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EVALUATION OF NOVEL MOTORWAY DESIGNS USING DRIVING SIMULATION

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Keywords: road design, traffic schemes, behaviour, driving simulation technology

1. INTRODUCTION

As the volume of traffic on motorways increases, the negative effects of congestion become more pressing. Increased journey times present a real cost to the economy in terms of lost productivity, increased fuel costs, and environmental impacts. In addition, congestion brings many vehicles into close proximity, raising the probability of collisions such as rear-end shunts or sideswipes (Webb, 1995). Potential solutions to these challenges may lie in alternative and innovative methods for utilising the current motorway network.

The UK's Highways Agency is exploring methods of maximising the capacity of the motorway network without significant changes to the existing infrastructure including novel Hard Shoulder Running and Dedicated Lanes schemes. These schemes have a number of original features regarding signs and signals, road layout, and road markings.

Of course, the introduction of such schemes must not lead to a reduction in safety standards and, furthermore, they must be reasonably intuitive (i.e. self-explanatory design) such that naïve users on the scheme do not feel threatened or insecure on their journey. Understanding how drivers are likely to behave in such schemes is critical in ensuring its safe and efficient operation. Motorists may be confused and react in unexpected ways which could alarm other drivers. This may not only compromise road safety but may also lead to a reduction in network performance as a consequence of inappropriate driving behaviour such as excessive braking and lane changing. Furthermore, drivers' opinions, attitudes and acceptance of novel schemes must be understood in order to create a scheme that is usable and viewed positively by the motoring public. Drivers' attitudes and opinions as well as their comprehension and compliance are major factors affecting the success of novel schemes.

Investigation of drivers' responses to such schemes in a real-world setting would produce data with the greatest validity. However, with real world observations, it is difficult to exert control over confounding factors such as the number or type of vehicles involved or the demographics of the driving population. Furthermore, to obtain statistically robust data, long observation periods are required typically exceeding 12 months. Studies on a dedicated test track allow for a considerably higher level of control. The use of instrumented vehicles would further allow for the collection of highly detailed

behavioural measurements. However, in both real world and test track settings, participants cannot be exposed to any risk of injury. Furthermore, development and actual implementation of novel designs is rather costly, and hence, neither real world nor test track studies may prove to be practicable. It is argued here that driving simulation technology can provide a cost-effective alternative in the evaluation of novel motorway designs and schemes.

Interactive driving simulation overcomes most of the limitations of real world and test track studies. Detailed and high resolution driving behavioural information can be obtained with regard to the driven vehicle relative to the environment and other vehicles. Driving simulation also allows for the collection of drivers physiological responses such as electroencephalography (EEG), heart rate, and eye tracking. These measures can provide complementary information on drivers' stress responses, mental workload, and gaze behaviour.

A further advantage of driving simulation technology is the ability to control surrounding traffic to create simulated scenarios presenting drivers with difficult and/or dangerous driving situations, whilst the participant is at no risk of real harm. Due to the immersive experience of driving simulation participants nevertheless perceive the element of risk and consequently produce behaviour that is representative of real driving. The complete control over simulated scenarios also means that the simulation can be precisely repeated with different participants.

The repeatability of trials, high level of scenario control, and the precise measurement of behaviour are huge benefits for the researchers charged with analysing driver performance. Furthermore, detailed participant profile information and subjective opinions about the test conditions can be obtained through pre- and post-trial questionnaires; all of which would be almost impossible to apply in testing conducted on real roads.

1.1 TRL driving simulator

The TRL driving simulator (Figure 1) comprises a Honda Civic family hatchback car with a five-speed manual gearbox. The driving environment is projected at a resolution of 1280x1024 pixels per channel onto three forward screens giving a 210° horizontal forward field of view and a rear screen providing a 60° rear field of view. Its engine and major mechanical systems have been replaced by an electric motion system that drives rams attached to the axles to each wheel. These impart limited motion in three axes (heave, pitch, and roll) and provide the driver with an approximation of the acceleration forces and vibrations that would be experienced when driving a real vehicle. A stereo sound system provides simulated engine, road, and traffic sounds at approximately 75dB(A). The driving simulation is generated by the SCANeR II software (OKTAL, Toulouse, France), and the driving performance data is recorded at a frequency of 20 Hz. An intercom facility allows for communication between the vehicle and the control room.



Figure 1: TRL driving simulator

Progress in computer graphics and 3D modelling now allows simulated environments to be created that match real road schemes being constructed. Driving scenarios can be created that include all elements of the roadway environment including roadway geometry (e.g. curvature, cross section, cross roads and intersections), traffic control devices (e.g. signals, signs, markings and sources of delineation), barriers and construction zone markers (e.g. cones, barrels), buildings and flora, interactive traffic and pedestrians (e.g. traffic density and behaviour), and environmental conditions (e.g. weather conditions, light levels).

2. CASE STUDIES

As part of the UK's Highways Agency managed motorways programme, a series of driving simulator studies have been conducted. These can broadly be categorised in studies into the use of dedicated lanes and hard shoulder running. As already mentioned, both schemes are intended to maximise the capacity of the motorway network without significant changes to the existing infrastructure. The principal aim of the studies described below was to evaluate such new schemes in the context of driving behaviour, road safety, network performance, and public opinion.

2.1 Through Junction Running

Use of the hard shoulder as an active running lane has been demonstrated to be an effective measure to reduce congestion and improve journey time reliability (e.g. Sultan et al., 2008). Current hard shoulder running schemes allow motorists to use the hard shoulder *between* junctions. A refinement that has the potential to improve traffic flows further would be to allow traffic to use the hard shoulder (HS) not only between but also *through* junctions and is referred to as Through Junction Running (TJR). Figure 2 shows the concept of TJR whereby the hard shoulder is permanently converted to a normal running lane through the junction by means of dashed road markings. The proposed scheme involved a combination of specific line markings, signs, and operational regimes.

A simulator study was designed to test participants' behaviour in response to TJR in terms of their ability to respond to the scheme in a safe and appropriate manner. A total of 96 (Younger vs. Older) drivers participated, each driving a 40 minute drive in the TRL driving simulator along a 4-lane motorway. With the exception of one junction, the hard shoulder was always open through the junctions. By varying the status of the hard shoulder (i.e. open or closed) between junctions, various scenarios were created. This way it was possible address questions such as whether participants chose to use the hard shoulder through the junction and how and where they chose to enter and exit the hard shoulder; whether the hard shoulder through junctions would be inappropriately used to undertake slower moving traffic in the normal running lanes; how well drivers leave and rejoin the motorway with traffic travelling in all lanes and along both on and off slip; as well as the level of contravention. The TJR scheme was evaluated on the basis of driving behaviour (speed, lateral position) and subjective impressions as assessed by a battery of questionnaires.

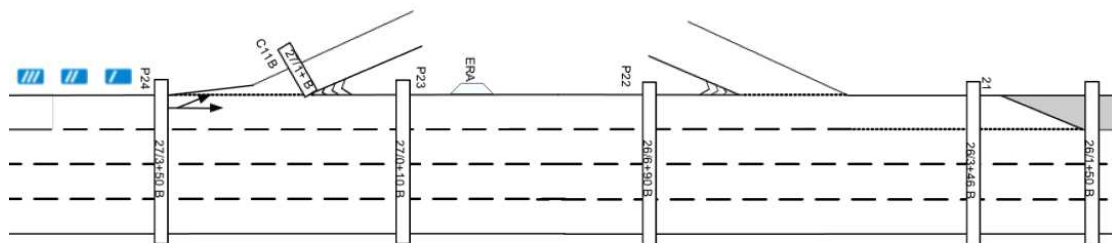


Figure 2: Schematic diagram of Through Junction Running (TJR)

The first observation was that upon encountering the first TJR junction, more than half (54%) of participants used the hard shoulder, with about 10% of the participants entering the hard shoulder from lane 1 within the junction. This indicated that despite unfamiliarity with TJR, the scheme was largely self-explanatory with a considerable proportion of drivers appropriately making use of the additional capacity provided.

An important consideration in the scheme design was that under conditions in which the hard shoulder is closed after the junction, drivers within the junction move out of the hard shoulder in time to avoid potential conflict with joining traffic. Results showed that, as intended, the vast majority moved out of the hard shoulder into lane 1 just before the start of the on-slip thereby avoiding any potential conflict with traffic joining the motorway (see Figure 3). None of the participants were found to continue driving on the hard shoulder following its closure.

It was further observed that the level of contravention (illegitimate use of the hard shoulder when the hard shoulder was closed for traffic) was very low (<5%). This was of particular relevance considering the mixed regime inherent to the TJR scheme whereby the hard shoulder *through* the junction is open to traffic on a full-time basis; *between* junctions, on the other hand, the hard shoulder is opened dynamically as function of traffic flow.

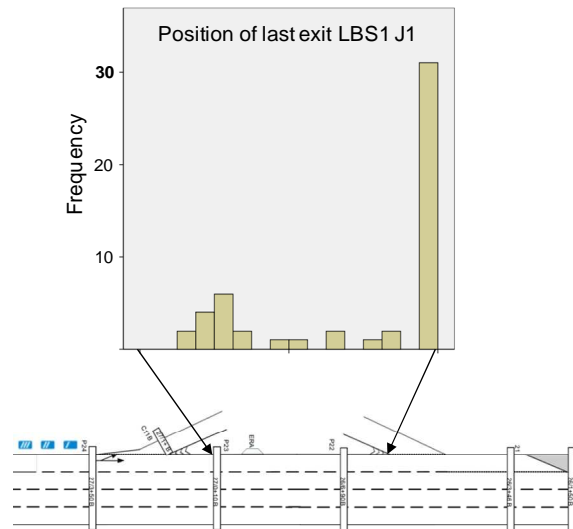


Figure 3: Frequency distribution of the position of last exit hard shoulder (LBS1) when hard shoulder closed after junction

This also raises the question if and to what extent drivers will use the additional lane within the junction when the hard shoulder is closed both before and after a junction. The simulation study indicated that under these conditions, 23% of the participants moved from lane 1 to the hard shoulder to make use of the additional capacity. It was concluded that the extra capacity within the junction was effectively used with drivers being able to rejoin the normal running lanes in time. Furthermore, with the hard shoulder open to traffic in the preceding as well as the following link, 73% of participants drove in the hard shoulder through the junction at some point, whereas 44% of the participants drove in the hard shoulder throughout the entire junction. Taken together, these results suggested that the majority of participants understood the concept of TJR properly.

In the context of road safety and network performance, some potential problems were however raised with regard to entering the motorway. With TJR, upon rejoining the motorway, traffic is likely to be present in the hard shoulder which means there is less space and opportunity to accelerate in order to join the through traffic on the motorway. It was found that the average speed at entering the motorway was considerably lower (60mph) than the traffic within the junction (70mph). In turn, this may lead to braking and lane changing behaviour on behalf of through traffic in the hard shoulder, which, in turn, may negatively affect road safety and traffic flow. Concerns were also expressed by participants who rated rejoining the motorway when the hard shoulder was open as less safe. Consequently, it was advised to consider a longer on-slip in future designs which would allow drivers more time to accelerate and smoothly join the motorway traffic.

The questionnaire results further indicated that TJR was thought to be beneficial in reducing congestion. However, a large number of participants expressed their concerns as to its effect on road safety and in particular the limited emergency services access and absence of a safe stopping place in case of vehicle breakdown. However, it should be noted that the concept of

Emergency Refuge Areas (ERA) was not discussed with participants and should be taken into account when interpreting these results.

On the basis of the driving simulation study, it was concluded that safety standards are unlikely to be compromised by the use of TJR and that network capacity could benefit from the scheme.

2.2 Emergency Refuge Area

Greater use of the hard shoulder as an active running lane places increased pressure on use of the Emergency Refuge Areas (ERA) as safe havens in the event of a vehicle breakdown. Positioned adjacent to the hard shoulder, ERAs are safe areas away from the traffic for use in the event of a breakdown or emergency. They are wider than the hard shoulder to provide additional safety and are connected to regional traffic control centres by both CCTV cameras and emergency roadside telephones.

In the light of proposals to extend hard shoulder running within junctions, i.e. Through Junction Running (TJR) (see section 2.1), this study investigated drivers' response and subjective evaluation of ERAs positioned both between and within junctions. In particular, TJR is currently considered to operate at 70mph (i.e. national speed limit) which may have implications for road safety, i.e. drivers' ability to safely rejoin the motorway from an ERA.

The Highways Agency's objective is to evaluate the possibility of creating ERAs that are less attractive as a non-emergency stopping point. This is because more than 80% of ERA use is non-legal and non-emergency with a commensurate increase in exposure to risk. In addition there is evidence that stops can occur in the wrong place within ERAs which may have consequences for emergency vehicle access as well as the ability to leave the ERA safely and rejoin the carriageway.

To discourage inappropriate ERA use, as well as to modify the stopping position within ERAs, a number of ERA design considerations were identified including ERA lighting conditions and ERA designs. The aim of this study was to evaluate the effect on driver behaviour of four ERA design modifications which are illustrated in Figure 4. Each of the four designs was evaluated compared to a current standard ERA.

Simulated breakdown scenarios were created requiring drivers to stop in an ERA. This allowed for the evaluation of drivers' ability to exit the motorway and drivers' stopping position within the ERA. By repairing the simulated fault, drivers were subsequently asked to rejoin the carriageway which in turn allowed for the evaluation of factors such as gap acceptance and speed choice. In the light of the 70mph intra-junction speed limit, drivers' ability to enter into live traffic travelling at 70mph was evaluated.

In the simulator study, a total of 72 drivers participated. Participants were evenly split into two age groups (Younger vs. Older). The study design required each participant to undertake three drives in the simulator for a period of around 10 minutes each. In the night drive, participants were asked to stop the vehicle in either the Unlit or Low lit ERA. In a second drive, they had to stop in either the Revised or Small ERA. In a third drive, participants had to stop the vehicle in a Standard ERA.

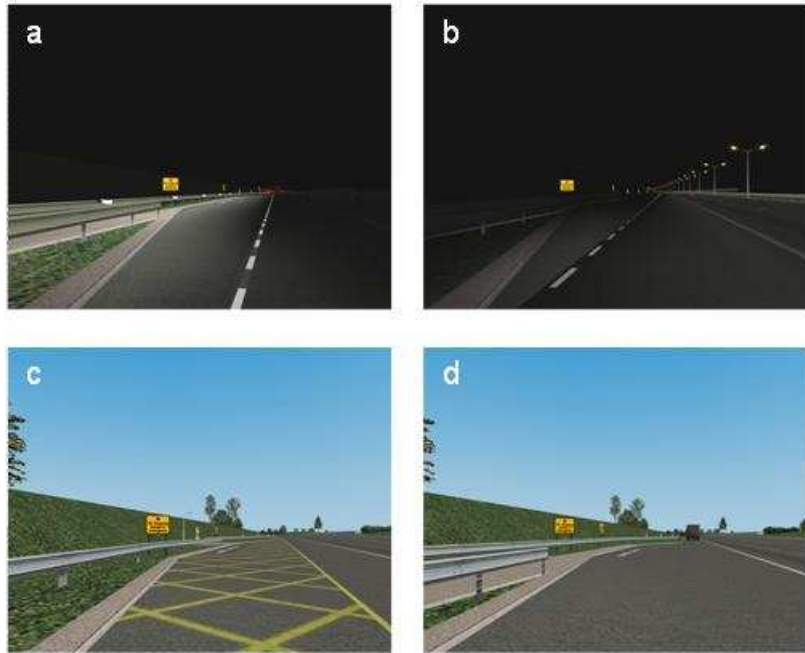


Figure 4: (a) Low lit ERA at unlit motorway (night drive); (b) Unlit ERA at fully-lit motorway (night drive); (c) Revised ERA design; (d) Small ERA design

Figure 5 shows the speed and braking profile on approach, entrance, and exit from each ERA design. With regard to the speed profile on approach and entrance to the ERAs, it was found that the average approach and entrance speed tended to be lower for the Small and Unlit ERAs. In addition, the braking profile for the Small and Unlit ERAs also showed considerable later and sharper braking levels compared to the Revised, Low lit, and Standard ERA. The highest maximum braking force applied within 100m preceding the start of and entrance to the ERA was observed in the Small and Unlit ERA.

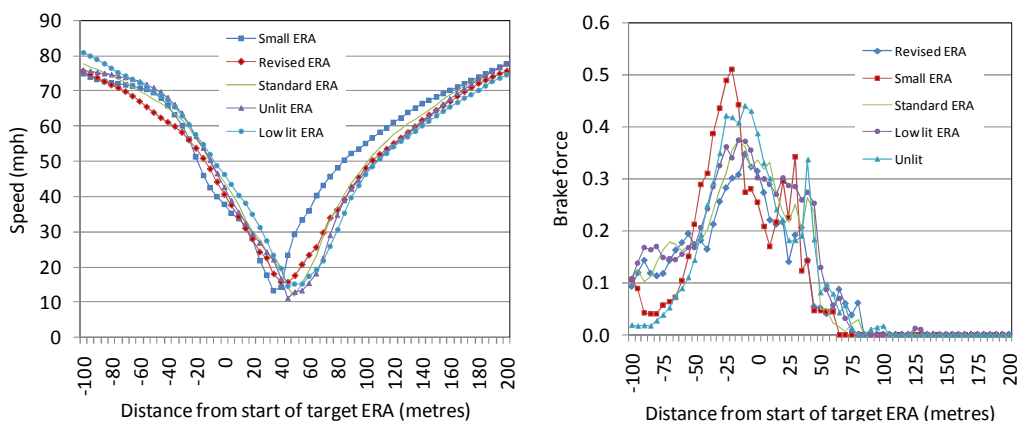


Figure 5: Speed (left) and braking (right) profile on approach, entrance and exiting from each ERA

These results can be interpreted as participants being more cautious when entering the Small and Unlit ERA. With regard to the latter this can be understood considering the reduced visibility making it harder for participants to locate the start of the ERA, judge the ERA's dimensions and whether the ERA provided sufficient space to bring the vehicle to a halt. As expected, when asked to indicate the ease of locating the ERAs, participants indicated that it was harder to locate the Unlit ERA compared to the other ERAs. A similar argument could be put forward for the small ERA whereby the reduced length of the ERA may have instigated participants to lower their travelling speed to ensure they can safely and comfortably bring the vehicle to a halt. Subjective comments provided further support for these interpretations.

Figure 6 shows the stopping positions (X and Y coordinates) of the vehicle in each of the five ERA designs. The largest number of participants parking the vehicle in the correct location was observed in the Small (75%) and Unlit ERA (78%). In the other ERA designs, including the Standard ERA, the percentage was lower and hovered around 60% of the participants.

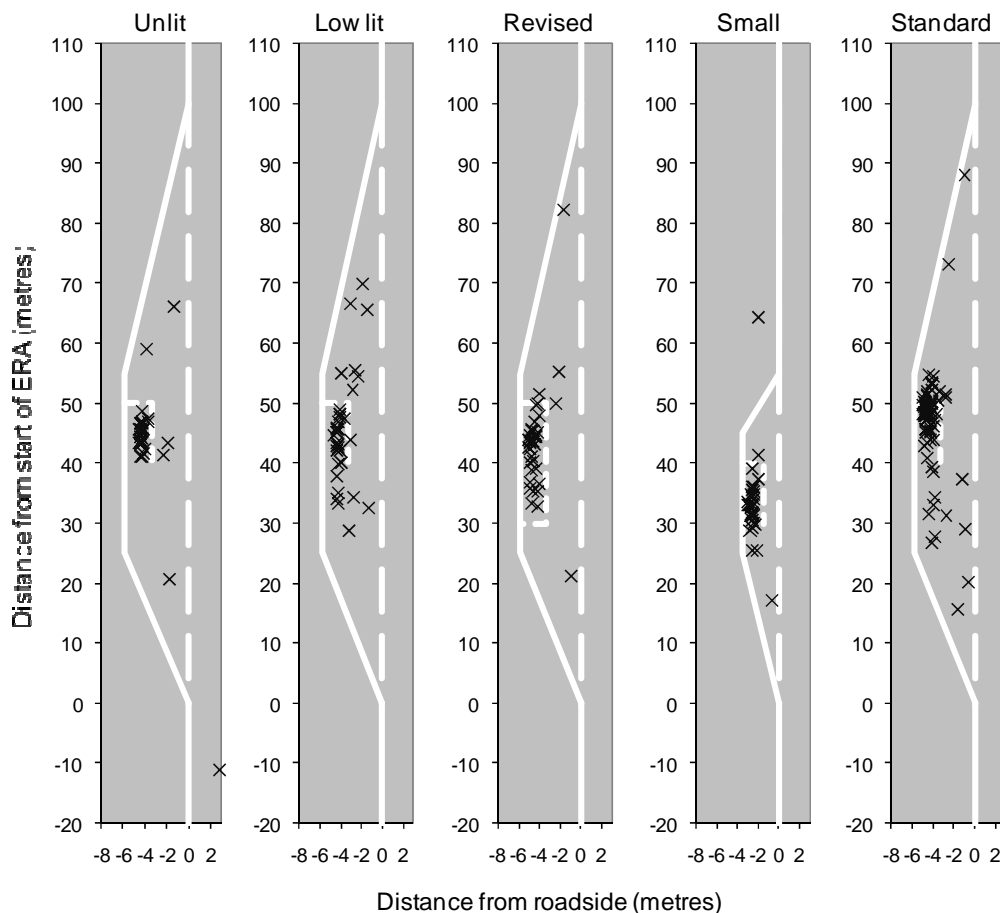


Figure 6: Stopping positions in each ERA

The hatched road markings in the Revised ERA had the intended effect of discouraging participants from parking in the hatched area. However, other design features (i.e. arrows signalling participants to park towards the front of

the parking bay) were not as effective. From this it was concluded that hatchings may provide an effective means to discourage drivers from parking on them, more so than the arrows that precede the delineated bay.

Parking at the beginning of the ERA in particular is considered to endanger the parked motorist and hinder emergency vehicle access. When comparing the stopping positions across the ERAs, the Standard ERA performed worst in that a larger proportion of participants parked not only at the beginning of the ERA, but also closer to the road side. From a road safety perspective, alternative ERA designs would therefore be preferable. The Revised ERA appeared to be the most robust design for ensuring correct parking positions under daytime conditions.

Regarding the Unlit ERA, a high percentage (78%) of participants parked the vehicle in the correct location. However, the ERA design appeared to have a significant shortcoming in that 4 out of 36 participants (11%) failed to stop in the dedicated ERA altogether despite being instructed to bring the vehicle to a halt in the upcoming ERA. Based on the assumption that the failure to use the ERA could be ascribed to reduced ERA visibility, the use of completely unlit ERAs therefore appeared not to be advisable. Failure to use the ERA might lead to motorists having to park on the hard shoulder thereby compromising road safety and network performance.

As a consequence of the limited acceleration space available in the Small ERA, driving speed upon re-entering the motorway was found to be significantly lower when leaving the Small ERA in comparison to the other ERA designs. Since this may negatively affect road safety and network performance due to the relatively high speed differential, it is important to optimise future designs with respect to acceleration space.

Subjective comments further indicated that, irrespective of ERA designs, participants were concerned about re-entering the motorway and indicated ERAs to be too small to pick up speed and safely rejoin the traffic at the motorway. Finally, a large number of participants indicated the advanced warning signs indicating the presence of the ERAs to be positioned too close to the ERAs and expressed a preference for placing signs further in advance of the ERA.

In summary, it was shown that the specific ERA designs can be expected to have a significant effect on driving behaviour. The simulator study was effective in identifying several critical design features that can be further explored in future research.

2.3 Dedicated lane schemes

Dedicated lane schemes refer to the use of an additional lane specifically designated for certain vehicle categories. Examples include high occupancy vehicle lanes, bus lanes, green lanes, and toll lanes. The scheme evaluated here involved the use of an additional lane, or fast lane, specifically designated for vehicles allowed using that part of the road.

TRL tested a dedicated lane scheme which introduced numerous novel features most motorists would be unfamiliar with including lane markings,

road layout, and signs. For example, the dedicated lane was delineated from the normal running lanes by means of double solid white lines. To allow motorists' to exit/enter the dedicated lane before/after junctions, access and egress zones were created using dashed line markings (see Figure 7 for an illustration). Dedicated lane-specific information (i.e. start and end, status (open – closed)) was displayed via Advanced Motorway Indicator (AMI) signs above each lane (lane-specific information) and Variable Message Signs (VMS) which were mounted on gantries spaced at 500m intervals.

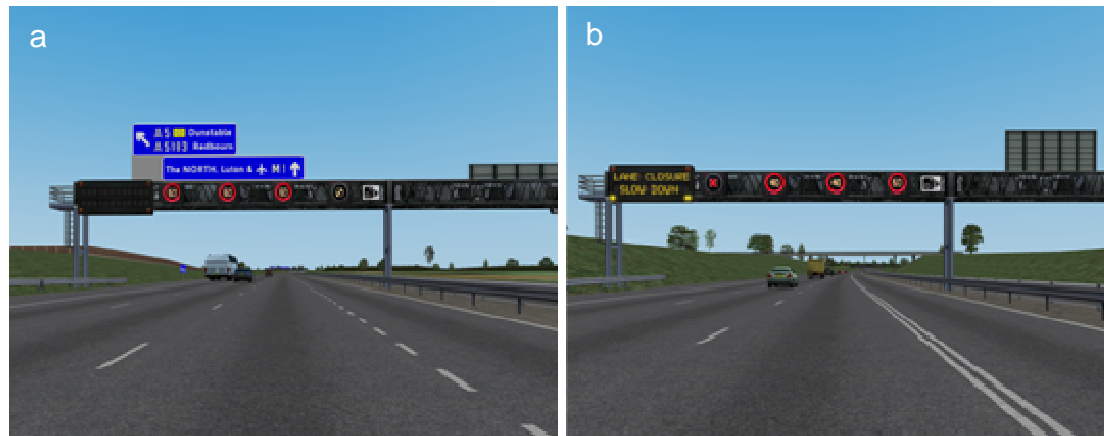


Figure 7: Screenshots from simulator database showing (a) access/egress zone of dedicated lane indicated by short dash road markings, and (b) dedicated lane delineated from normal running lanes by double solid lines

By manipulation of the traffic density (e.g. simulated congestion on toll lane) and lane status (e.g. lane closure), it was possible to investigate driving behaviour under different conditions relevant to the workings of such a scheme. Particular issues addressed were the level of contravention and unintended use, effective use of additional capacity provided, understanding of lane markings and signs, and motorists' ability to leave the dedicated lane when instructed to exit the motorway.

Forty-eight participants were recruited and were assessed across experimental factors of Information (Informed vs. Uninformed about the workings of the scheme), Authority of use (allowed vs. non-allowed vehicle category), and Age (Younger vs. Older drivers). To test participants' willingness to contravene the lane segregation in order to make most rapid progress along the route, participants were told that they were 'late for an urgent meeting and must hurry to get there in time'. After their drive, participants completed a questionnaire that investigated participants' subjective responses to driving through the scheme as well as their attitudes towards such a scheme.

The results of the study showed that the majority of participants used the scheme correctly and took advantage of the benefits that it provided when appropriate. Under conditions of heavy traffic, the use of the dedicated lane significantly increased compared to light traffic conditions. It was further found

that there was a low level (n=3) of violation of the dedicated lane and illegitimate crossing of the double white line separating the dedicated lane from the normal running lanes. This was also found to be the case in the uninformed group which suggests the scheme to be largely self-explanatory.

Concerns were however raised as to the difficulty to reach the exit from the dedicated lane. This was also reflected in the driving behavioural data (see Figure 8) Whereas motorists in the normal running lanes arrived in the inside lane (lane 1) well in advance of the exit, dedicated lane users arrived considerably later in the inside lane. This represents a potentially serious difference in driver behaviour between dedicated lane users and other motorists whereby the ‘swooping’ across lanes may negatively affect both road safety and traffic flow. It was subsequently advised to carefully consider the length of access/egress zones in future designs.

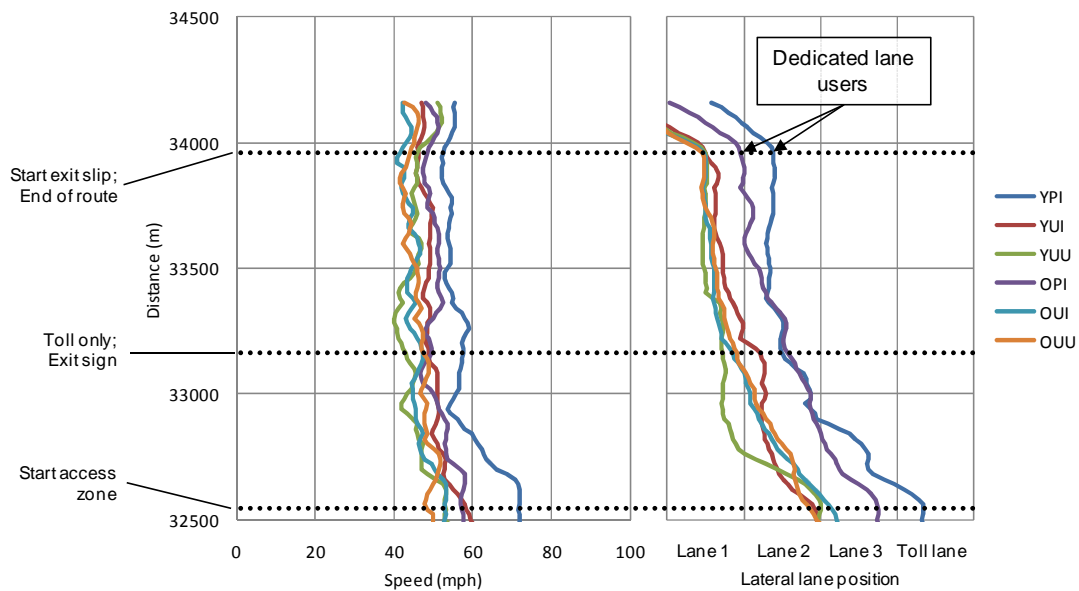


Figure 8: Example of simulator mean speed and lateral position across six experimental groups upon exiting the motorway

The questionnaire data gathered was used to gain insights into a range of driver opinions regarding the scheme, including how intuitive and acceptable they found the scheme to be. Differences between informed and uninformed drivers were identified as key in determining potential differences in how experienced and naive drivers may interpret the signs. A general pattern emerged where informed drivers rated the scheme more positively.

When asked to judge how acceptable they found the scheme opinions were mixed. There was a slight expectation that the scheme would decrease congestion, improve journey times and become more predictable. However, the implementation of the scheme was thought to reduce road safety. To maximise understanding of its workings, willingness to use it, and ultimately acceptance of similar schemes, it was concluded that effective publicity campaign would be desirable.

3. SUMMARY & CONCLUSIONS

The aim of this paper was to illustrate that driving simulation technology can play a useful role in the evaluation of novel road designs and schemes. Three case studies were described which investigated drivers' responses to a dedicated lane scheme, hard shoulder running scheme, and different configurations of emergency refuge areas.

Although investigation of these schemes in a real-world setting would produce data with the greatest validity, this may not always be possible or desirable. With regard to the schemes and road designs described here, it is apparent that real-world testing would have been prohibitive not only from a monetary perspective, but also from a safety one.

Novel road designs and schemes can be prototyped easily and evaluated in a driving simulator. The examples described in this paper indicate that simulator technology can be an effective means in the identification of key road design characteristics of novel road layouts and can form part of an iterative design process. The ERA case study, for example, showed how new designs can be modelled and compared against current standard designs. Also, simulation studies can be performed in short time frames. Whereas initial creation of simulator databases is relatively time-consuming, database adaptations can be made easily and allow for rapid evaluation of alternative designs.

The high level of control over the road environment, driving scenarios, and participant demographics further allow for the collection of robust driving behavioural data. Unlike real-world and test track studies, driving simulation has the additional advantage that a rich data set can be obtained including numerous driving behavioural measures at high resolution.

In summary, it was shown that driving simulation provides a cost-effective and safe method to enable evidence-based decisions to be made before infrastructure is in place.

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