Article:
Jamson, SL, Benetou, D and Tate, F (2015) The impact of arc visibility on curve negotiation. Advances in Transportation Studies, 37. pp. 79-92. ISSN: 1824-5463

The impact of arc visibility on curve negotiation

Samantha Jamson[1], Despoina Benetou[2] and Fergus Tate[3]

[1]Institute for Transport Studies, University of Leeds, Leeds, UK, LS2 9JT
[2] Institute for Transport Studies, University of Leeds, Leeds, UK, LS2 9JT
[3]New Zealand Transport Agency, Wellington, New Zealand

Abstract

A high percentage of serious accidents occur on sharp horizontal curves, especially on two-lane rural roads. A growing body of literature has examined driving behaviour on horizontal curves, with most research relating the effect of curve radius on driver's speed and steering behaviour. There is an agreement that increasing degrees of road curvature result in less safe curve negotiation performance and consequently more accidents. Few studies, however, have further explored the effect of limited visibility on curve negotiation. This paper reports the results of a driving simulator study aimed at examining drivers' behaviour on horizontal curves, in terms of speed and lateral position, in relation to varying levels of visibility of the curve's arc. A two-lane rural road was designed and implemented in a desktop driving simulator and ten curve scenarios were examined with five different levels of visibility (20%, 40%, 60%, 80% and 100%), and of two curve radii (150m and 250m). Thirty drivers participated in the experiment; statistical analysis showed there to be a clear effect of radius on driver speed, as would be expected. However, when visibility decreased, reductions in driver speed were only found at the lowest level (20% preview). This speed reduction, however, was not sufficient enough for drivers to be able to negotiate the curve without detriment to their lateral positioning. Drivers tended to decelerate later and more sharply in the poor visibility curve and then have to compensate by moving towards the centre-line in order to flatten out the curve. It is concluded that whilst drivers can adapt sufficiently on curves that have moderate pre-view, when visibility deteriorates below a threshold (in this case 20% preview) drivers are unable (or willing) to reduce their speed appropriately and thus risk lane excursion.

Keywords – curve, safety, behaviour, visibility, clutter

1. Problem background and review

Horizontal curves, and particularly those on two-lane rural roads, are associated with a higher accident risk than curves on urban roads or straight sections of rural roads [39]. This is a universal problem:

- On New Zealand's rural state highways, loss of control on curves is the largest cause of road accidents. In 2009, they comprised 49% of all reported injury crashes on rural state highways and 36% of all reported injury crashes regardless the type of road [8].
- On rural roads in Victoria, Australia, from 1997 to 2001, accidents on horizontal curves constituted 21% of the total number of road accidents, and were more severe than crashes on straight sections of road [34]. Overall in Australia, it has been estimated that 48% of all fatal crashes on rural roads are associated with curves, with 70% of those crashes occurring on curves where the curve radius is less than 300 m [9].
- In the United States, negotiating a curve was the second most common vehicle manoeuver for reported fatality crashes, comprising 22% of all the reported fatal crashes [28].
- In the UK, accidents on rural single-carriageway roads account for 1.1 deaths per 100 million vehicle kilometres compared to 0.24 on motorways and 0.75 on urban roads. Around 18% of accidents on rural single carriageway roads occurred on curves [12].

Overall, it has been estimated that accident risk on curves is 2 to 4.5 times higher than on the tangents of the same road [9]. A wide range of interventions have been proposed to improve the safety of curves; interventions related to the driver, the environment and the vehicle. However, it is essential first to identify the possible factors contributing to crash frequency and severity on such road curves. When the causative factors are acknowledged then the accident frequency or severity can be dealt with more successfully, by identifying more suitable road designs, Intelligent Transport Systems or other interventions.

Road factors associated with curve accidents include the following [10]:

i. Degree of curvature or the radius of the curve - sharp curves are more difficult to negotiate, therefore they have higher potential accident rate.

ii. Lane width - a narrow road can force the driver to cross the roadway leading to head-on collisions. Vehicles negotiating curves tend to occupy more road area than on straight sections.

iii. Surface and side friction on the curve - low levels of friction impacts negotiation and the braking distance required for the vehicle to stop is greater

iv. Length of the curve - accident statistics have shown that shorter curve lengths have higher crash rates compared to longer ones.

v. Sight distance -an obstruction located near the roadside may block the driver's view reducing the line of sight and therefore can lead to slow brake reaction time which increases injury severity in the case of an accident.

vi. Super-elevation - inadequate super-elevation may cause vehicles to skid while driving on a horizontal curve [14]. Sharper curves require greater super-elevation for safe negotiation at higher speeds.

In order to minimize the detrimental effects of these factors, most countries adhere to road design principles which provide guidance on, for example, sight distance. Where an object at the side of the road such as a building or natural growth restricts sight distance, the minimum radius of curvature is determined by the stopping sight distance. The goal is to determine the required clear distance from the centre line of the inside lane to the obstruction for a given design speed, using the radius of curvature and minimum sight distance for that design speed.

Charlton and de Pont [9] suggested that driver errors associated with horizontal curves are the result of the three interconnected issues. First, negotiating a curve requires more attentional resources than driving on a straight section of the road. Consequently, the driver's attention can more easily be diverted or the driver may fail to notice a curve ahead due to distraction, psychological fatigue or some other factor. Sight distance through the curve (curvature) was also found to be one of the most important contributory factors associated with decreased attention. Secondly, curve approach and entry speed are often underestimated by drivers, particularly when they drive at higher speeds on the tangents before the curve. Curves which require the driver to considerably reduce his speed have been proven to be less safe and over-represented in the accident statistics. Finally, poor lane positioning can lead to loss of control of the vehicle, head-on collisions or other types of accidents. Analysis of accident data on curves has shown that in most cases the driver's first manoeuvre is towards the outside of the curve rather than in the direction of it, which causes excess of the lateral traction limits and increased friction demands.

1.1 Curve design and crash rates

McLean [27] concluded that curve negotiation speed is influenced by both curve radius and sight distance. Empirical findings show a positive association between horizontal curvature and accident rate especially in two-lane rural roads where the prevalence of curves is quite high (e.g. Charlton and de Pont [9]); in addition increasing degrees of road curvature results in more accidents particularly when the radius is less than 400m [30]. In order to explain the strong effect of curve radius on accident rates, a growing body of literature has investigated driving behaviour on horizontal curves of different radii, using diverse safety indicators such as speed, lateral placement errors, and acceleration. Gawron and Ranney [16] conducted a driving simulator study in order to investigate driver's performance on horizontal curves of radii ranging from 57.3m to 94.2m. Curve-entry speed increased as radius of curvature increased and total lateral position error was highest in the curve with the smallest radius, due to the curve-cutting strategies frequently observed on small radius curves. Fitzpatrick et al. [15] investigated acceleration patterns of rural horizontal curves and found that the only sites where acceleration and deceleration rates approached the value of 0.85 m/s^2 (a common value proposed in previous studies) were those with curve radii less than 250m, and that operating speeds on horizontal curves dropped sharply when the radius was below 250m.

McFadden and Elefteriadou [26] investigated which geometric variables predicted outcome variables such as 85th percentile speed difference into and out of the horizontal curve. They reported a significant association between curve radius and the 85th percentile speed difference into and out of the horizontal curve. In other words, the smaller the curve radius, the higher is the expected reduction in speed for a vehicle entering the curve. This indicator of speed differential between approach tangent and curve is commonly seen in the literature for the evaluation of the design consistency, as there is a direct correlation between safety and variability in speed [26].

Turner and Tate [38] examined the relationship between curve negotiation speed and curve radius. After collecting data from 488 curves and analysing the speed profiles for a sample of young, predominately male drivers, they concluded that the speed which the sample drivers chose to negotiate the curves was influenced by the curve radius rather than the curve design speed (which can be dependent on sight distance and road friction). In sharp curves below 300m radius, drivers tend to negotiate the curve with lower speeds than on large-radius curves.

Shinar [32] investigated the misperception of curvature phenomenon, where he suggested that the accident risk is higher on curves which are perceived as nearer, less sharp and more visible than they actually are, and horizontal curve geometry (radius, length and total angle) may be irrelevant. Chen [10] states that roadside objects such as poles or trees can affect sight distance and judgement which increases injury severity. Taragin and Leisch [35] reported a relationship between curve speed and minimum sight distance whereby the operating speeds were considerably lower at locations where the minimum sight distances were below 250 feet (76.2m) than at locations where the lowest sight distances were greater than 500 feet (152.4m). It was observed that drivers did not change their speeds considerably after entering a horizontal curve, but the speed adjustment was mainly made during the approach tangent; thus the sight distance should be at least 400 feet (121.9m).

Thus, Shinar et al. [33] proposed that the geometric design of horizontal curves should not be based only on the classical engineering approach, but should be related more to the driver's behaviour and their perception of the curve. The engineering approach assumes that the vehicles follow the roadway path with geometrical exactness, which is unrealistic, particularly for rural roads where the design speed is frequently exceeded. Moreover, the driver doesn't normally have a full view of the curve as the road designers assume. The driver may have a limited view due to visual obstacles on the roadside, such as trees or buildings. Therefore, the driver prior to an unfamiliar curve may select a speed according to the limited view the driver has, and then change it according to the information received while curve perception is improving. Curve negotiation is a dynamic process; drivers when approaching a curve continuously modify their speed according to the demands [33]. Shinar et al. examined this issue comprehensively, with several laboratory and field studies and one of those studies was particularly focused on curves which were obscured by hills. The authors concluded that the driver approaching a curve on an open road may not appreciate their high speed due to the lack of peripheral visual stimulation. On the other hand, drivers who approaching the same type of curve on a road lined with trees drove at significantly lower speeds. Therefore, they concluded that the driver's performance can be changed by affecting the driver's perception of the roadway without actually changing the physical features of the road.

To summarise, there is previous literature indicating a relationship between curve radius and sight distance and drivers' performance on horizontal curves. The sharper the curve (below 300m radius) the lower is the speed the drivers tend to negotiate it. Regarding the speed differential, the smaller the curve radius, the higher is the expected reduction in speed for a vehicle entering the curve. Similarly, deceleration rates on the approach to the curve and acceleration rates on the departure tangent are higher when the curve radius drops below 250m. Some argue that the effect of limited sight distance on speed is not as strong as that of curve radius, but a correlation does exist; others report that the perception of the curve is the key factor affecting driver's behaviour, with geometry being of little importance.

Thus this study focussed on the external feature of sight distance and to a lesser extent on curve radius or, as frequently encountered, the degree of curvature (defined as the angle formed by an arc of 100 feet length) and examines the effects of sight distance on steering regulation and subsequently on speed and driver position in the lane. Specifically, we investigate how sight distance restrictions can potentially block a driver's view of the upcoming road segment and affect negotiation speed and further performance, as they are unable to see more than "X" percentage of the curve's arc.

2 Methodology

2.1 Driving simulator

A driving simulator was chosen as the most appropriate tool since they allow experiments to be carried out in controlled conditions, the scenario development is very flexible and the scenarios can easily be repeatable under the exact same conditions. In addition, driving simulators allow a high degree of realism, low costs in conducting experiments, easy data collection and the highest degree of safety for the test drivers [1]. The methodology allows us to look for relative (not absolute) changes in behaviour, between different conditions. All of these practical advantages would have been impossible to achieve in a real-life driving environment. LabSim is a low-cost alternative to the full-scale 2nd generation driving simulator of the University of Leeds, running the same software, but with less immersive driver controls and image generation. The driver sits at a desk accommodating a Logitech Momo force-feedBAck steering wheel and pedals. A real-time, fully textured and anti-aliased, 3-D graphical scene of the virtual world is displayed on a Samsung 40" flatpanel display in front of the driver. The display is a single 920x1080 channel with a horizontal field of view of 85° and a vertical field of view of 48°, Figure 1. The visual display update and data collection rates were 60Hz.

Fig. 1: The driving simulator

2.2 Road design

A two-lane rural road, one lane in each direction, was designed and implemented in the driving simulator. The road was without shoulders with a width of 7.30m. The experimental route consisted of 5 left-hand curves of 150m radius (153m in length) and 5 left-hand curves of 250m radius (252m in length). Each was circular in design with a deflection angle of 58º. The approach tangent to each curve was 200m and completely straight.

In order to achieve varying degrees of curve arc visibility, the curve radius was masked using a combination of road banking and trees. The height and position of the roadside banking was varied in order to achieve different preview distances. For example where the banking was closer and higher, the preview distance was less. In order to systematically vary the preview distance, it was necessary to implement an objective process prior to the main study. This was achieved by placing hazard marker posts (HMPs) along the centre line of the curve, so that when an observer was static at 50m before curve entry, the amount of curve visible to the drivers was judged by counting the number of marker posts visible. This distance of 50m was not intended to reflect sight distance in any way – it was simply a way of ensuring comparability across the different preview categories (the HMPs removed before the study commenced). A total of 30 HMPs were placed along the centre-line and the banking was then incrementally altered to achieve the following curve arc previews:

- 20% preview (6 HMPS visible)
- 40% preview (12 HMPS visible)
- 60% preview (18 HMPS visible)
- 80% preview (24 HMPS visible)
- 100% preview (30 HMPS visible)

Identical filler sections, consisting of right-hand curves of 750m radius and long straight sections in between, were inserted in order to separate the ten curves under investigation. The speed limit of the road was 90 km/h and the total road length 33km long with no vertical curvature. In order to ensure that the drivers were not influenced by the presence of other vehicles, there was no traffic either in the driver's lane or in the opposite direction. Examples of the ten curves presented, by combining the five levels of preview distance with the two curve radii, are presented in Figure 2.

20% visibility 60% visibility 100% visibility

Fig. 2 Tested scenarios

The presentation of the ten curves was counterbalanced as far as possible across participants to minimise order effects.

2.3 Participants

Participants were recruited at the University, based on the following criteria:

i. Ownership of a current driving license for more than four years;
ii. More than 3,000 miles driving experience per year on average);
iii. Additional driving experience on rural roads (more than 1,000 miles the last year)
iv. Not prone to motion sickness; and
v. No influence of drugs or alcohol that could alter perception, cognition, and attention.

The drivers had no prior experience with the driving simulator. Each participant drove 10 minutes on a familiarisation route which comprised of straights and curves but with no visual obstruction. They then drove the experimental route lasting around 20 minutes. Thirty participants, 11 women and 19 men with age ranging between 23 and 56 years (mean = 28.2 years; s.d. = 6.4 years) completed the experiment. Their average number of years of driving experience was approximately 9.5 (s.d. = 6.9 years), and the average annual driven distance was about 7900 miles (s. d. = 6300 miles). Upon arrival, each driver was briefed on the requirements of the experiment and signed an informed consent form.

2.4 Data processing and analysis

All data were collected at 60Hz. Values of speed were collected from 200 metres before curve entry and 200m after curve exit, which exceed the recommended sight distance stated by Taragin and Leisch [35]. The examination of speed profiles are essential in road design and in the examination of drivers' behaviour in order to track speed differences between tangents and curves; the deceleration and acceleration rates are also required in order to establish the speed reduction profile in the curves and preceeding tangents [31]. Driver's deceleration and acceleration profiles can help a lot in evaluating the safety of the design consistency of the road. Sharp curves lead to high deceleration rates when the drivers approach a horizontal curve and high acceleration rates when they depart the horizontal curve [23]. Finally, lateral position was also measured, as drivers' errors on horizontal curves are often due to their failure to maintain a proper lateral position [19]. Lateral positon is defined as the location of the vehicle's longitudinal axis relative to a longitudinal road reference system [29].

Cluster analysis was carried out in order to test if the driver's speed and lateral position behaviour when negotiating the different curve scenarios was substantially different. Cluster analysis is a statistical technique used for classifying data into data groups for the aid of the analysis. Hierarchical cluster analysis using Ward's method was first performed on separate segments. For the 150 m length curves the data were divided into four segments as follows: (a) from -200m to -100m, (b) from -100m to 0m, (c) from 0m to 150m and (d) from 150m to 350m. For the 250m curves, the segments were: (a) from -200m to -100m, (b) from -100m to 0m, (c) from 0m to 250m and (d) from 250m to 450m. The position "0" denotes curve entry. Then, having inspected the agglomeration schedule and calculating the changes in the coefficients, the optimum number of clusters was determined (which in all cases was 2). This was also confirmed via the dendograms. Then, the hierarchical cluster analysis was re-performed using two clusters and cluster membership was calculated. This method was repeated for each of the road sections and separately for the two curve radii.

Following cluster analysis, which agglomerated all date across a road section, repeated measures ANOVAs were performed on the spot speed and lateral positions, using visibility as the independent factor.

3 Results

3.1 Cluster analysis

The results for speed on the 150m radius curves are shown in Table 1, indicating the percentage of speed observations among the 30 participants and for each road segment that were assigned to the first or the second cluster respectively. Overall, the cluster analysis did not show a difference in speed observations among these curves. That is to say the drivers' speed behaviour was not substantially different negotiating the 150m curves under different visibility levels.

Tab. 1: Speed clustering results for 150m radius curves

Preview	[-200,-100]		[-100,0]		[0,150]		[150,350]	
	Cluster 1	Cluster 2	Cluster 1	Cluster 2	Cluster 1	Cluster 2	Cluster 1	Cluster 2
20%	79.1%	20.9%	68.9%	31.1%	58.0%	42.0%	53.9%	46.1%
40%	74.5%	25.5%	72.2%	27.8%	61.1%	38.9%	54.4%	45.6%
60%	72.1%	27.9%	65.4%	34.6%	59.9%	40.1%	58.1%	42.0%
80%	73.0%	27.0%	73.2%	26.8%	66.1%	33.9%	59.0%	41.1%
100%	66.4%	33.6%	60.3%	39.7%	59.4%	40.6%	58.6%	41.4%

The values in Table 2 indicate the percentages for the lateral position observations. Here, the results did show a quite different behaviour of drivers negotiating the 20% preview curve compared to the rest of the scenarios. There is a noticeable difference especially throughout the curve section (from 0m to 150m) where the majority of the lateral placement observations are assigned into a different cluster for the 20% preview than for the rest of the preview percentages (75% v 25%).

Tab. 2: Lateral position clustering results for 150m radius curves

Preview	[-200,-100]		[-100,0]		[0,150]		[150,350]	
	Cluster 1	Cluster 2	Cluster 1	Cluster 2	Cluster 1	Cluster 2	Cluster 1	Cluster 2
20%	58.6%	41.4%	46.8%	53.2%	75.0%	25.0%	50.3%	49.7%
40%	38.6%	61.4%	61.5%	38.5%	35.0%	65.0%	45.1%	54.9%
60%	45.2%	54.8%	52.0%	48.0%	36.7%	63.3%	46.2%	53.8%
80%	49.2%	50.8%	50.4%	49.6%	34.2%	65.8%	42.9%	57.1%
100%	44.3%	55.7%	49.1%	50.9%	35.9%	64.1%	49.9%	50.1%

Regarding the clustering results for the 250m radius curves, these are shown in Table 3 and Table 4, for speed and lateral position respectively. In the 250m curves there is little difference between the visibility conditions for the speed data, however the lateral position data shows a clear difference with the 20% visibility condition being markedly different from the rest (82% v 17%) as measured at curve entry (0-250m).

Tab. 3: Speed clustering results for 250m radius curves

Preview	[-200,-100]		[-100,0]		[0,250]		[250,450]	
	Cluster 1	Cluster 2	Cluster 1	Cluster 2	Cluster 1	Cluster 2	Cluster 1	Cluster 2
20%	73.2%	26.8%	68.2%	31.8%	56.2%	43.8%	26.4%	73.6%
40%	65.0%	35.0%	70.8%	29.2%	42.2%	57.8%	38.6%	61.4%
60%	62.7%	37.3%	74.0%	26.0%	40.6%	59.4%	39.4%	60.6%
80%	57.3%	42.7%	74.6%	25.4%	48.9%	51.1%	32.5%	67.5%
100%	58.6%	41.4%	70.7%	29.3%	43.4%	56.6%	33.0%	67.0%

Tab. 4: Lateral position clustering results for 250m length curves

Preview	[-200,-100]		[-100,0]		[0,250]		[250,450]	
	Cluster 1	Cluster 2	Cluster 1	Cluster 2	Cluster 1	Cluster 2	Cluster 1	Cluster 2
20%	49.6%	50.4%	60.4%	39.6%	82.6%	17.4%	47.1%	52.9%
40%	64.1%	35.9%	43.3%	56.7%	38.0%	62.0%	52.9%	47.1%
60%	45.1%	54.9%	47.5%	52.5%	43.7%	56.3%	51.5%	48.6%
80%	63.4%	36.6%	44.1%	55.9%	35.3%	64.7%	56.5%	43.6%
100%	55.9%	44.1%	51.1%	48.9%	43.0%	57.0%	53.4%	46.6%

Overall, the cluster analysis showed a quite different lateral positioning behaviour of drivers negotiating the 20% preview curves compared with the ones with greater visibility levels.

3.2 The effect of arc visibility

From the cluster analysis it can be seen that drivers approach a curve with limited view in a different way compared to when presented with a full view of the curve. This is particularly so when visibility is limited to only a 20% preview. However drivers approaching with more modest reductions in view do not appear to be adapting their speed, compared to full view. The cluster analysis focused on speed and lateral positioning profiles; further analysis was undertaken using spot measurements at approach, entry and apex of the curve. Data were inspected for normality within the groups (via the Shapiro-Wilk test) and homogeneity of variance (via the Levene's test). Therefore, repeated measures ANOVA were performed to test differences in driver performance between the two factors of Visibility (5 levels) and Radius (2 levels), with a significance level set at $p<.05$. Interaction effects were also tested.

3.2.1 Driver speed

There was a main effect of Radius on apex speed [$F(1,29)=14.04$, $p<.001$; $\eta p^2=0.326$], see Figure 3 whereby, speeds at the apex of the curve were higher in the 250m radius curve by approximately 3km/h. A main effect of Visibility on speed at apex was also found [$F(4,116)=2.98$, $p<.05$]; post-hoc testing using repeated contrasts revealed a significant difference between 20% and 40% visibility, being around 4km/h. No additional additive changes in speed were found as visibility increased. There were no effects of either Radius or Visibility on approach or entry speeds.

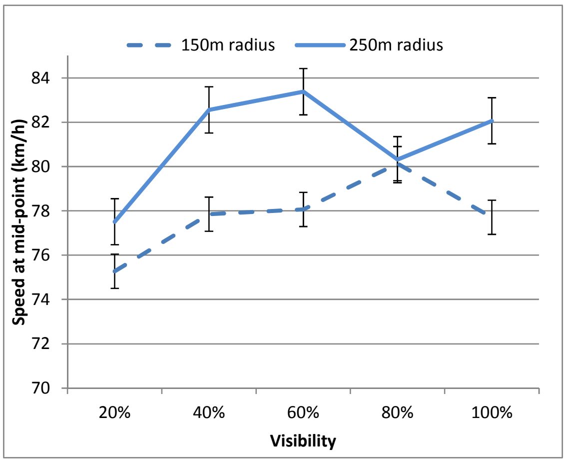

Fig. 3: Speed at curve apex across Visibility and Radius conditions

Regarding the differential between the speed on the approach tangent (200m prior to curve entry) and speed at the apex of the curve, a main effect of Visibility [$F(4,116)=3.98$, $p<.01$; $\eta p^2=0.267$], was found with post-hoc testing revealing that the difference lay solely between the 20% and 40% visibility conditions. The speed reduction reported for the lowest visibility curve was approximately 14 km/h (Figure 4). A main effect of Radius was also present [$F(4,116)=4.14$, $p<.01$; $\eta p^2=0.371$], with drivers reducing their speed more on approach to the lower radius curves.

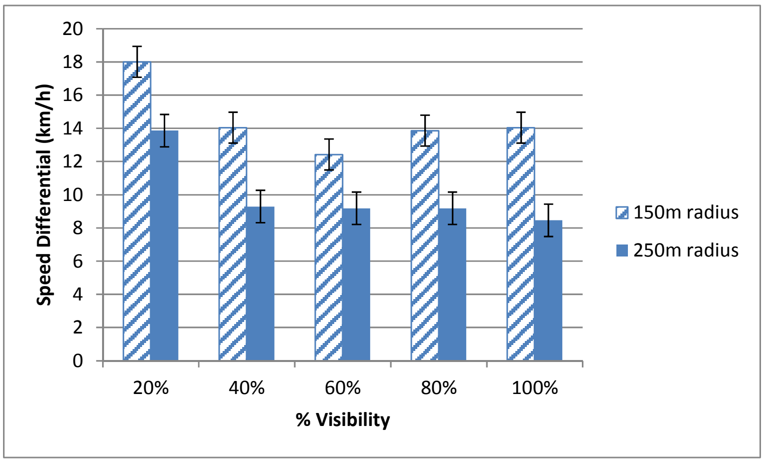

Fig. 4: Speed differential from the approach tangent to the curve's apex

3.2.2 Lateral position

There was no main effect of Radius on any of the lateral position parameters. However, there were significant effects of Visibility on lateral position at curve approach [$F(4,116)=2.54$, $p<.05$; $\eta p^2=0.108$], curve entry [$F(4,116)=7.57$, $p<.001$; $\eta p^2=0.207$] and at the apex of the curve [$F(4,116)=12.24$, $p<.001$; $\eta p^2=0.297$], Figure 5. At all locations, lateral position on the 20% visibility curves was significantly different to that on all other curves such that as preview of the curve decreased, drivers tended to position themselves more towards the centre of the road.

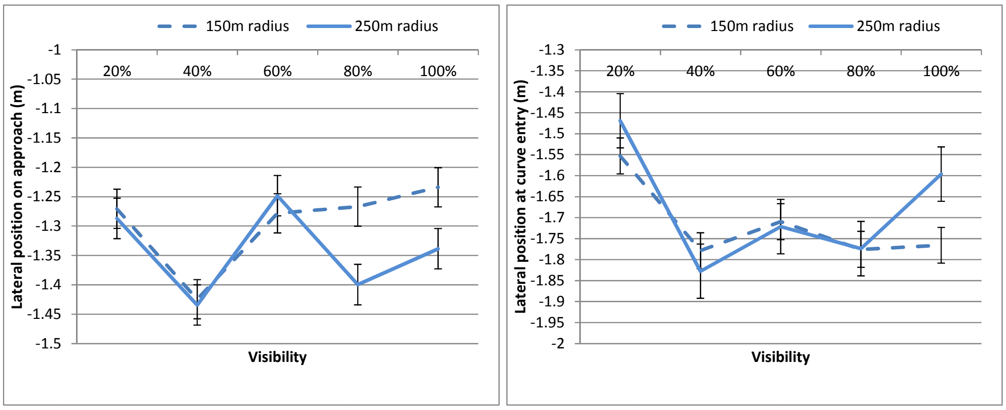

Fig. 5: Lateral position across Visibility and Radius conditions (values closer to zero indicate a closer position to the centreline)

This effect was stable across both curve radii and supports the findings of the cluster analysis. A summary of the results are found in Table 5, showing that Visibility had more consistent effect on driver performance measures.

Tab. 5: ANOVA tests of visibility and curve radius

	Visibility	Radius	Visibility*Radius
Approach speed (-50m)	ns	ns	ns
Entry speed	ns	ns	ns
Apex speed	sig	sig	ns
Approach Lat. Pos. (-50m)	sig	ns	ns
Entry Lat. Pos.	sig	ns	ns
Apex Lat. Pos.	sig	ns	ns

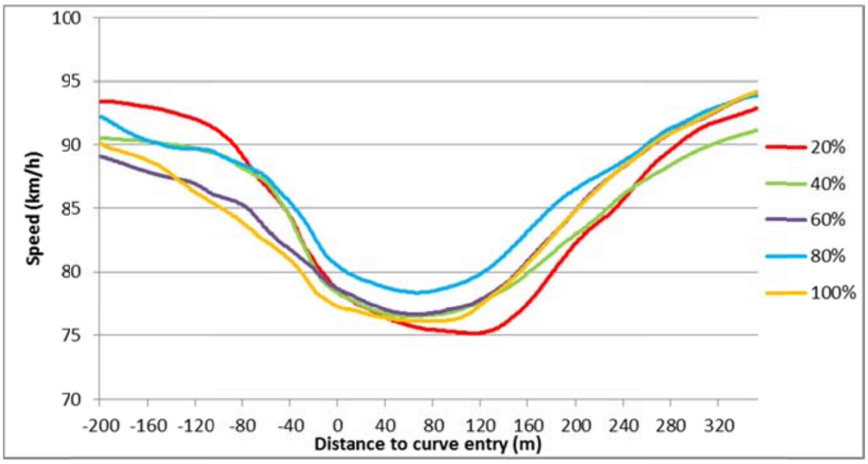

Fig. 6 Speed profiles for 150m curve

For the 150m radius curves, in the 20% visibility condition, speed decreases gradually 100m-200m before curve entry and a clear speed reduction is not observed until the last 100m of the approach tangent. Where the driver had full visibility of the curve, they completed a large proportion of their speed reduction before entering the curve, with only minimal deceleration in the curve, thus allowing them to reach their minimum speed at the curve apex. In the lowest visibility scenario, drivers are still reducing their speed after entering the curve, reaching their minimum speed in the last quarter of the curve.

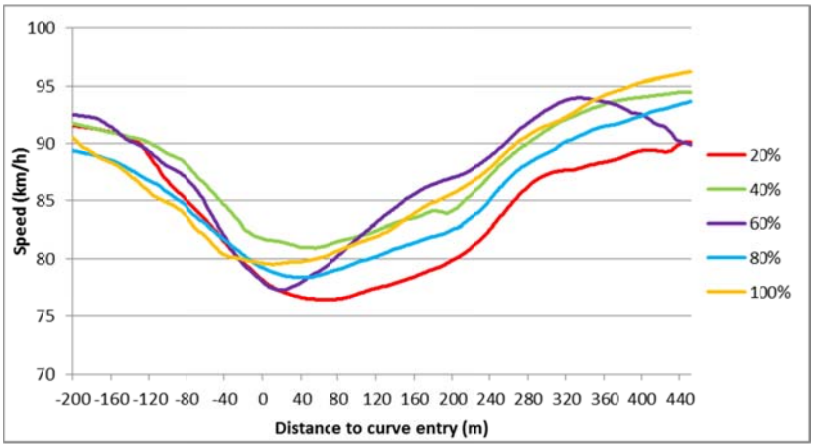

Fig. 7 Speed profiles for 250m curve

4 Discussion

The use of a driving simulator in this study has allowed a comparison of ten different rural curves, five of 150m and five of 250m radius, with varying levels of arc visibility. Speed and lateral position data from thirty participants were collected at 60Hz frequency on approach tangent and through the curve section of each tested curve. Each of the drivers encountered all the curves in a counterbalanced order. In summary, the results showed:

- curve radius influenced curve apex speed
- visibility influenced curve apex speed, but only when visibility was minimal (20% view of curve arc)
- this led to compensatory behaviour in terms of lateral position

Whilst the relationship between curve speed and curve radius is relatively well documented [27], that between curve arc visibility and speed adaptation is less well understood. Of particular interest is the amount of degradation in visibility that needs to be present in order to influence driver speed. Whilst we had no a priori assumptions, such a clear distinction between 20% visibility and the remaining conditions was not anticipated.

As found in real-life observations of driver speed on curves [6], this simulator study showed that curve radius influenced speed whereby drivers were travelling on average at 76km/h at the apex of the 150m curve and at 82km/h in the 250m curve. In terms of absolute validity, these values are higher than real-life values, which Bonneson et al. [6] estimate should be approximately 64km/h and 74 km/h respectively. However, speed perception studies have shown that observers tend to underestimate their velocity in simulated environments [22, 17]. Higher speeds in simulators compared to real life have been observed on both straight [5] and curved road sections [36, 37, 20, 13,21]. Thus, relative validity in simulator studies is the key issue as opposed to absolute validity. This is particularly relevant as this study used a relatively basic simulator; this basic simulator has been found to be a reliable tool as compared to a more sophisticated study, with respect to speed measurements [7,24].

Visibility of the curve's arc also affected driver speed, again at the apex of the curve. However, driver speed was significantly lower only when visibility was very low (20%). There appeared to be no significant adaptation of driver speed when visibility was 40-80%, compared to full visibility, a finding similar to Calvi [7]. Speed choice at horizontal curve approach and entry greatly influences lateral lane position within the curve, as centripetal force pushes a vehicle to the outside of a curve when the operating speed exceeds the curve design speed. Moving outwards in this way increases the radial path of a vehicle to compensate for excessive speed, known as curve flattening. Zador et al. [42] reported in his study of 46 US rural horizontal curves that many vehicles shifted towards the edgeline on an outside curve (left-handed curve) and closer to the centreline on an inside curve (right-handed curve). Comparing this to the current study, where drivers were traversing inside curves only (UK, driving on the left, around left-hand curves), we can see that in Figure 5, lateral position shifted even more towards the centre of the road at low visibility (20%). Presumably this was due to drivers not having sufficient view of the curve arc in order to make the appropriate speed adjustment – this led to them having to compensate by flattening out their path by moving towards the centre line and potentially closer to oncoming traffic. The speed profiles in Figure 6 and Figure 7 demonstrate this quite clearly. Thus, significantly masking a curve's arc could lead to poor speed choice and more risky lateral positioning.

5 Implications

This study used a low-cost simulator to investigate a little-researched area. Whilst the simulator may not have the face validity of more high-fidelity facilities, we have been able to demonstrate subtle difference in behaviour which varies according to the road design. Low-cost simulators can be a useful first tool for road safety engineers to carry out behavioural research. High-fidelity (wide projection, motion-base) are often not available to city planners and transport engineers, due to resource restrictions. As usual in any experimental research made, there are some caveats to be raised at this stage, especially those relating to driver behaviour and the level of perceived risk in a simulated environment. A driving simulator is not the real world; nevertheless, it can still allow the collection of reliable data, looking for relative and not absolute changes in driver behaviour under different conditions. Furthermore, the sample size of 30 is on the boundary between a small and a large sample size, while, regarding age and gender distribution of the participants, mostly young male drivers participated in the experiment. However, due to time constraints a largest sample that could be more representative was not feasible. Another possible limitation of the experimental design is that it is known that drivers will move away from an object that they perceive as an obstacle. If the obstacle is located on the left side (UK), it will cause drivers to move closer to other traffic [39].

The results from this research suggest that visual obstructions on the inner part of a rural horizontal curve can limit the sight distance of the driver negotiating the curve, and affect their curve negotiation performance in terms of lane position and speed profile. This study has not only replicated known findings relating to speed choice on curves, but also shown that drivers attempt (either consciously or not) not to reduce their travel speed unless the conditions are critical – a curve arc visibility of only 20% appears to be the tipping point. Such a cut-off point has not been reported in the literature as yet and serves as a useful benchmark for transport engineers. Similarly Glennon et al. [17] found that drivers wait until they are close to the curve before beginning to adjust their speed, independent of the curve's radius. The authors suggest that this reflects the desire to estimate an appropriate curve speed based on their own assessment of curve sharpness. Where visibility is poor, this could lead to even later decision making.

The driver should have as full visibility as possible of the curve ahead in order to anticipate the severity of the curve and adjust their road path. Such consideration should be taken into account when designing new roads such that where possible a curve should be site away from landscape that might reduce visibility (banking etc.). For existing curves with such poor arc visibility additional speed reducing measures should be considered. For example, transverse bars, have been found to be effective at reducing speed on curves [1, 40]. Alternatively, the curve arc could be highlighted using vertical posts in order to improve accuracy in judging radius [25]. Further research should focus on broadening the range of curve radius investigated and including right-hand curves in the experimental design.

6 References

1. Agent, K.R. (1980). Transverse pavement markings for speed control and accident reduction. Transportation Research Record, 773 (1980), pp. 11–14.
2. Bella, F. (2009). Can the driving simulators contribute to solving the critical issues in geometric design? *Transportation Research Record* No. 2138. TRB of the National Academies, Washington, D.C., 120-126.
3. Bella, F. (2011). How traffic conditions affect driver behavior in passing maneuver. *Advances in Transportation Studies* RSS2011 Special Issue, pp 113-126.
4. Bella, F. (2013). Driver perception of roadside configuration on two-lane rural roads: Effects on speed and lateral placement. *Accident Analysis and Prevention* 50 (2013), pp. 251-262.
5. Blaauw, G.J. (1982). Driving experience and task demands in simulator and instrumented car: a validation study. Human Factors 24(4), pp 473-486.
6. Bonneson, J.A., Pratt, M. Miles, J. and Carlson P. (2007). Development of Guidelines for Establishing Effective Curve Advisory Speeds. FHWA/TX-07/0-5439-1. Texas Department of Transportation, Austin, Texas.
7. Calvi A (2015). A Study on Driving Performance Along Horizontal Curves of Rural Roads. Journal of Transportation Safety & Security, Vol. 7(3), p. 243-267.
8. Cenek, P. D. et al. (2011). A prioritisation scheme for the safety management of curves. *Proceedings of 3rd International Surface Friction Conference, Safer Road Surfaces – Saving Lives*, Gold Coast, Australia 2011.
9. Charlton, S. G. and de Pont, J. J. (2007). Curve speed management. *Land Transport New Zealand*: Research Report 323.
10. Chen, S. H. (2010). Mining patterns and factors contributing to crash severity on road curves. *PhD thesis, Queensland University of Technology*.
11. Chrysler et al. (2009). Driver Response to Delineation Treatments on Horizontal Curves on Two-Lane Roads. *Texas Transportation Institute*, Report No. FHWA/TX-09/0-5772-1.
12. Comte, S. L. and Jamson, A. H. (2000). Traditional and innovative speed-reducing measures for curves: an investigation of driver behaviour using a driving simulator. *Safety Science* 36 (2000), pp. 137-150.
13. Duncan, B. (1995). Calibration trials of TRL driving simulator. Transport Research Laboratory. Unpublished Project report. PA13079195. S221AlRB.

14. FHWA, (2007). Mitigation Strategies for Design Exceptions - July 2007. Available from: http://safety.fhwa.dot.gov/
15. Fitzpatrick, K. et al. (2000) Alternative Design Consistency Rating Methods for Two-Lane Rural Highways. *Federal Highway Administration.* Report 99-172.
16. Gawron, V.J. and Ranney, T.A. (1990). Curve negotiation performance in a driving simulator as a function of curve geometry. *Applied Ergonomics* 21, pp. 33-38.
17. Glennon, J.C., T.R. Neuman, and J.E. Leisch. Safety and Operational Considerations for Design of Rural Highway Curves. FHWA/RD-86/035. Federal Highway Administration, U.S. Department of Transportation. 1985.
18. Groeger, J.A., Carsten, O.M.J., Blana, E., Jamson, A.H., 1997. Speed and distance estimation under simulated conditions. In Gale, A.G., Brown, I.D., Haslegrave, C.M. and Taylor, S.P. (Eds.): Vision in Vehicles VII. Elsevier Science, Amsterdam.
19. Hallmark, S. L. (2012). Relationship between Speed and Lateral Position on Curves. *Center for Transportation Research and Education Iowa State University*. Final report, part of the Midwest Transportation Consortium Project 2009-03.
20. Harms, L. (1993). Driving Performance on a real road and in a driving simulator: results of a validation study. Paper presented at the 5th International Conference on Vision in Vehicles, Glasgow.
21. Harms, L., Alm., H. and Tornos, J. (1996). The influence of situation cues on simulated driving behaviour: a summary of three validation studies. Paper presented at the Symposium on the Design and Validation of Driving Simulators. ICCTP'96. Valencia.
22. Howarth, P.A.,1998. Oculomotor changes within virtual environments. Applied Ergonomics, 30, 59-67.
23. Hu, W. and Donell, E. T. (2010). Models of acceleration and deceleration rates on a complex two-lane rural highway: Results from a nighttime driving experiment. *Transportation Research Part F* 13 (2010), pp. 397–408.
24. Jamson SL; Jamson AH (2010). The validity of a low-cost simulator for the assessment of the effects of in-vehicle information systems, Safety Science, 48, pp.1477-1483.
25. Kallberg, V. (1993). Reflector posts: signs of danger? Transportation research record. No. 1403.
26. McFadden, J. and Elefteriadou, L. (2000). Evaluating Horizontal Alignment Design Consistency of Two-Lane Rural Highways - Development of new procedure. *Transportation Research Record* 1737, Paper No. 00-0813.
27. McLean, J.R. (1974). Driver behaviour on curves – a review. *Proceedings of the 7th Australian Road Research Board (ARRB) Conference*, Adelaide (1974), pp.129-147
28. NHTSA, (2011). Traffic Safety Facts 2011 - A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System. *National Highway Traffic Safety Administration*, National Center for Statistics and Analysis, U.S. Department of Transportation Washington, DC 20590.
29. Porter, R. J. et al. (2004). Evaluation of Effects of Centerline Rumble Strips on Lateral Vehicle Placement and Speed. *Transportation Research Record*: No. 1862, National Research Council, Washington, D.C., 2004, pp.10–16.
30. Profilidis and Botzoris, (2005). Analysis and Modeling of Road Safety Parameters. (Original title in Greek: Ανάλυση και μοντελοποίηση των παραμέτρων οδικής ασφάλειας). 3ο Πανελλήνιο συνέδριο οδικής ασφάλειας, Πάτρα, 10-11 Οκτ., 2005
31. Said, D. Abd El Halim, O. and Hassan, Y. (2009). Methodology for Driver Behaviour Data Collection and Analysis for Integration in Geometric Design of Highways. *Proceedings 4th International Symposium on Highway Geometric Design*.
32. Shinar, D. (1977). Curve Perception and Accidents on Curves: an illusive Curve Phenomenon? *Zeitschrift fur Verkehrssicherheit,* Vol. 23, 16–21.
33. Shinar, D. et al (1980). The effects of changes in driver perception on rural curve negotiation. *Ergonomics* 23, pp.263-275.
34. Symmons, M. et al. (2004). Rural Road Safety - Overview Of Crash Statistics. *Monash University Accident Research Centre*: Report No. 212.
35. Taragin, A. and Leisch, L.E., (1954). Driver performance on horizontal curves. *Highway Research Board Proceedings* 33 (1954), pp.446-466.
36. Tenkink, E. (1990). Effects of road width and a secondary task on speed and lateral control in car driving (in Dutch). Report IZF 1990 C-27. TNO Institute for Perception. Soesterberg. The Netherlands.
37. Tenkink, E. and Van Der Horst, A.R.A. (1991). Effects of road width and curve characteristics on driving speed (in Dutch). Report IZF 1991 C-26. TNO Institute for Perception. Soesterberg. The Netherlands.
38. Turner, S. and Tate, F. (2009). Relationship between Road Geometry, Observed Travel Speed and Rural Accidents. *New Zealand Transport Agency*, Research Report 371.
39. van der Horst, R. and de Ridder, S. Influence of Roadside Infrastructure on Driving Behavior: Driving Simulator Study. Transportation Research Record: Journal of the Transportation Research Board, No. 2018, Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 36–44.
40. Vest, A. and Stamatiadis, N. (2005), "Use Of Warning Signs and Markings to Reduce Speeds on Curves". The 3rd International Symposium on Highway Geometric Design, Chicago Illinois, United States. http://pubsindex.trb.org/document/view/default.asp?lbid=760638
41. Wochinger, K. and Pecheux, K. (2001). Driver Perception of Horizontal Curves on a Simulated Two-Lane Rural Highway. *Proceedings of the 1st Human-Centered Transportation Simulation Conference,* The University of Iowa City, Iowa, November 4-7, 2001.
42. Zador, P., H. Stein, P. Wright, and J. Hall. Effects of Chevrons, Post-Mounted Delineators, and Raised Pavement Markers on Driver Behavior at Roadway Curves. Transportation Research Record, Vol. 1114, TRB, National Research Council, Washington, D.C., 1987, pp. 1-10.