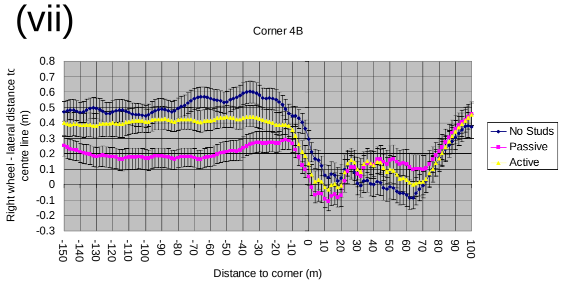
(v)



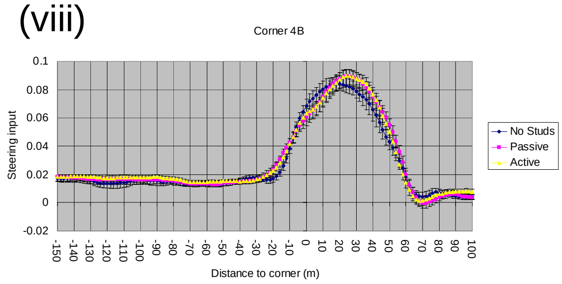
(vi)



(vii)



(viii)

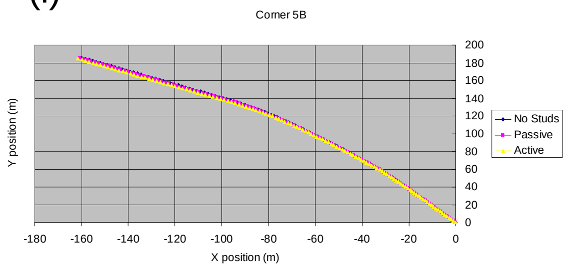


<u>Key to charts:</u>

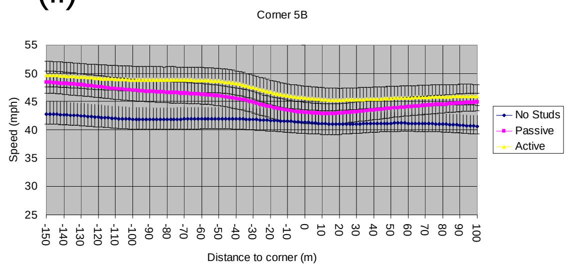
(i)	X-Y position (m)	(ii)	Speed (mph)
(iii)	Accelerator pedal depression (0-1)	(iv)	Brake pedal depression (0-1)
(v)	Time to line crossing - path (sec)	(vi)	Left wheel distance to verge (m)
(vii)	Right wheel distance to centreline (m)	(viii)	Steering input

Corner 5B

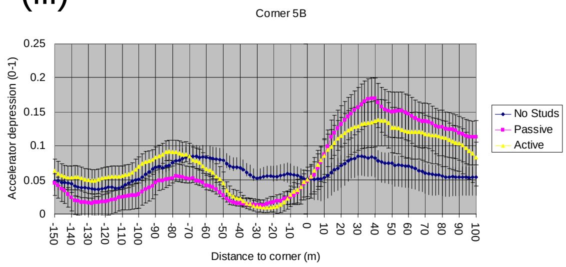
(i)



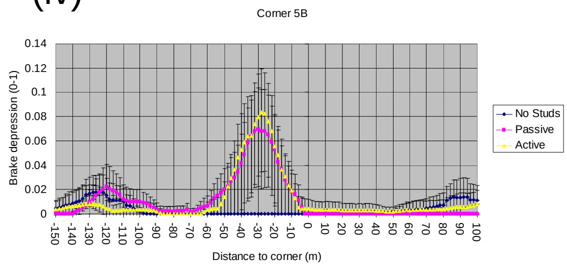
(ii)



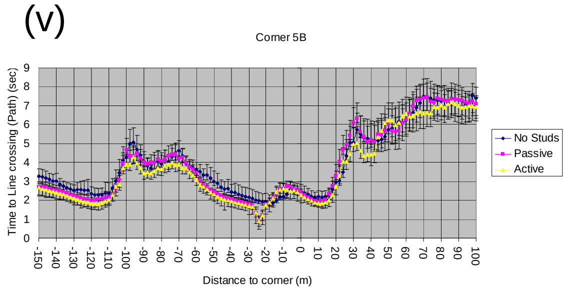
(iii)



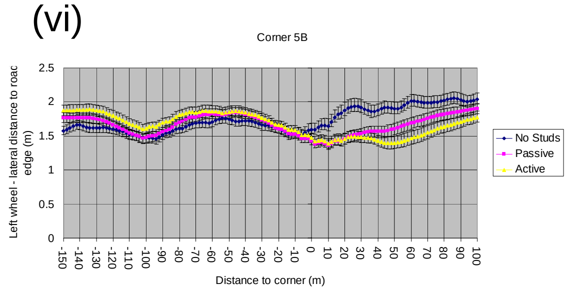
(iv)



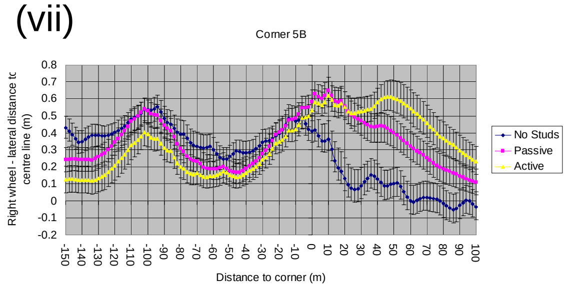
(v)



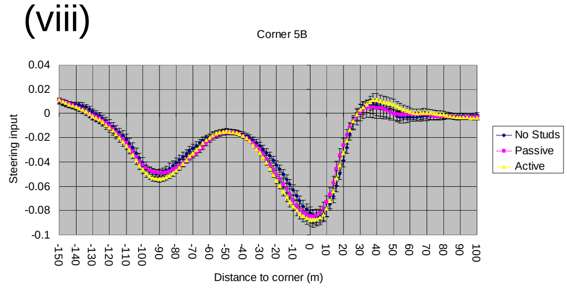
(vi)



(vii)



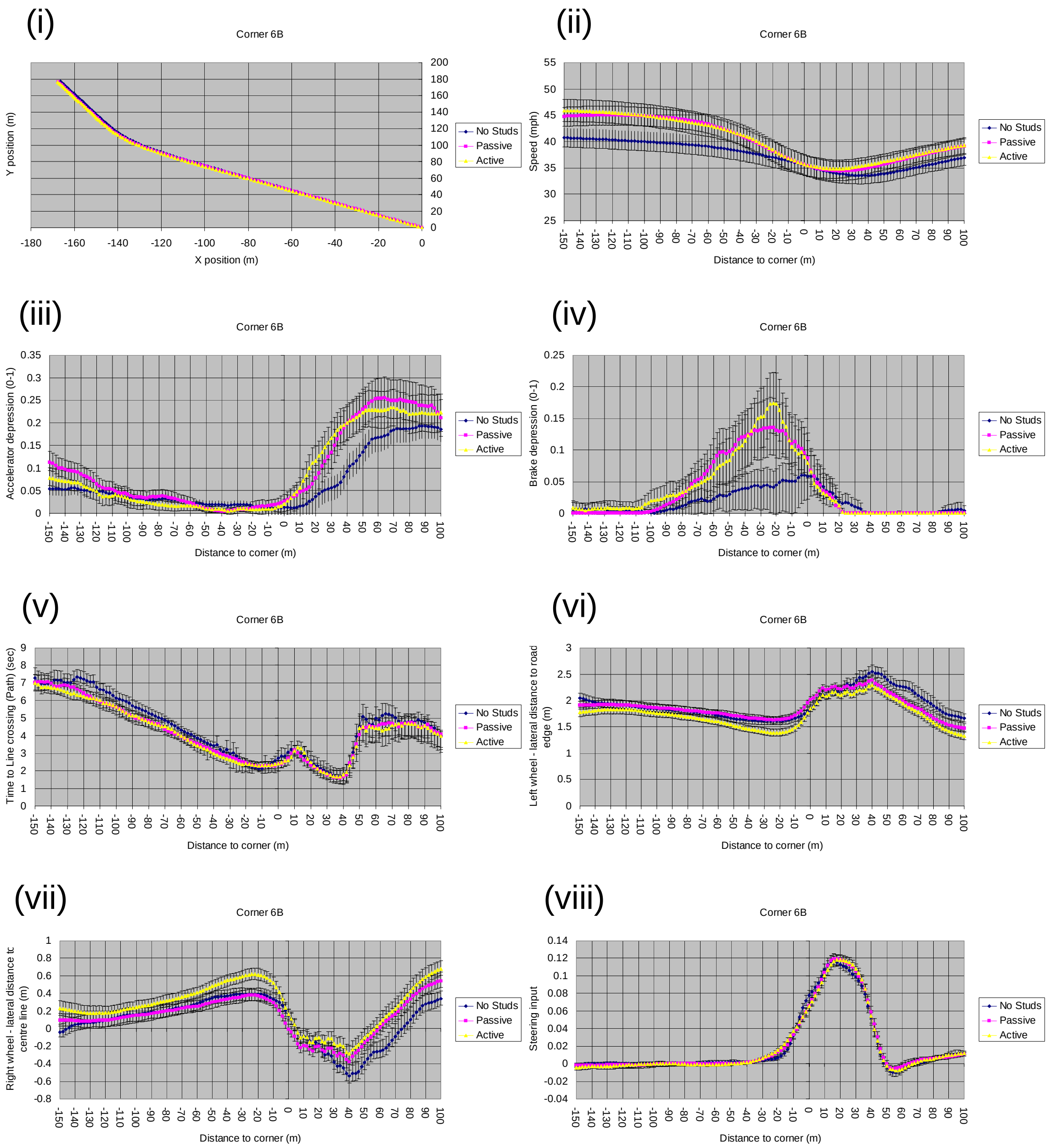
(viii)



Key to charts:

(i)	X-Y position (m)	(ii)	Speed (mph)
(iii)	Accelerator pedal depression (0-1)	(iv)	Brake pedal depression (0-1)
(v)	Time to line crossing - path (sec)	(vi)	Left wheel distance to verge (m)
(vii)	Right wheel distance to centreline (m)	(viii)	Steering input

Corner 6B



Key to charts:

(i)	X-Y position (m)	(ii)	Speed (mph)
(iii)	Accelerator pedal depression (0-1)	(iv)	Brake pedal depression (0-1)
(v)	Time to line crossing - path (sec)	(vi)	Left wheel distance to verge (m)
(vii)	Right wheel distance to centreline (m)	(viii)	Steering input

