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Driving simulators for robust comparisons: A case study evaluating road safety engineering treatments

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ABSTRACT

Road authorities considering the implementation of speed management interventions should have access to the results of scientifically robust evaluations on which to base their decisions. However, studies that evaluate a diverse range of interventions with comparable metrics are rare, with most focussing on one type, for example, types of signage, perceptual countermeasures or physical traffic calming. This paper describes a driving simulator study designed to overcome these constraints. Twenty diverse speed-reducing treatments were developed and tested in urban and rural road environments. Forty participants encountered all the treatments allowing a comparison to be made with their driving behaviour when the treatment was not present. A number of speed parameters were developed to encapsulate the range of effects of the treatments. The results suggest that whilst straight sections of road are difficult to treat, speed reductions can be obtained by increasing risk perception. In contrast, alerting treatments had more effect at junctions, particularly in an urban environment; drivers approaching curves demonstrated improved speed adaptation if the curve radius was highlighted (either implicitly or explicitly). The study highlights how driving simulators can be used to overcome methodological constraints encountered in real-world evaluations of this type.

1. Introduction

The benefits of using driving simulators in road safety research are well documented (e.g. Bella, 2008) and evidenced by the fact that over 60 full-scale research driving simulators exist worldwide, owned and operated by academic institutions, government research establishments and vehicle manufacturers. Driving simulators can aid researchers in their understanding of theoretical concepts such as workload (e.g. Backs et al., 2003) and situation awareness (e.g. Gugerty et al., 2004); however they can also play a role in more applied work, particularly in conjunction with road authorities (e.g. Laurie et al., 2004; Knodler et al., 2006). These practical applications of driving simulator research serve two main aims—first they engage researchers with policymakers and second they raise the credibility of driving simulator research within the external community.

One of the most unrelenting issues that policymakers debate is that of drivers' speed choice. Some progress in reducing speeds has almost certainly been made. For example the latest UK figures show that in the 10 years from 1997, the percentage of vehicles exceeding the 30 mph speed limit in free flow conditions has reduced. In 1997, 70% of cars travelled at speeds in excess of the limit but by 2007, this dropped to less than 50% (Department for Transport, 2008). Increases in the numbers of speed cameras may have contributed to this reduction, however with almost half of drivers still exceeding the speed limit in urban areas there is scope for improvement.

A driver's choice of speed is influenced by a variety of factors. Some are transient such as time of day (Lenné et al., 1997), fatigue (Philip et al., 2005) and perceived threat of enforcement (Keall et al., 2001), whilst others are more durable in nature such as personality (Dahlen et al., 2005) and gender (Shinar et al., 2001). This diversity is reflected in the range of speed-reducing treatments that have been developed, most commonly categorised as enforcement, education or engineering interventions. Each of these types has received significant research attention with varying levels of success. For example, Mountain et al. (2004) evaluated the impact of 62 fixed speed enforcement cameras on UK 30 mph roads and reported an average of 25% reduction in personal injury accidents. The effects of driver education have also shown some promising results with Carstensen (2002) reporting that following improvements to the Danish licensing procedures, the accident rate of inexperienced drivers fell by almost 20%. There are, of course, always caveats to these research findings; in the case of the speed camera study there was no effect on serious or fatal accidents and the improved Danish driver training program had no effect on single-vehicle accidents.

Engineering treatments have also been the subject of evaluation, with measures such as vehicle activated signs (VAS) (Winnett and Wheeler, 2003) and surface treatments (Meyer, 2001) proving

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successful. However, studies that compare a wide range of engineering treatments are relatively rare and it is more usual that they focus on, for example, types of signage, or types of road markings. This is partly due to the fact that it can be a challenge to make comparisons between very different types of measures. For example, a road sign, being vertical, is conspicuous further upstream than a horizontal measure, such as road markings. Their effects on the road user may therefore be very different in both magnitude and location. One of the few papers to systematically compare a wide range of engineering schemes is Mountain et al. (2005) whose evaluation comprised 79 speed enforcement cameras and 71 engineering schemes of various types. They found that engineering schemes which incorporated vertical deflections (such as speed humps or cushions) offered the largest benefits (44%—and double that of speed cameras). Engineering schemes were also the only type of scheme to have a significant impact on fatal and serious accidents.

Engineering schemes therefore are promising in terms of reducing speeds and accidents. However, the driving public can be averse to physical measures such as speed humps (Webster et al., 2001) and road authorities are becoming interested in using more subtle cues in the road environment to reduce speed. One example is the use of perceptual measures that attempt to increase the perceived workload or risk attached to a particular driving situation. For example, hatched areas painted on the road surface decrease the perceived lane width, which in turn reduces speeds (e.g. Pau and Angius, 2001).

Making only subtle changes to the road environment is attractive to road authorities, representing good value for money with a high rate of return. Evaluating these speed treatments in the real world would not only be costly but also methodologically challenging. Holding variables such as traffic flow and weather conditions constant is difficult, making direct comparisons between treatments impossible. Driving simulators, on the other hand, provide a controlled environment where each driver meets exactly the same treatment at the same point on the road under the same conditions. Likewise, treatments can be positioned on identical stretches of road to enable a robust comparison using the high resolution data collection techniques that a driving simulator affords. An additional advantage of using a driving simulator in this type of evaluation relates to data quantity: in contrast to on-road measurements of speed where there are financial and practical limitations on the number of data collection points, in the laboratory speed can be continuously measured both up- and down-stream of the treatment. This allows researchers greater flexibility in the type of statistical analysis they undertake.

Road authorities have to decide not only which intervention is the most effective, but also which is most effective in various road environments (urban versus rural for example). Collision severity varies across road type with motorways being the safest road type, partly due to their high standards of road design. Rural roads account for a much higher proportion of accidents: in the UK, accidents are seven times more likely to occur on a rural road than on a motorway (Department for Transport, 2007). Mosedale and Purdy (2004) found that excessive speed is a contributory factor in twice as many rural road accidents (18%) as urban road accidents (9%). Overtaking and curve negotiation are two of the most risky manoeuvres on rural roads and involve excessive or erroneous speed choice.

Despite the fact that rural roads continue to be problematic in terms of casualty rates in the UK, this study did not exclude other road categories. To do so would ignore the fact that pedestrians are overrepresented in accidents on urban roads (Department for Transport, 2007). Over 70% of fatal pedestrian accidents occur on urban roads, compared to 26% of car occupants. Speed reducing schemes appropriate for rural and urban road environments were therefore considered in the study.

This paper reports a driving simulator study with two main aims. Firstly, driver speed behaviour on approach to and through 20 low-cost engineering treatments was measured and compared to baseline conditions. Secondly, the data were subjected to a number of analyses to establish which metrics were the most suitable for making statistical comparisons between the various treatments. Speed estimation by drivers is known to be affected by a variety of sensory inputs, including visual (Gibson, 1979), auditory (Matthews, 1978), kinaesthetic and vestibular (McLane and Wierwille, 1975). This study was therefore carried out on a high-fidelity simulator which provided realism in the simulation of all these cues.

2. Methodology

2.1. Driving simulator

The study was performed using the University of Leeds Driving Simulator, see Fig. 1. The simulator's vehicle cab is based around a 2005 Jaguar S-type, with all of its driver controls fully operational. The vehicle's internal Control Area Network (CAN) is used to transmit driver control information between the Jaguar and one of the network of nine Linux-based PCs that manage the overall simulation. This 'cab control' PC receives data over Ethernet and transmits it to the 'vehicle dynamics' PC, which runs the vehicle model. The vehicle model returns data via cab control to command feedback so that the driver seated in the cab feels (steering torque and brake pedal), sees (dashboard instrumentation) and hears (80 W 4.1 sound system provides audio cues of engine, transmission and environmental noise).

The Jaguar is housed within a 4 m diameter, spherical projection dome. Six visual channels are rendered at 60 frames/s and at a resolution of 1024×768. The forward channels provide a near seamless field of view of 250°, and the rear view channel (40°) is viewed through the vehicle's rear and side view mirrors.

Fig. 1. The University of Leeds Driving Simulator.

The simulator incorporates a large amplitude, 8° of freedom motion system using a railed gantry and electrically driven hexapod. The motion-base enhances the fidelity of the simulator by providing realistic inertial forces to the driver during braking and cornering. It also provides lifelike high frequency heave, allowing the simulation of road roughness and bumps.

2.2. Simulated road scenarios

Six road scenarios were modelled with road markings, widths and signage conforming to current UK legislation (Design Manual for Roads and Bridges, 2005). The six scenarios were urban straight, urban junction, rural straight, rural junction, rural bend and village entry, see Fig. 2.

In order to accommodate all scenarios and all treatments, 45 road sections were modelled and used to develop three separate routes. Each route took approximately 25 min to drive and incorporated urban and rural scenarios. A total of 20 speed-reducing treatments were developed, representing various types suitable for implementation on each road layout, see Table 1. The treatments were randomly allocated across the three routes, along with a corresponding baseline section. Each treatment or baseline section was preceded by approximately 2.5 km of road. Some treatments were duplicated across road types in order to evaluate whether they were equally as effective in rural areas as in urban areas.

Traffic was present in the opposite lane, however drivers were not constrained by vehicles ahead.

2.3. Participants

Studies have suggested that speeding is predominantly a male pastime (e.g. French et al., 1993; Shinar et al., 2001) and with regards to age, speeding is typically associated with young drivers (e.g. Parker et al., 1992; Stradling et al., 2000). This study therefore recruited young, male drivers only, and by doing so we could be more confident that the speed-reducing treatments would be effective even on these "hard to reach" road users.

Forty drivers were recruited whose age ranged between 19 and 25 years, with a mean age of 22 years. Participants' annual mileage ranged between 100 and 20,000, on average being approximately 7000 miles. The participants had obtained their driving licence, on average, 3.78 years previously and reported they drove, on average, three times a week, mostly on urban roads.

2.4. Procedure

Upon arrival at the laboratory, each participant was briefed on the experimental procedure before reading and signing an informed consent form. Participants then completed a practice drive to familiarise themselves with the simulator controls. Following this, each participant drove all three routes, with a rest of 10 min in between. The order of the routes was counterbalanced across participants. On completion of the three routes, drivers were debriefed and paid £20.

2.5. Data analysis

Using a within subjects design allowed the direct comparison between a driver's baseline speed and their speed at each of the treatments. Two derivatives of speed are commonly used to determine the relationship between speed and accident likelihood: absolute speed and speed variation. However, as the treatments ranged from signage, to road markings to physical objects, they differed both in length and their potential impact on driver speed.

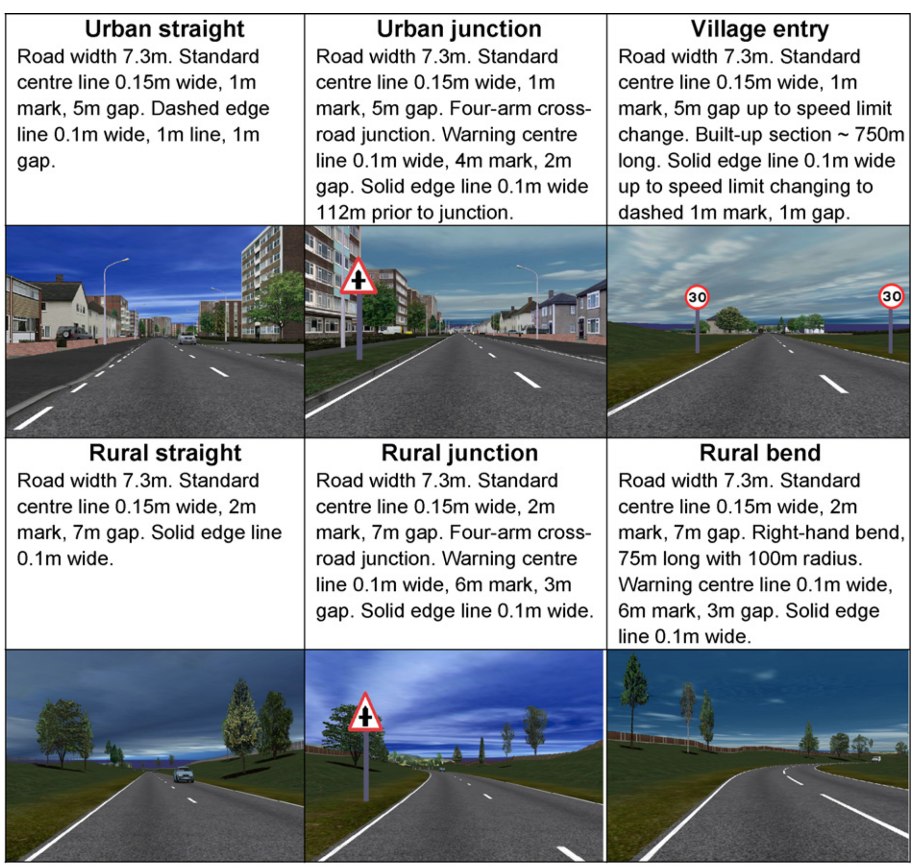

Fig. 2. Simulated road scenarios.

Table 1
Treatment characteristics.

Treatment	Snapshot	Road type						Geometric details
		Urban straight	Urban junction	Rural straight	Rural junction	Rural curve	Village entry	
Pedestrian refuges		√						Pair of rounded rectangular refuge islands 1.8 m × 1.8 m × 0.26 m, located 2 m apart. Marked hatched area on road surface introducing the 1.8 m reduction in lane width tapered in and out over 72 m, preceding and following refuge pair.
Peripheral hatching		√		√		√		Carriageway reduction of 0.825 m using hatched area. Hatching to left-hand edge of each carriageway and tapered in/out over 33 m.
Peripheral hatching with coloured surface		√		√				As above with road surface of hatched area fully filled and highlighted in dark red.
Central hatching		√		√		√		Roadway reduction via 1.35 m wide hatched central area (effective carriageway reduction of 0.675 m). Tapered in over 54 m.
Central hatching with coloured surface		√		√				As above with road surface of hatched area fully filled and highlighted in dark red.
Rumble strips with flat profile			√		√			Three rumble sets with each set consisting of 12 yellow transverse road markings (strips), each 15 cm wide separated by 0.5 m, covering a total of 7.3 m. Each set was separated by 1 s of travel at road design speed.
Rumble strips with raised profile			√		√	√	√	As above with a vertical heave frequency (simulating vibration effect of rumble strip) felt by driver.
VAS with Slow Down			√		√	√	√	2.3 m × 1.3 m sign, vehicle activated regardless of speed 10 s prior to sign at road design speed.
VAS with Slow Down and yellow backing			√					As above, with sign backed in yellow.
Static sign Reduce Speed Now			√		√	√		Permanent static triangular sign (1.32 m wide) with "Reduce Speed Now" printed in white on 1.5 m × 1.0 m red backing.
Static sign Reduce Speed Now and yellow backing					√			As above but with both signs positioned on 2.5 m × 1.5 m yellow backing.

Table 1 (*Continued*)

Treatment	Snapshot	Road type						Geometric details
		Urban straight	Urban junction	Rural straight	Rural junction	Rural curve	Village entry	
Static sign with advisory speed limit						√		Fixed 1.32 m wide curve warning sign with 1.5 m × 0.5 m advisory speed limit sign located below.
Hazard marker posts						√		1 m high × 0.125 m wide hazard marker post, consisting of alternate black and white areas (each 20 cm high) with red/white reflector in upper (fifth) section.
Chevrons						√		3 m wide × 1.75 m high curve warning sign of chevrons denoting curve direction. Three white chevrons (0.2 m wide) marked on black sign surface. Treatment made up of three signs located from curve onset to apex.
Countdown signs							√	Countdown warning signs (1.6 m × 0.7 m) prior to speed limit change. Each sign included the speed limit roundel (0.5 m diameter) and 1, 2 or 3 black diagonal stripes on white background to denote 100, 200 and 300 m warning.
Trees				√		√	√	Average tree height 11 m located on average 2 m from edge of road surface. Trees were separated by 5 m (on average) throughout treatment on either side of the roadway.
Combs						√	√	Extra-wide (30 cm) parallelogram-shaped white edge lines, 0.1 m long, each separated by 0.1 m. Combs marked in white in addition to standard edge-lines, inboard by 15 cm. Combs located 120 m prior to hazard.
Combs with chevrons						√	√	As above but with additional chevron-shaped road markings, centre located in carriageway centre. Each chevron set made up of 4 cm × 15 cm markings, separated by 15 cm. Each 1.0 m wide chevron set separated by 3 m.
Dragons teeth							√	0.6 m long triangular road markings marked inboard on either side of carriageway extremity to achieve perceptual narrowing. Each triangle separated by 1.5 m and located over 60 m region prior to village entry.
Build-outs							√	0.6 m wide × 2.4 m long area marked with three 1 m high marker posts, reducing available carriageway width. Build-out centre located at village entry and tapered in and out over 24 m.

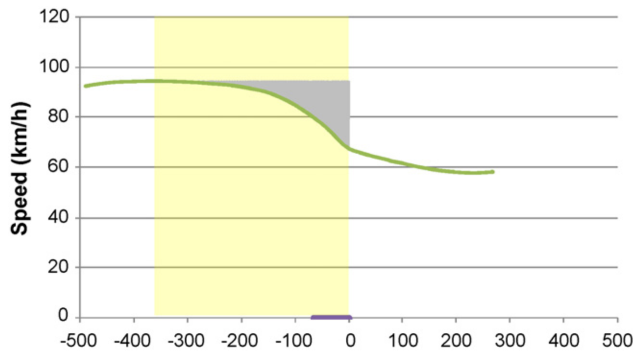

Fig. 3. An example graph of speed profile for village entry treatment.

This was clearly evident when the speed profiles were plotted and so each treatment was therefore assigned its own "impact zone". The starting point of the impact zone was defined as being where drivers could perceive the first visual cue regarding the road layout. This was established by subjective means using members of the research team. The end of the impact zone was defined as the point on the route when the target point was reached.

An example impact zone for village entry is shown in Fig. 3 where the impact zone is highlighted in yellow. It starts when the 30 mph speed limit signs and houses become visible (approximately 350 m prior to the speed limit sign), and ends at the entrance to the village (at the speed limit sign). The position of the actual treatment is denoted by the horizontal line at the base of the *y*-axis.

Following inspection of the speed profiles, three measures of speed were developed:

(i) Speed change (Δ) within the impact zone, per metre of treatment (Δ/m): this standardises the Δ enabling comparison across treatment types. Refer to grey area in Fig. 3.
(ii) Speed at maximum Δ (v@maxΔ): this refers to vehicle speed at the point at which the change in speed is greatest.
(iii) Percentage of speed change across the impact zone: $v2 - v1/v1$. A negative percentage indicates speed reduction.

The parameter Δ/m, presents useful information about the shape of the speed distribution. For example, Fig. 4 shows two speed profiles with identical v@maxΔ as well as identical impact zone start and end speeds; Δ/m detects the different rates of speed reduction. The smaller the Δ/m, the greater the treatment effect.

The example speed profile shown in Fig. 3 suggests that v@maxΔ would always simply equal the speed at the end of the impact zone. However, some speed profiles showed that when approaching a junction, drivers increased their speed again before actually reaching the entry point of the junction. The same was applicable to curves and straight sections; i.e. v@maxΔ did not always occur at curve apex or at end of treatment on a straight section of road. Hence, with regard to assessing the effectiveness of a treatment, v@maxΔ provides useful information. Driver speed in each treatment was compared to that on a corresponding length of baseline road, using the indicators outlined above.

3. Results

The average speeds recorded in each of the six road scenarios are detailed in the following sections. In all cases the corresponding baseline treatment is shown in each graph, as well as the results of the analysis. Each of the treatments was compared to the baseline using paired *t*-tests. Where drivers' speed choice at the treatments was significantly different ($p < .05$) from the baseline, this is denoted with *. For clarity, only those treatments which demonstrated success in two or more of the speed parameters are shown in the graphs below.

3.1. Urban road scenarios

As evidenced by the speed parameters in Fig. 5, speed reductions in the urban straight sections were small, with significant differences only for only one parameter (Δ/m).

The central hatching treatments were not successful in lowering speeds on straight sections of urban road. Peripheral hatching, on the other hand, encourages drivers to travel closer to the centre line and opposing traffic, was more successful. The physical presence of pedestrian refuges also reduced driver's speed significantly, although again only for (Δ/m).

At urban junctions, four out of five treatments were successful (only the static sign warning of the junction ahead did not reach significance) (Fig. 6). Both types of rumble strips were effective, but more so the vehicle activated signs which achieved an 8% speed reduction. Introducing additional alerting features such as raised rumbles and the yellow backing on the VAS, did not offer additional benefits at urban junctions.

3.2. Rural road scenarios

The speed reducing schemes for rural straight sections of road were more successful than those trialled in the urban environment,

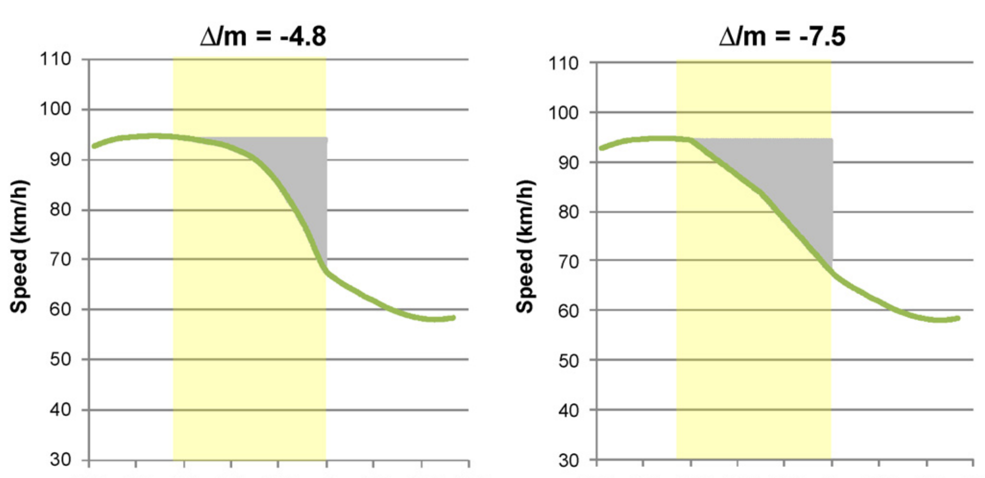

Fig. 4. Illustration of Δ/m.

Speed limit = 50km/h	Δ/m	v@maxΔ	% change
Baseline	1.1	60.9	3%
pedestrian refuges	-0.2*	59.2	-2%
peripheral hatching	-0.6*	61.6	-1%
peripheral hatching with coloured surface	-0.8*	60.2	-1%

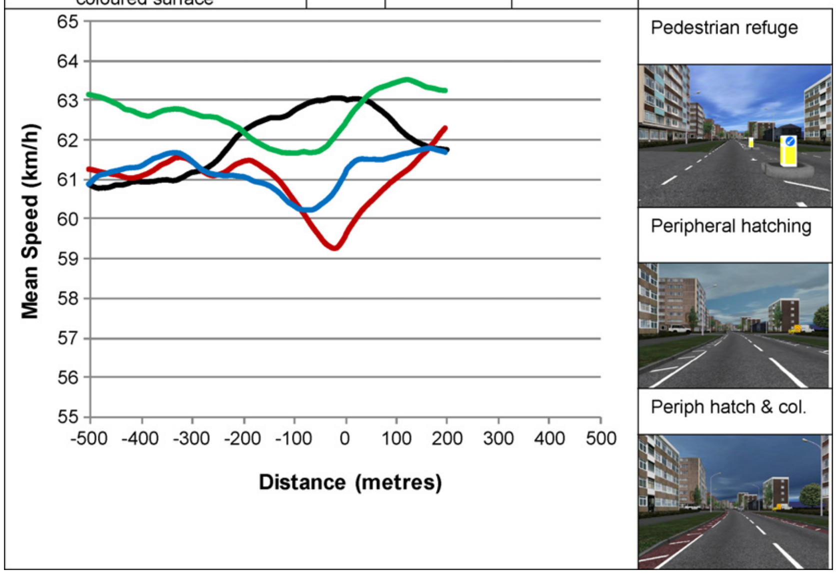

Fig. 5. Speed profiles in urban straight.

Speed limit = 50km/h	Δ/m	v@maxΔ	Speed change
Baseline	-0.2	61.3	-1%
rumble strips with raised profile	-1.3*	56.9	-5%*
rumble strips with flat profile	-1.6*	58.3	-5%*
VAS with SLOW DOWN	-2.3*	55.4*	-8%*
VAS with SLOW DOWN on yellow backing board	-2.6*	55.2	-7%*

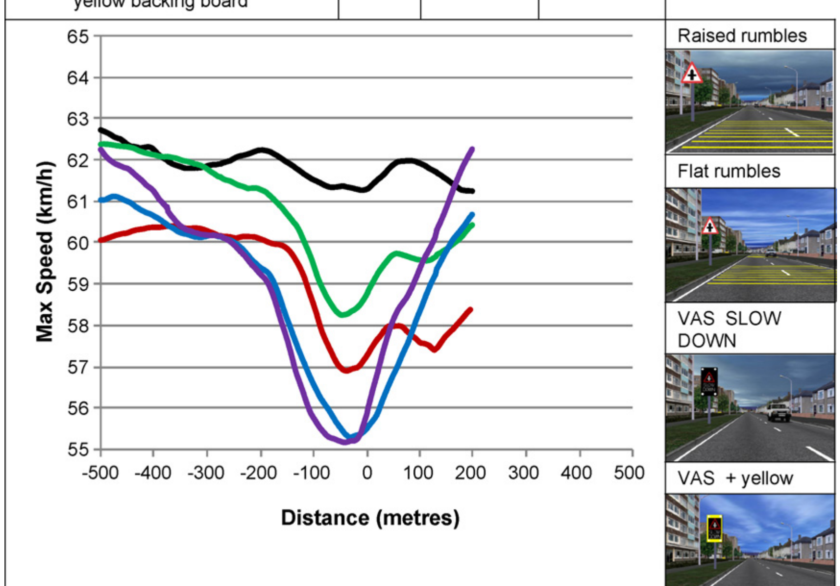

Fig. 6. Speed profiles in urban junction.

Speed limit = 96km/h	Δ/m	v@maxΔ	Speed change
Baseline	-1.0	99.5	-1%
central hatching	-2.4	102.7*	0%
central hatching with coloured surface	-4.0*	100.9*	-2%
peripheral hatching	-3.5*	98.0	-3%*
peripheral hatching with coloured surface	-3.5*	96.1	-4%*

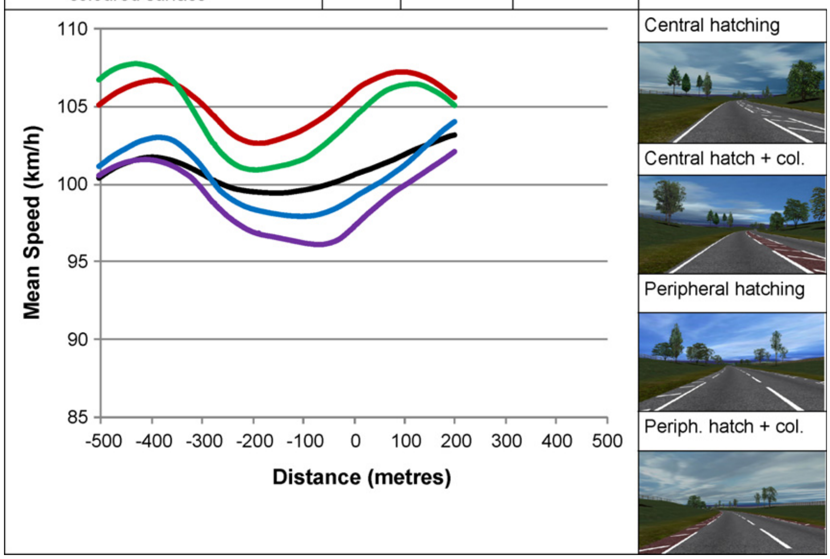

Fig. 7. Speed profiles in rural straight.

Speed limit = 96km/h	Δ/m	v@maxΔ	Speed change
Baseline	-8.7	62.4	-39%
chevron signs	-12.2*	57.5	-42%*
hazard marker posts	-11.6*	55.0*	-44%*
static sign with AdvSL	-13.0*	59.0	-41%*
static sign with REDUCE SPEED NOW	-11.7*	61.5	-40%*

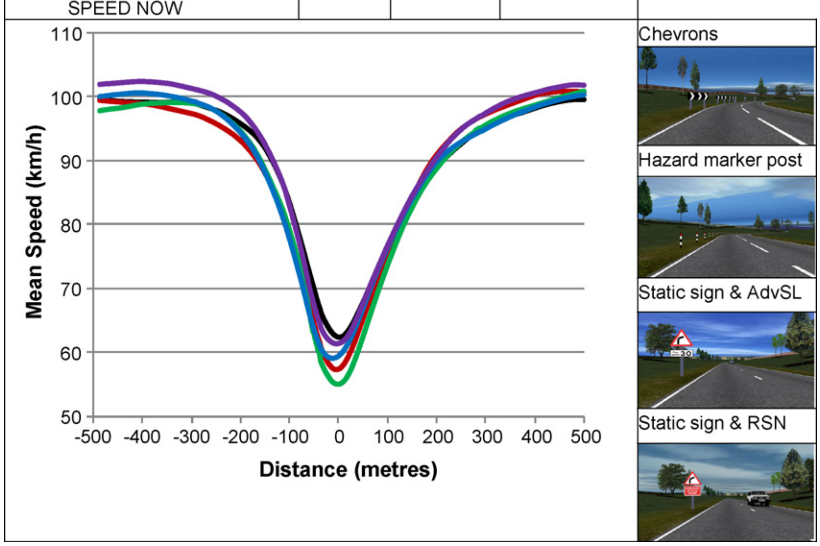

Fig. 8. Speed profiles in rural bend.

Speed limit = 96km/h	Δ/m	v@maxΔ	Speed change
Baseline	-4.8	95.8	-8%
static sign with REDUCE SPEED NOW on yellow backing board	-7.1*	89.2*	-13%*
static sign with REDUCE SPEED NOW	-6.4*	89.3*	-12%*
VAS with SLOW DOWN	-7.4*	87.9*	-14%*

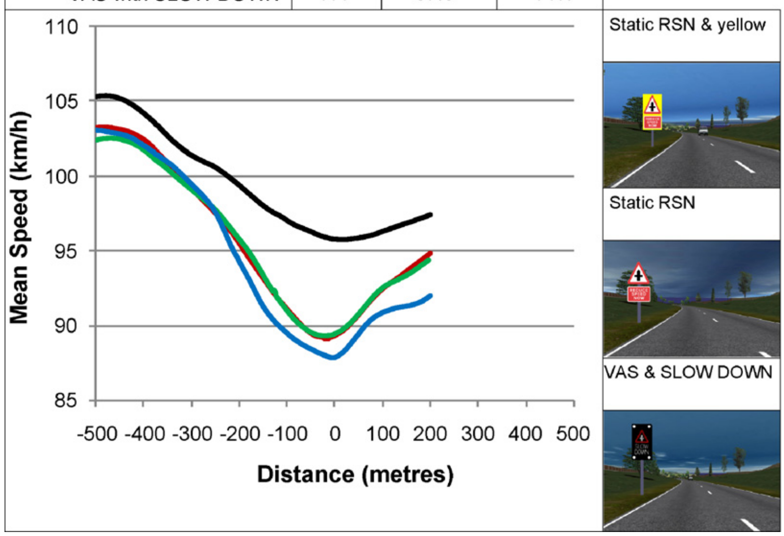

Fig. 9. Speed profiles in rural junction.

Speed limit = 96km/h to 50 km/h	Δ/m	v@maxΔ	Speed change
Baseline	-6.6	76.3	-26%
rumble strips with raised profile	-12.0*	67.6*	-33%
dragons teeth	-7.7*	67.8*	-28%
countdown signs	13.5*	61.2*	-35%

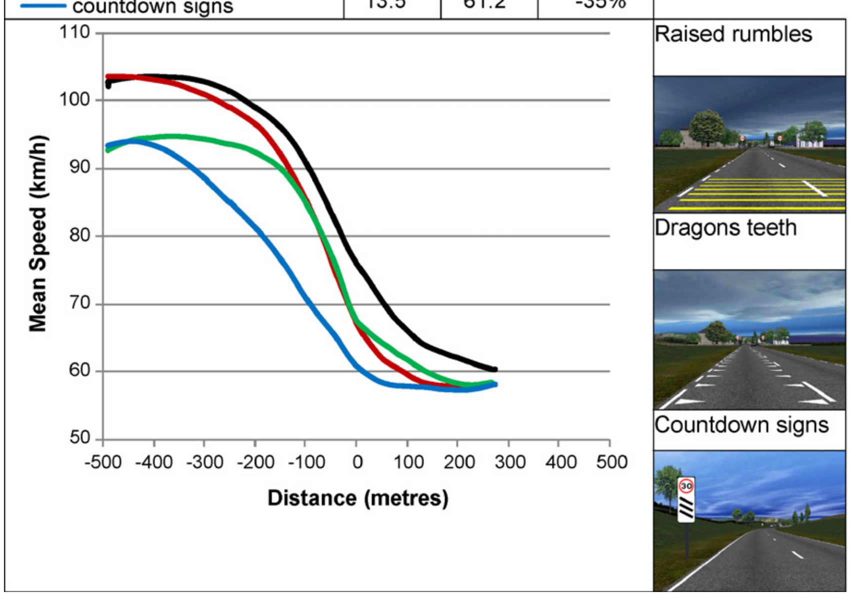

Fig. 10. Speed profiles in village entry.

with only the treatments involving vertical narrowing (trees) not demonstrating significant results (Fig. 7). In contrast to the urban results, both central and peripheral hatching significantly reduced speed. With respect to absolute speed, peripheral hatching was the most effective treatment, as indicated by $v@\max\Delta$, which also achieved the greatest speed reduction in percentage.

However, in terms of the shape of speed profile, central hatching with coloured surface also achieved good results in speed reduction; i.e. the value of Δ/m being −4.0 which is the best result among all treatments tested for rural straight sections. For both types of hatching, there appears to be some added benefit of using colour.

Of the treatments tested on the rural bend, the most successful four (out of 11) are presented in Fig. 8 and can be grouped into two distinctive groups. The first group highlighted the position of the apex of the curve, i.e. chevron signs and hazard marker posts and to some extent provided drivers with information about the severity of the curvature. These two treatments achieved the lowest $v@\max\Delta$.

The second class of successful treatments was signage, which gave advanced warning over an extended distance ahead of the apex, as demonstrated by Δ/m. It is worth noting that the static sign with advisory speed performed consistently better than VAS across all three performance indicators, which suggests that a clearly defined advisory speed limit gives a more effective warning than a standard phase such as 'Slow Down' or 'Reduce Speed Now'.

In the rural junction scenario, signs outperformed other treatments with VAS achieving the best results in speed reduction. It is also worth noting that the signs with a yellow background performed only marginally better than signs without (Fig. 9).

Most of the eight treatments tested for village entry were effective to some extent, with the most successful shown in Fig. 10. Countdown signs were the best-performing treatment consistently across all three performance indicators. The speed profile of the countdown signs is also evidently different from other treatments. This suggests that progressive warning (i.e. 300, 200, 100 yards to the change of speed limit) achieves better results in speed reduction than other types of treatments.

It is worth noting that the rumble strip with raised profile treatment was the second best-performing treatment for village entry. Although the location and duration of rumble strips are similar to other surface treatments, such as dragon's teeth, the unique tactile feedback seems to reinforce the warning in addition to visual presentation.

4. Discussion and conclusions

Using a driving simulator in this study has allowed a robust comparison of 20 diverse speed-reducing treatments. Speed data were collected at 60 Hz on approach and through the treatments and comparable baseline sections. Each of the drivers encountered all the treatments, one of the most effective ways of controlling for extraneous variables. All of these methodological benefits would have been impossible to achieve in the real world.

The results have shown that a combination of speed measures is required in order to make comparisons across different groups of treatments. For example, some of the treatments demonstrated a good percentage reduction in speed, whilst others were better evaluated by taking their length into account.

As can be seen in Figs. 5 and 7, the drivers in this study were travelling, on average, 20% above the speed limit in urban straight sections and 10% above in rural straight areas. Relatively straight sections of road are known to facilitate higher speeds and indeed a study which derived a relationship between road curvature and collisions reported a negative relationship—districts with straighter roads had more crashes (Haynes et al., 2007). Coupled with the fact that drivers tend to focus on the horizon in straight road sections (Mourant and Rockwell, 1970; Shinar et al., 1977) it is perhaps not surprising that in both urban and rural sections of road in the current study, the treatments produced only small speed reductions—in the order of 2–4%. Local road authorities find it is notoriously difficult to treat long straight sections of road and hence in recent years have turned to enforcement measures, specifically speed cameras.

These inflated speeds in the straight sections may be attributed to the driving simulator environment. A number of driving simulator studies (Boer et al., 2000; Simsek et al., 2000; Blana, 2001) all report that drivers traverse relatively straight roads faster in simulators than on the real road. Explanations for this include the lack of vestibular and other motion cues, but more likely in the current study the faster speeds were due to lower perceived risk, as in Fuller's (2005) theory of task difficulty and risk. The urban areas, in particular, were low in demand as no pedestrians or cyclists were featured in the simulation. This is supported by our finding that the lowest speeds in the urban areas were found in proximity to the pedestrian refuges which represent a physical threat and alert the driver to the potential presence of pedestrians.

In the straight, rural sections of road, it appears that this mechanism of increasing risk perception by physical means is also effective. Placing trees by the roadside had no effect on driver speed, perhaps because they did not present an immediate threat. In contrast, by narrowing the road width using peripheral hatching, drivers were forced to position themselves closer to oncoming traffic. This had the same effect of lowering speeds (and in the same order of magnitude) as the pedestrian refuges in the urban setting.

On approach to junctions, the results indicate that driver speed can be reduced by using alerting mechanisms. Static signs were the least effective treatment in the urban scenario; this could have been due to the complexity of the external environment and the inability of static signs to visually "pop out" at the driver. Vehicle activated signs and rumble strips proved effected countermeasures at urban junctions, whilst for rural environments it appears that signage is the best option. Both static and vehicle activated signs were effective in lowering speed around rural junctions, achieving double the speed reduction compared to the urban junction scenario. This finding lends support to the suggestion that it may be more difficult to alert drivers in an already cluttered, high-workload, urban environment (Anttila and Luoma, 2005).

With accidents at rural curves being overrepresented in many European countries, this current study evaluated eleven treatments. The top-performing treatments appear to be those that provide the driver with guidance regarding the appropriate curve negotiation speed. Informing drivers explicitly (using an advisory speed sign), or implicitly (using chevrons or hazard marker posts) appear to work similarly well. Other research studies have shown that drivers do slow down more for curves they perceive as being sharper (Shinar, 1977) but it could be that the perceptual characteristics giving rise to the perceived sharpness of a curve are not always clear (Shinar et al., 1980). There could be merit in experimenting with these implicit guidance treatments by making alterations to their surface pattern or their placement. This could take advantage of the theory that treatments that delineate the sharpness of the curve provide perceptual cues that can be processed in a bottom-up (data-driven) manner, without conscious deliberation (Charlton, 2007).

These successful curve treatments provide drivers with sufficient time in order to make the requisite speed changes, a feature associated also with the most effective treatment at a village entry. Here, countdown signs worked well, suggesting that early, as well as continual, reminders are necessary.

Overall, the results suggest that treatments which have different underlying mechanisms (informative, alerting, etc.) are differentially effective in urban and rural settings. The speed metrics developed were able to capture these subtle changes in driver behaviour and, more importantly, allow the best-performing treatments to be identified.

5. Implications

Using a driving simulator has allowed a robust comparison of a large number of diverse road safety engineering treatments. The usual caveats of laboratory research must apply, in particular those relating to driver motivation and the level of perceived risk in a simulated environment. In addition, only young, male drivers participated in this study which, although it increased our confidence in the "strength" of the treatments, may limit the generalisability of the results. However, it is clear from the results presented that drivers do react differently to the various treatments and this variability in the data lends support to the immersive nature of the simulation. When making direct comparisons between different types of treatments, the benefit of the simulator is clear: data can be measured over a far enough distance, and at sufficient resolution, to enable detailed analysis of speed profiles. This produces a number of speed measures that a road authority can use to inform their decisions regarding treatment implementation. Further research, however, should be undertaken to evaluate the durability of these treatments—does their value diminish with time? Again, this type of study is suited to a driving simulator environment whereby repetitions of the same treatment can be presented to the same driver under identical conditions.

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References

Anttila, V., Luoma, J., 2005. Surrogate in-vehicle information systems and driver behaviour in an urban environment: a field study on the effects of visual and cognitive load. Transport. Res. Part F 8, 121–133.

Backs, R.W., Lenneman, J.K., Wetzel, J.M., Green, P., 2003. Cardiac measures of driver workload during simulated driving with and without visual occlusion. Hum. Factors 45 (4), 525–538.

Bella, F., 2008. Driving simulator for speed research on two-lane rural roads. Accid. Anal. Prev. 40, 1078–1087.

Blana, E., 2001. The behavioural validation of driving simulators as research tools: a case study based on the Leeds Driving Simulator. Ph.D. Thesis, Institute for Transport Studies, University of Leeds, U.K.

Boer, E.R., Girshik, A.R., Yamamura, T., Kuge, N., 2000. Experiencing the same road twice: a driver comparison between simulation and reality. In: Proceedings of Driving Simulation Conference DSC 2000, Paris.

Carstensen, G., 2002. The effect on accident risk of a change in driver education in Denmark. Accid. Anal. Prev. 34, 111–121.

Charlton, S.G., 2007. The role of attention in horizontal curves: a comparison of advance warning, delineation, and road marking treatments. Accid. Anal. Prev. 39, 873–885.

Dahlen, E.R., Martin, R.C., Ragan, K., Kuhlman, M.M., 2005. Driving anger, sensation seeking, impulsiveness, and boredom proneness in the prediction of unsafe driving. Accid. Anal. Prev. 37, 341–348.

Department for Transport, 2007. Road Casualties Great Britain: 2006. Department for Transport. HMSO, London.

Department for Transport, 2008. Transport Statistics Bulletin: Road Statistics 2007: Traffic, Speeds and Congestion. HMSO, London.

Design Manual for Roads and Bridges, 2005. Department for Transport. HMSO, London.

Fuller, R., 2005. Towards a general theory of driver behaviour. Accid. Anal. Prev. 37, 461–472.

French, D., West, R., Elander, J., Wilding, J., 1993. Decision-making style, driving style and self-reported involvement in road traffic accidents. Ergonomics 36 (6), 627–644.

Gibson, J.J., 1979. The Ecological Approach to Visual Perception. Houghton Mifflin, Boston.

Gugerty, L., Rakauskas, M., Brooks, J., 2004. Effects of remote and in-person verbal interactions on verbalization rates and attention to dynamic spatial scenes. Accid. Anal. Prev. 36, 1029–1043.

Haynes, R., Jones, A., Kennedy, V., Harvey, I., Jewell, T., 2007. District variations in road curvature in England and Wales and their association with road traffic crashes. Environ. Plann. A 39, 1222–1237.

Keall, M.D., Povey, L.J., Frith, W.J., 2001. The relative effectiveness of a hidden versus a visible speed camera programme. Accid. Anal. Prev. 33, 277–284.

Knodler, J., Noyce, D.A., Kacir, K.C., Brehmer, C.L., 2006. Analysis of driver and pedestrian comprehension of requirements for permissive left-turn applications. Transp. Res. Rec. 1982, 65–75.

Laurie, N.E., Zhang, S., Mundoli, R., Duffy, S.A., Collura, J., Fisher, D.L., 2004. An evaluation of alternative Do Not Enter signs: failures of attention. Transport. Res. Part F 7, 151–166.

Lenné, M.G., Triggs, T.J., Redman, J.R., 1997. Time of day variations in driving performance. Accid. Anal. Prev. 29, 431–437.

Matthews, M.L., 1978. Speed limit compliance and judgment of velocity by car drivers. In: Proceedings of the Human Factors Association of Canada 11th Annual Meeting, 1978.

McLane, R.C., Wierwille, W.W., 1975. The influence of motion and audio cues on driver performance in an automobile simulator. Hum. Factors 17, 488–501.

Meyer, E., 2001. A new look at optical speed bars. ITE J. 71 (11), 44–48.

Mosedale, J., Purdy, A., 2004. Excessive Speed as a Contributory Factor to Personal Injury Road Accidents. Department for Transport. HMSO, London.

Mountain, L., Hirst, W.M., Maher, M., 2004. A detailed evaluation of the impact of speed cameras on safety. Traffic Eng. Control 45 (8), 280–287.

Mountain, L.J., Hirst, W.M., Maher, M.J., 2005. Are speed enforcement cameras more effective than other speed management measures? The impact of speed management schemes on 30 mph roads. Accid. Anal. Prev. 37, 742–754.

Mourant, R.R., Rockwell, T.H., 1970. Mapping eye-movements patterns to the visual scene in driving: an exploratory study. Hum. Factors 12, 81–87.

Parker, D., Manstead, A.S.R., Stradling, S.G., Reason, J.T., Baxter, J.S., 1992. Intention to commit driving violations: an application of the Theory of Planned Behaviour. J. Appl. Psychol. 77 (1), 94–101.

Pau, M., Angius, S., 2001. Do speed bumps really decrease traffic speed? An Italian experience. Accid. Anal. Prev. 33, 585–597.

Philip, P., Sagaspe, P., Moore, N., Taillard, J., Charles, A., 2005. Fatigue, sleep restriction and driving performance. Accid. Anal. Prev. 37, 473–478.

Shinar, D., 1977. Curve perception and accidents on curves: an illusive curve phenomenon. J. Traffic Saf. 23 (1977), 16–21.

Shinar, D., Mcdowell, E.D., Rockwell, T.H., 1977. Eye movements in curve negotiation. Hum. Factors 19, 63–71.

Shinar, D., Rockwell, T.H., Malecki, R., 1980. The effects of changes in driver perception on rural curve negotiation. Ergonomics 23, 263–275.

Shinar, D., Schechtman, E., Compton, R., 2001. Self-reports of safe driving behaviours in relationship to sex, age, education and income in the US driving population. Accid. Anal. Prev. 33, 111–116.

Simsek, O., Bittner Jr., A.C., Levison, W.H., Garness, S., 2000. Development of Prototype Driver Model for Highway Design. Task B: Speed-Decision Simulator Experiment. Battelle Human Factors Transportation Center, Seattle.

Stradling, S., Meadows, M., Beatty, S., 2000. Characteristics of speeding, violating and thrill-seeking drivers. In: Paper presented at the International Conference on Traffic and Transport Psychology, Bern.

Webster, D., Savill, T., Kennedy, J., 2001. Review of the impact of road humps on vehicles and their occupants. TRL Report, Crowthorne, Berkshire.

Winnett, M.A., Wheeler, A.H., 2003. Vehicle-activated signs—a large scale evaluation. TRL Report 548. Transport Research Laboratory, Crowthorne, Berkshire.