An analysis of differences in driver speed and lane position for experienced and inexperienced drivers through high and low risk rural curves

by

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ABSTRACT

Road crashes at rural curves result in a high number of deaths and serious injuries. Speed has been identified as a significant contributor to such crashes, but some researchers have suggested that an understanding of other elements is also required. This study was designed to broaden the understanding of the mechanisms that lead to elevated crash risk at curves. A better understanding of these issues might provide insight into methods for improving safety at curves. This study included an assessment of the elements of curve design that are linked to side force and crash risk, including speed, curve radius and driver lane position. These issues were assessed for high risk and low risk curves. Differences between inexperienced and experienced drivers were also compared.

40 male drivers (20 inexperienced and 20 experienced) drove a set rural route in a test vehicle which was instrumented to collect data. Measures of speed, side force and lane position were taken on a continuous basis for each curve on the route. Information regarding the design elements for each curve was also collected, including curve radius, curve direction (left or right) and curve risk (calculated based on the difference between curve approach speed and minimum curve speed). Based on the calculation of curve risk 20 high risk curves, and 20 low risk curves were identified and data for each included in the study.

Differences in speed, side force and lane position through high and low risk curves were assessed, as were the differences between inexperienced and experienced groups of drivers on these same measures. This information was collected at key points on approach and through curves.

Results indicated that when comparing high risk curves with low risk curves speeds were lower for high risk curves; acceleration and deceleration levels were greater; side force was greater; and variance between drivers was greater. Deceleration continued through and beyond the curve mid-point for high risk curves. Given this is a high risk point within a curve (i.e. where the side force is greatest, and the chance to lose control highest) it is highly desirable that drivers will have already fully decelerated by this point.

There were substantial differences in lane position on approach and through high risk compared to low risk curves. Lane position was also statistically and substantively different for inexperienced compared with experienced drivers. For high risk curves, experienced drivers ‘cut the corner’, reducing side force to a greater degree than inexperienced drivers.

These results relating to speed (particularly the need to reduce speed at or before the curve mid-point) and lane position provide useful information on possible sources of risk to drivers through curves. The findings support the hypothesis that in order to understand risk at curves, factors such as speed and lane position should be considered in combination. The results presented provide additional opportunities to help improve safety. Earlier deceleration coupled with more appropriate lane position would act to reduce side force through curves, and therefore lead to improved safety outcomes.

THESIS DECLARATION

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I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

Signed

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1 INTRODUCTION

1.1 Background

Although it is difficult to accurately estimate, it is thought that around 1.3 million people die in road traffic crashes worldwide every year, and that up to a further 50 million are injured (WHO, 2009). Road injuries are the leading cause of death in the 15 to 29 year age group and rank in the top three in the 4 to 44 year age group (WHO, 2009). This represents a major burden on health systems, as well as inflicting an unknown amount of pain and suffering. Jacobs et al. (2000) estimated that the total cost of crashes worldwide is around US$518 billion per year.

Although already considered a problem of significant proportions, the situation is set to worsen, with estimates that by 2030 road crashes will be the fifth leading cause of death, topping 2.4 million fatalities per year unless action is taken (WHO, 2009). At that time it is estimated that deaths resulting from road crashes will exceed those for more well-known causes of death such as HIV/AIDS, malaria and violence.

In Australia too, road crashes result in a large number of deaths and injuries every year. It is estimated that in the 20th century, around 200,000 people died on Australian roads, around double the number of those who died in wars during that same period (BITRE 2009). Over the five year period between 2010 and 2014, on average 1250 people have died on roads each year (Department of Infrastructure and Regional Development, 2015). About 72% of these deaths were males. The estimated total cost of all road crashes in Australia is $27 billion per year.

Of concern is the finding that the reported number of serious injuries (defined in this case as those admitted to a hospital) is increasing. Between 2001 and 2012, these increased steadily from around 27,000 to 34,000 per year (Department of Transport and Regional Development, 2015).

Crash types and risks

Information on key crash types and risks for all of Australia is scarce with this sort of analysis more typically undertaken by individual states and territories. As part of the development of the most recent Australian road safety strategy an assessment of these risks was undertaken (ATC 2011). The basis for this analysis was not provided, and there appear to be some inconsistencies between these results and those from more detailed analyses. However, the information could be considered to provide an indication of some of the main types and/or causes of injuries and deaths. Some of the key outcomes from that analysis included:

- 32% of fatal and serious casualties occur at intersections
- 30% result from run-off-road crashes
- 8% are from head-on crashes
- Heavy vehicles account for around 8% of all travel, but are involved in 18% of all deaths
- Motorcycle usage accounts for less than 1% of travel, but motorcycle riders make up 22% of fatal and serious injuries
- Pedestrians make up 9% of total road deaths and serious injuries
- Local roads (i.e. roads managed by local government) account for more than 50% of fatal and serious casualties in some states
- Speeding contributes to 34% of deaths, and 13% of deaths and serious injuries
- Drink driving contributes to 30% of deaths and 9% of deaths and serious injuries. Drug driving is also a significant contributor
- Fatigue contributes to 20-30% of deaths and 8% of deaths and serious injuries
- Restraint non-use contributes to 20% of deaths and 4% of deaths and serious injuries.

1.2 Rural road safety

A number of studies have highlighted the high proportion of crashes (including crashes per head of population and crashes per amount of travel), and the severe outcomes that occur on rural roads. Definitions of ‘rural’ vary across different jurisdictions and in the overseas literature. Some reviews consider all locations outside of major cities as rural, while others make a distinction based on speed limit. For example the term ‘open road’ is used in New Zealand for areas with a speed limit greater than 70 km/h, while in Australia roads with a speed limit of greater than 80 km/h are often considered rural. In this study, a broad definition for rural roads has been adopted, with this term generally referring to higher speed roads outside of urban areas.

Incidence of crashes on rural roads

The high incidence of crashes on rural roads has been identified in various countries. Based on data from OECD countries it was estimated that 60% of road deaths occurred on rural roads (OECD, 1999). In the US, rural crashes accounted for 57% of fatalities, despite less than a quarter (23%) of the population living in rural areas (NHTSA 2007). The rate of crashes (per km travelled) was 2.5 times greater than for urban roads.

In a review of road safety on rural roads, Tziotis et al. (2006) calculated that 60% of fatal crashes in Australia occur on the rural high speed road network. Based on data from that time this resulted in over 1,000 fatalities per year in Australia, and more than 22,000 injuries. More recent data for all of Australia is difficult to find, but applying this percentage to data from more recent years (Department of Infrastructure and Regional Development, 2015), and assuming the same percentage applies, it is likely that around 750 people currently die each year in Australia on rural roads.

Baldock et al. (2008) report that rural crashes are quite severe when they do occur. In an in-depth study of 236 rural crashes it was identified that one in every ten vehicle occupants died during or after a rural crash, while one in four were admitted to hospital.

Risk factors

A number of different studies have identified risk factors for rural roads. As an example Tziotis et al. (2006) identified a number of road environment factors that contributed to rural crashes, including the road condition, road design, the roadside environment and speed limits. The predominant crash types identified were vehicles travelling ‘off path’ (i.e. run off road) followed by vehicles travelling in the same direction (e.g. side swipes, lane changes and rear end crashes), and opposite direction (including head-on) crashes. The analysis identified specific groups as having a higher level of risk. These high risk groups included young male drivers, local residents, truck drivers and indigenous people. It is not clear from the study whether exposure for each of these groups was included in the analysis. Other behavioural factors shown to increase risk in this study included fatigue, speed, alcohol and cannabis use, driver error, and failure to wear a seatbelt.

Curves (as illustrated in Figure 1.1) have been shown to have an elevated level of risk, producing a significant amount of all crashes.

Figure 1.1: Typical rural curve

Tziotis et al. (2010) identified that around half of all rural crashes resulted from vehicles running off the road, and around a quarter of all rural crashes were vehicles running off the road at curves. Different causal mechanisms were identified including vehicles skidding off the road, or losing their lane position and either running off the road, or striking a vehicle in the oncoming lane. Inexperienced drivers were again identified as being at particular risk at rural curves.

When road engineers design curves, account is made of side force or 'centripetal acceleration' (Austroads 2010). If critical side force values are exceeded, vehicles will lose traction with the road surface leading to a potential loss of control. This side force is a function of vehicle speed and radius. The element of speed is well documented as a contributor to crash risk at curves. Hallmark and McDonald (2007) suggested that more than half of all curve crashes are the result of excess speed and much of the research on curve safety has focused on this issue. However, other risk elements are also likely to have a significant role. Indeed, Spacek (2005) suggested that an understanding of safety at curves is not possible if based solely on speed. Less well known is the contribution to risk of other factors that contribute to side force, such as curve radius. The radius of a driver's trajectory through a curve is dictated by the design radius of the curve and can be altered by driver action, through driver selection of lane position on approach and through curves.

1.3 Research need and objective

Deaths and serious injuries occur in large numbers at rural curves and are greatly over-represented at these locations. Despite extensive research on safety at curves over many years, and different approaches (including behavioural and road engineering) that have been used to address this issue, the crash problem at curves remains substantial. Much attention has been given to the role of speed in crash risk at curves, but there are other elements that are likely to influence risk, either on their own or in combination with speed. The key objective of this research is to better understand some of the mechanisms that lead to elevated crash risk at curves. This includes an understanding of the elements of curve design that are linked to side force and crash risk, including speed, curve radius and driver lane position. A better understanding of these issues might provide insight into mechanisms for improving safety at curves. Inexperienced drivers were identified as having elevated levels of crash risk at curves. This forms an additional area of interest, with the potential that an understanding of risks for these drivers might lead to better methods for improving safety for this group, but also for all drivers.

1.4 Structure of dissertation

This dissertation is based on a detailed review of literature, and an experiment to determine factors relating to driver risk through curves, including those relating to curve design such as speed, side force and lane position. The structure of this dissertation is outlined in Figure 1.2, with details provided in the section below.

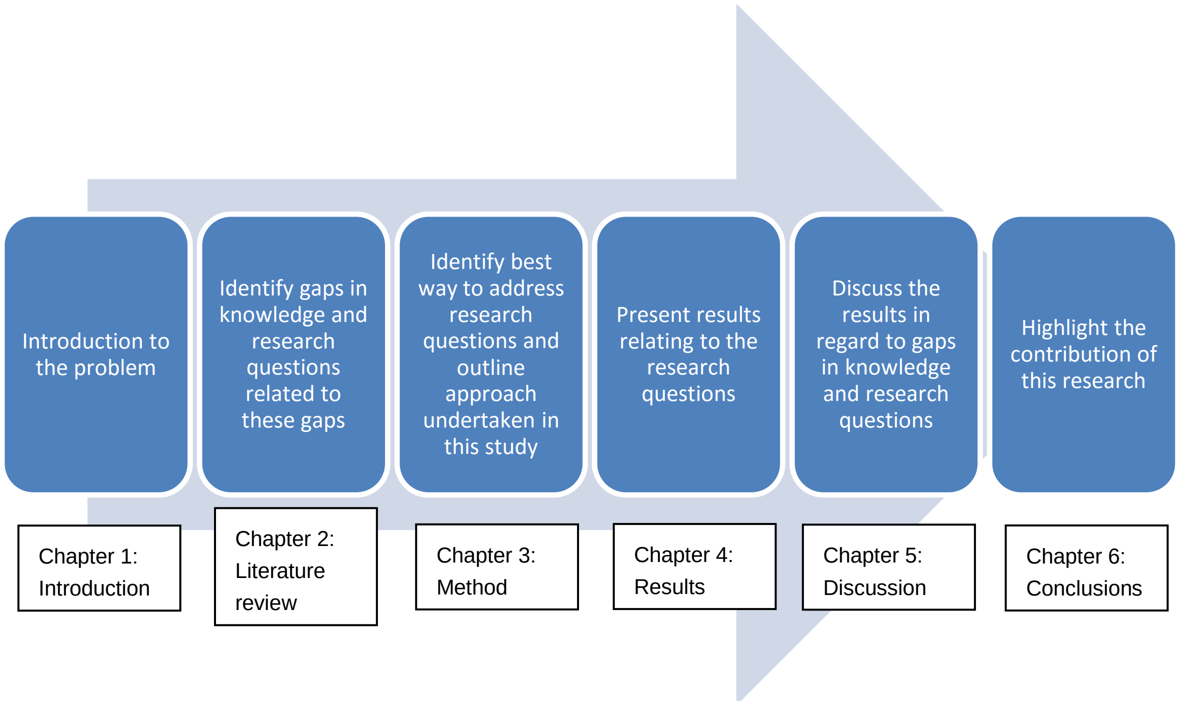

Figure 1.2: Structure of research thesis

Chapter 2 provides a review of the literature in order to identify gaps in knowledge relating to driver risk through curves and the research questions and hypotheses that arise from these. Chapter 3 provides details on the methodology used for an experimental study, and how the study addresses the key research questions arising from the literature review. Aspects relating to selection of a relevant test method are also reviewed. Chapter 4 provides results from the experimental study. The results include general descriptive results that test the hypotheses. Chapter 5 provides a discussion on the practical significance of the results. Chapter 6 provides conclusions from this research, including a discussion on the unique contributions that have been made by this study to understanding of crash risk at rural curves.

2 LITERATURE REVIEW

2.1 Introduction

The literature review was undertaken to establish the extent of knowledge relating to safety at rural curves, and particularly the elements that relate to curve design. As identified in Chapter 1 these elements include vehicle speed, curve radius, lane position and side force. The review is intended to identify gaps in knowledge and ultimately the key research questions to be examined in this study. The overall structure of the literature review is provided in Figure 2.1.

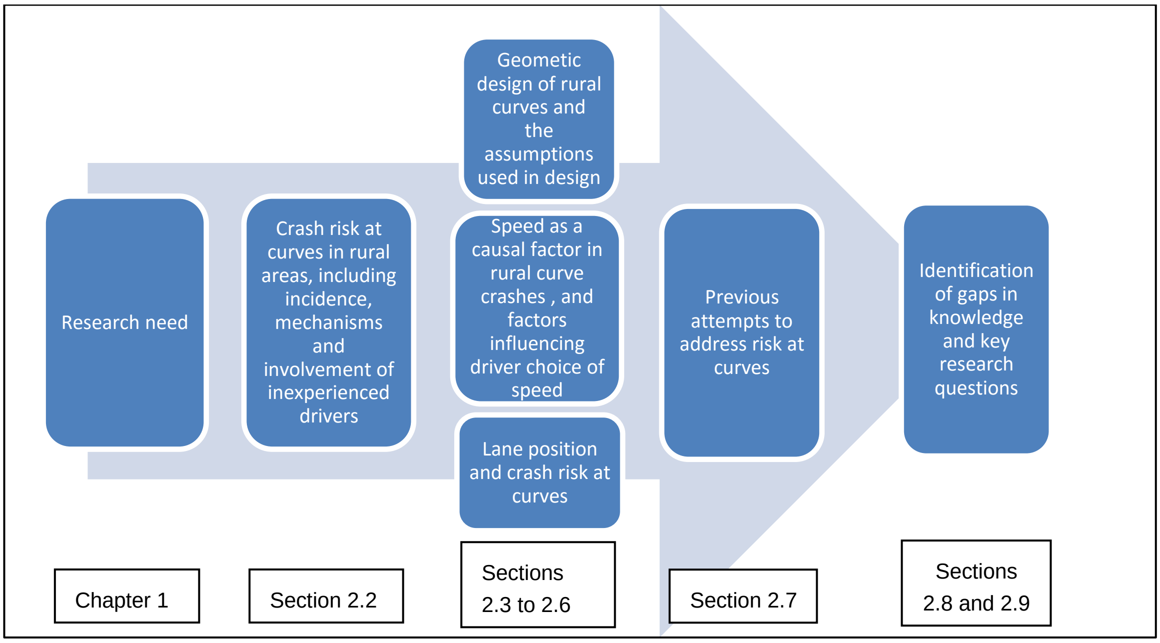

Figure 2.1: Structure of literature review

Section 2.2 provides a detailed assessment of crash risk at curves, and examines the role that driver experience plays, including at rural curves. The section includes an analysis of the mechanisms involved in crashes at curves providing a framework for later review.

Section 2.3 provides a brief description of elements relating to road design and crash risk at curves. This includes an examination of the assumptions used in the design of rural curves as well as the design assumptions relating to crash risk.

Section 2.4 discusses the role of speed in crash risk, including speed as a contributor to crashes at curves, and the issues relating to speed and inexperienced drivers. This is supported by a discussion in Section 2.5 which addresses issues relating to driver selection of speed, including road related factors.

Section 2.6 discusses the role of lane position in crashes at curves, providing an examination of the limited previous research on tracking behaviour through curves.

Section 2.7 gives a summary of options that can be applied to address safety at rural curves, particularly through the management of speed. The overview is supported by a more detailed review (found in Appendix A) that includes a discussion on road, vehicle and road user-based interventions.

A summary of the key issues identified through the literature review can be found in Section 2.8, including discussion on key gaps in knowledge. These gaps lead to the formulation of the research questions and hypotheses explored in the remainder of this study (presented in Section 2.9).

2.2 What is known about rural curve crashes?

This section of the literature review explores the contribution of curves to the rural crash problem. It is also intended to identify some of the key risk factors and mechanisms involved in rural curve crashes.

2.2.1 Incidence

Road users have an elevated level of risk at curves, resulting in a significant amount of all rural crashes as documented in a number of studies, both internationally and in Australia. For example, Steyer et al. (2000) report that around half of all rural road crashes in Germany occur at curves. McGee & Hanscom (2006) found that nearly a quarter of all fatal crashes in the US occur at curves, and that around 75% of all fatal crashes occur in rural areas. Retting and Farmer (1998) report that around 40% of fatal roadside crashes in the US occur at curves.

Turner & Tate (2009) found that in New Zealand, curve related crashes (loss of control and head-on) are the single biggest cause of rural injury crashes. This crash type comprises 45% of all rural crashes, while the next largest crash type (running off the road and head-on crashes on straights) comprised a relatively small 19%.

A study by Cenek et al. (2011) identified that in New Zealand, loss of control on curve crashes represented around half (49%) of all injury crashes in 2009 on rural state highways. That study identified that around 26% of the rural state network is curved (defined as having a curve radius of 500 m or less), meaning that crashes at these locations are vastly over-represented. A similar finding by Preston (1999, cited in Hallmark et al., 2013) was that between 25% to 50% of severe road departure crashes in Minnesota occurred on curves, but that curves only account for 10% of the network.

Much of the research presented above relies on analysis of aggregated crash data, typically collected by police at the time of a crash, or soon after. This type of assessment is open to subjective interpretation (e.g. the attribution of speed as a casual factor by police is based on judgement and not typically measures), but the results are supported by more detailed investigation. For example, a study by Kloeden et al. (1997) examined fatal crashes for motorcyclists and car drivers at curves in South Australia (this included urban and rural crashes). Based on an examination of coronial data, which is far more detailed than information typically found in police reports, it was identified that 40% of motorcyclist fatal crashes, and 36% of car occupant fatal crashes occurred at curves. A similar result was identified by a later study from South Australia. Baldock et al. (2008) conducted an in-depth multidisciplinary investigation of 236 rural crashes. This methodology involved detailed investigation of crashes, typically involving engineers who make a detailed assessment of road-related variables. This study identified that curve crashes were common with over 40% of their sample crashing at these locations.

Not only are crashes at rural curves significant in number, an analysis of crashes in Victoria (conducted for this study using CrashStats; accessible from www.vicroads.vic.gov.au) indicates that rural curve crashes have decreased at a lesser rate than other crash types. Between 1987 (the year for which the data is first available) and 2010, rural curve crashes reduced by 34% (from 933 per year to 612), while all crashes reduced by almost 42% (from 22,600 to 13,190). As a proportion of all crashes, rural curve crashes have increased.

2.2.2 Crash types and risks

In order to better formulate specific research questions relating to driver risk at rural curves, an understanding of key crash types and risks is required. A number of studies have been undertaken on the causes of crashes at curves. In a study that included an extensive review of previous research Charlton (2007) suggested that a variety of factors have been proposed, including:

- increased attentional demands and diverted attention
- misperception of speed
- misperception of curvature
- failure to maintain lateral position.

It was suggested by Charlton that curves require more driver attention than straight sections of road, and that decreased attention may lead to failures to notice appropriate cues in the environment, including warning signs. Driver perception of speed was suggested as an obvious cause of curve crashes, especially at locations where drivers are required to substantially reduce their speed. Misperception of curvature was suggested as another cause, especially as the perceived sharpness of curves is not always clear. These types of errors were thought to be exacerbated by inability to maintain appropriate lane position, leading to run-off-road, head-on, or other crash types.

As discussed in Section 2.4.2, excessive speed has been associated with crashes at curves. Again, much of the research is based on analysis of aggregated data obtained from police reports and so is subject to subjective interpretation. As examples of such research, Turner & Tate (2009) identified that speed was a factor in 37% of curve related crashes in New Zealand, while Hallmark & McDonald (2007) put this figure at over half (56%) of all fatal run-off-road crashes at curves in the US. Studies in both Australia (Turner 2009) and the UK (Richards et al. 2010) identified that speed related crashes are over-represented at curves.

A number of studies have examined individual road design elements and their contributions to risk at curves. Several studies found that severity of curve (or curve sharpness) has a large impact on risk. For example, Veith et al. (2010) assessed previous research on the effect of horizontal alignment (curves) on crash risk. From an evaluation of significant research on this topic it was estimated that the level of risk increased sharply below a radius of around 400 m, with around twice the level of risk for any individual motorist compared to a straight road. With a 100 m radius the risk was six times greater than on a straight road. This finding is supported by earlier Australian research (e.g. McLean 1981) and similar results have also been identified in overseas research (e.g. Choueiri and Lamm 1987; Harwood et al. 2000; Haywood 1980; Krammes et al. 1995; Zegeer et al. 1992).

One interesting finding from the Veith et al. (2010) analysis was that results from previous research varied substantially in regard to risk below a curve radius of around 200 m. The relative risks ranged from 2.7 to 10 for curves of this radius compared to curves with a 1400 m radius. One interpretation of this finding is that factors other than curve radius may play a role in risk. This assertion is supported by several studies including a report by the OECD (1999) which suggested that isolated curves or the first curve in a series present the highest risk, particularly as the result of inappropriate speed and lane position. Similarly, Krammes et al. (1995) identified ‘local factors’, or those at the curve, including curve features, cross-section, roadside hazards, stopping sight distance and vertical alignment. However, they also listed geometric context variables, such as sight distance on approach, distance to adjacent curves, and distance from the curve to the nearest driveway or intersection as having a role. Krammes et al. (1995) suggested that much of the previous research has focused on local factors, or assessed curves in isolation. In their own study, Krammes et al. (1995) found that the mean crash rate on horizontal curves increased in a linear manner with mean speed reduction from the approach tangent to the curve. This finding indicates that assessment of risk at curves needs to consider more than just local factors (i.e. factors at the crash curve) to fully understand risk. This issue appears to be important in the context of assessing risk at curves, and is discussed in more detail in Section 2.4.2.

A number of other factors aside from curvature have been found to influence safety at curves. Hummer et al. (2010) conducted an extensive review of previous literature, and found that other factors include traffic volumes, curve length, right shoulder width (note that driving was undertaken on the right side of the road for this study), presence of spiral transitions and roadway width. In their own analysis of data, Hummer et al. (2010) analysed more than 51,000 collisions on two-lane curves in North Carolina. These were compared with collisions on all two-lane roads. Over-represented factors at curves included collisions on grades; rural roads; and striking fixed objects. Crashes were more severe, and off-peak crashes were over-represented.

Several studies have examined the mechanisms involved in curve-related crashes, including details of what happened during and following these situations. Levett (2005) identified that around a quarter (27%) of run-off-road crashes in the state of New South Wales, Australia were the result of vehicles running off to the left hand side of the road on a right hand bend (note driving is undertaken on the left side of the road in Australia). An in-depth analysis of fatal crashes by Levett (2005) involving vehicles running off the road to the right at right hand bends indicated that many of these were initially caused by the motorist losing control to the left hand side, and then over-steering. That study concluded that improvements to increase the width of road shoulders on the left hand side of both left and right hand bends would produce substantial safety improvements.

Kloeden et al. (1997) identified a number of crash characteristics that appeared to be over-represented in crashes on curves. An examination of vehicle movement for crashes at these curves indicated that 36% of car occupants ran off the road to the right and into an object; 28% ran off the road to the left and into an object; and 23% had a head-on crash with another vehicle. Of lesser prominence were vehicles running off the carriageway on a left and right hand curve (5% each), out of control on a curve

(2%), left and right turn in front of another vehicle at an intersection (0.4% each) and out of control while overtaking (0.4%). No crashes were identified where a vehicle collided head-on while overtaking. Other risk factors identified by Kloeden et al. (1997) included drivers under 30 years of age, a BAC level of 0.08 or over, crashes at night and at weekends, crashes in 100 km/h+ environments, unsealed roads, wet road surfaces, and single vehicle crashes.

Baldock et al. (2008) also identified that right curves are over-represented compared to left (note that this study was undertaken where driving is undertaken on the left hand side of the road). From their in-depth investigation they suggested that it was common for drivers in single vehicle crashes to leave the road to the left (on both left and right hand curves) and then overcorrect their steering, thereby worsening the effect of the loss of control.

Doecke & Woolley (2013) also used in-depth crash data to assess the mechanisms involved in rural curve crashes. They found that the most common type of lane departure was a single yaw on a right hand bend (note that driving was undertaken on the left side of the road). The crashes involved drivers either losing control within their lane, or on the road shoulder to the left of the lane. Drivers then cross the centreline departing the road to the right. Although the departures were instigated within the curve, it was also noted that almost half of vehicles left the road after the bend.

Garber & Kassebaum (2008, cited in Hummer et al. 2010) found the predominant crash type to be run-off-road, thus supporting the evidence from Australia on this issue (Kloeden et al. 1997). Torbic et al. (2004) reported that 76% of fatal curve crashes involve either a vehicle striking a roadside object (trees, utility poles, rocks etc.) or the vehicle overturning. A further 11% were the result of vehicles drifting into the opposing lane and striking another vehicle head-on. This latter group may result from vehicles cutting the curve or while over-correcting after having run onto the road shoulder. A further 9% involved angle crashes, while 2% involved rear-end crashes.

It appears then that crashes at rural curves represent a significant safety issue. Crashes are also highly over-represented on rural curves with estimates indicating that up to half of rural crashes occur at these locations, but that curves make up only between 10% and 25% of the rural network (Cenek et al., 2011; Preston, 1999, cited in Hallmark et al., 2013). A variety of causes have been identified including speed and lane position (discussed in following sections), as well as road design related factors such as curvature. The most common crash types at curves were vehicles running off the road (either to the left or right) and vehicles drifting into oncoming lanes resulting in head-on collisions. Evidence from Australia indicated that these crash types accounted for around 97% of all curve crashes, a finding that is supported by international evidence. Roadside objects have also been highlighted as a significant factor resulting in injury once vehicles leave the road at curves. Lastly, right hand curves have been highlighted as being of higher risk than left curves, although little information is provided to explain why this might be.

2.2.3 Crash risk for inexperienced drivers

As already highlighted, worldwide, road crashes are the leading cause of death for young people aged 15 to 29 years (WHO, 2009). Research has also consistently identified that inexperienced drivers, and particularly inexperienced male drivers, are over-represented in crashes. A large number of studies have been undertaken over many years examining this issue. A brief summary is provided below, with a particular emphasis on inexperienced driver crash risk at curves. For a more comprehensive review, see Senserrick & Haworth (2004).

The term 'inexperienced driver' is sometimes used inter-changeably with 'young driver' but there is a subtle difference between these terms. As implied by the names, inexperienced (or 'novice') drivers are those that have a limited amount of driving experience, and this is irrespective of age. There is obviously a strong correlation between age and driving experience, with a significant number of inexperienced drivers being younger.

A study by Catchpole et al. (1994) examined the crash involvement (based on police reports in Victoria) of young drivers. This study found that young drivers were over-represented in crashes, particularly in crashes involving run-off-road on straights and at curves. This crash type represented 19% of crashes for 18-20 year olds, compared with 11.3% of crashes for 21-25 year olds, and 8.6% of crashes for 30-59 year olds. A more detailed analysis of police reports identified that for run-off-road crashes at curves, young drivers were significantly more likely to have been travelling at 'excessive speed' (either too fast for the conditions or 10% or more above the posted speed limit).

Baldock et al. (2008) found that young and/or inexperienced drivers were over-represented in rural crashes. Based on their in-depth examination they concluded that these drivers were major contributors to single vehicle crashes at curves (i.e. loss of control) as well as head-on crashes at curves.

It appears that young drivers (particularly young male drivers) are over-represented in rural crashes (Tziotis et al. 2006), rural speed crashes (Turner 2009), and rural run-off-road crashes (Tziotis et al. 2010). Delaney et al. (2003, cited in Tziotis et al. 2010) found that young drivers are over-represented in crashes with fixed objects in run-off-road crashes based on an examination of Victorian data.

Catchpole & Edgar (1999) reviewed the crash involvement of inexperienced drivers, comparing police reports of crashes involving novice drivers with experienced drivers. The third and fourth most over-represented crash types for novice drivers (0 to 11 months driving experience) were 'off right bend into object' and 'off left bend into object' (the highest were 'other on path', and 'left off carriageway into parked car or object'). Novice drivers were around three times more likely than experienced drivers (15 years plus driving experience) to have these crash types. Inexperienced male drivers were even more highly represented at around 3.5 times the crash rate of experienced drivers. 'Off bend left or right, but not into an object' also featured highly, with both over-represented in the top 10 crash types. Both were more than 2.3 times more likely crash types for novice drivers than for experienced drivers.

More detailed analysis of this 'off bend' crash type using finer experience groupings found that crash involvement for 'off bend' crashes peaked for the newest of drivers before decreasing as drivers gained experience (Figure 2.2).

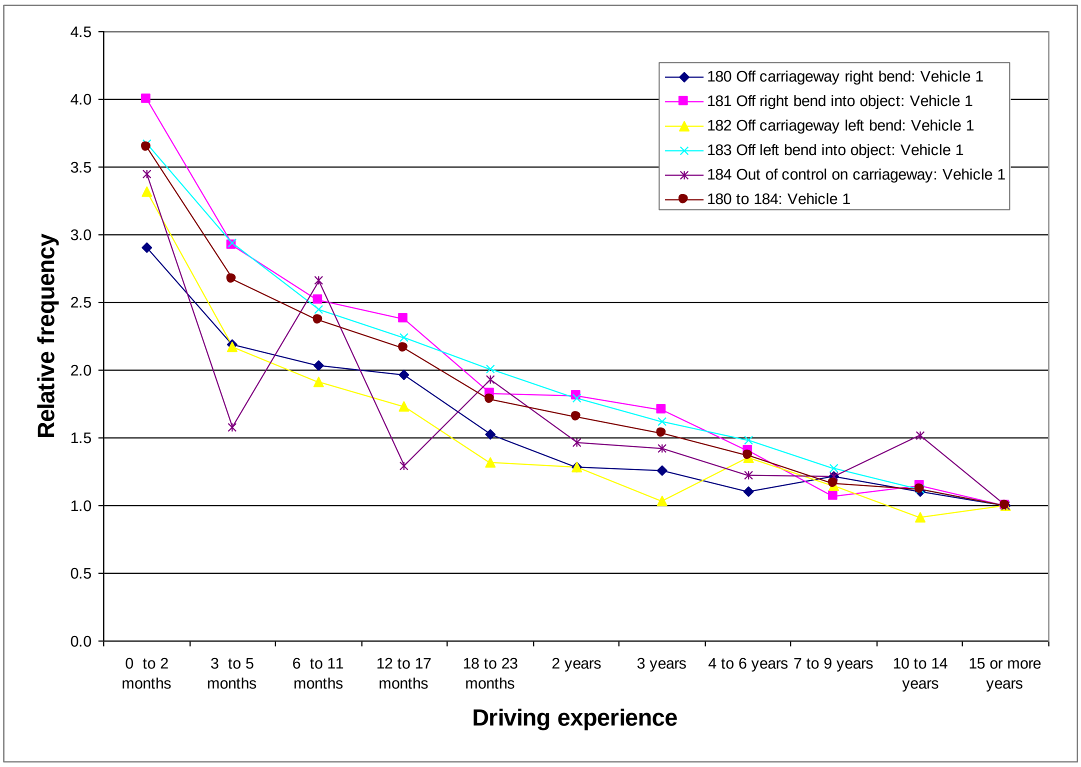

Figure 2.2: Relative frequency of crash types by driver experience (from Catchpole & Edgar, 1999)

Drivers with 0 to 2 months experience were more than 3.5 times over-represented (compared to experienced drivers); with one year's experience they were almost 2.5

times over-represented; and between 2 and 3 year's experience they were more than 1.5 times over-represented.

Wundersitz (2012) also examined the role of young drivers in crashes using the results from in-depth crash investigations. The study assessed the results from more than 250 crashes involving drivers aged 16 to 24 years. Comparisons were made between drivers aged 16 to 19 years, and those aged 20 to 24. The analysis confirmed that the younger drivers were more likely to be involved in crashes on high speed roads; in single vehicle crashes (including running off the road); in crashes on undivided roads; and in crashes in rural areas. Decision making errors were the most common error type amongst the young drivers, present in around two-thirds (62%) of crashes followed by vehicle operating errors (51%). Of the decision making errors, the most common were excessive speed (22% of all crashes) and speeding for conditions (11%). For vehicle operating errors, inadequate directional control was most common (36% of all crashes). This category included most prominently over-correcting, under-steering, or over-steering the vehicle on a curve.

One additional interesting finding from the Wundersitz study was that there was a higher rate of speed related crashes for the sample compared to other studies that have investigated younger drivers. It was suggested that this was because of the in-depth nature of the study, where there is access to information which allows the speed before the crash occurred to be estimated.

Based on this research it appears that crash risk is greater for young and inexperienced drivers, including for crashes at rural curves. Young drivers were found to have crash rates around three times greater than experienced drivers at rural curves. Loss of control and head-on crashes were found to be key crash types. Speed has been identified as a key contributor to these crashes. Over-correcting, under-steering, or over-steering the vehicle on a curve have also been identified as issues. Further information on the mechanisms and behaviours surrounding these outcomes would be of high interest as they would help in identifying possible solutions to this significant crash problem.

2.2.4 Summary

In summary, road deaths and injuries place a considerable burden on society. Crashes at rural curves are a particular problem. Reducing crashes at rural curves would significantly improve safety on our roads. Crash types at curves most commonly include vehicles running off the road, or drifting into oncoming lanes resulting in head-on collisions. A variety of causes have been identified including inappropriate speed and lane position. Road curvature is likely to be a significant contributor to risk at curves, although other factors are likely to also influence risk. A better understanding of the mechanisms and behaviours leading to these crashes would provide useful information that may assist in addressing these crashes. It would be particularly interesting to understand more about the differences in crash mechanisms resulting from issues such as inappropriate speed and lane position as they apply to curves with different risk profiles.

Young and inexperienced drivers are involved in a disproportionate number of road deaths and injuries. This is so for all crashes, as well as those that occur at rural curves. Young drivers were found to have crash rates around three times greater than experienced drivers at rural curves. Speed has been identified as a key contributor to these crashes. Lane keeping errors have also been identified as issues, although there is little information on this. More information regarding the mechanisms leading to these crashes would be of high interest in understanding why these crashes occur. A better understanding of errors made by inexperienced drivers may also provide better insight into why crashes occur for more experienced drivers.

Having established that the rural curve crash problem is a significant one, and some of the mechanisms involved, the following section provides a review of rural curves from a road design perspective. Of greatest interest are those elements of design that relate to risks identified in the discussion above.

2.3 Design of rural curves

2.3.1 Introduction

Various guidance documents exist from around the world on the design of roads, including at curves (e.g. AASHTO 2004 in the United States; Highways Agency, 1993 in the United Kingdom; and Austroads 2010 for Australia and New Zealand). The issue of curve design was reviewed to better understand the key variables that contribute to driver risk through curves, and the assumptions currently used when designing roads. Those relating to speed and lane position were of particular interest. This section also provides definitions for some of the terms used in the remainder of this study. Lastly, content is included on design speed, and particularly the assessment of curve risk from a design perspective.

The Australian guide (Austroads 2010) describes roads as a series of straights (or ‘tangents’) and circular curves that may be connected by transition curves with tangents as the most common element. Although (as discussed previously) the risk is greater at curves, the guidance states that straight sections can introduce fatigue (due to monotony) as well as speeding, and that it is desirable to introduce curvature to combat these issues. Indeed one kilometre is suggested within this guidance as an excessive length for a straight that may encourage motorists to travel in excess of the design speed, and something to be avoided. It is interesting to note that evidence to support this assertion is not provided.

It is likely that many curves do not meet current standards. Such design may exist for historic reasons including that the road was constructed before knowledge of good design principles were available or that the road use may have changed. In many cases roads have evolved over time, often starting as walking or horse tracks. As the function of the road or mix of traffic has changed, minor improvements have been made, but the basic alignment may remain unchanged. The extent of this non-conformance with standards is currently unknown, but it is likely that poor design contributes to the poor safety performance at such locations.

2.3.2 Operating speed model, and relevant design elements

Design of rural roads relies on the use of an operating speed model (see Austroads, 2010) to determine the predicted speeds of vehicles. This in turn influences the design parameters used. Operating speed models, and research related to driver selection of speed through curves has been examined in detail. Research in North America in the 1930s and 40s related design speed to the higher end of the desired travel speed (i.e. a higher percentile operating speed), and this formed the basis of early development of design guidance (McLean 1978). With an improvement in vehicle design and roads, higher speeds were possible, and these often exceeded the design speed. New relationships for design were required, particularly at horizontal curves where drivers often exceeded the design speed. McLean (1978) reported that a number of different government agencies developed curve speed prediction models during the 1960s to address this problem. The simplest of these related speeds with curve radius. Although this relationship still forms the basis of current design guidance, the models have become more sophisticated in recent years, and include more variables.

Of particular note is the inclusion of desired, or approach speed in curve speed models. This variable was included in Australian models following work by McLean (e.g. 1981). McLean defined desired speed as the 85th percentile speed of free-flowing passenger cars on long tangents. The research by McLean (1981) identified that desired speed is a function of the overall alignment standard, particularly terrain type (flat, undulating, hilly or mountainous). This factor has also been included in other international models. As an example, Kanellaides et al. (1990) conducted research and developed a model that included desired speed as an explanatory variable.

Krammes et al. (1995) suggested that the introduction of desired speeds to curve speed models increased their reliability. Models based on local characteristics (those relating to the individual curve, such as degree of curvature, grade and cross-section) produce correlations (R^2) between 85th percentile speed estimates and actual speeds of between 0.65 and 0.84. Introducing desired speed variables such as terrain and the overall characteristics of the alignment increase this to 0.92.

Recent models defining desired speed have included a number of different variables that help identify some of the factors that may influence driver's selection of speed through curves. These include curve change rate, or changes in vehicle heading (often expressed as degrees per km, e.g. Lamm et al. 1986); tangent length, speed for the preceding curve, speed for the following curve, and a measure of acceleration and deceleration rates (Krammes et al. 1995).

In related research Bonneson and Pratt (2009) reviewed literature on curve speed and identified a variety of factors that have been identified as influencing curve speed. These included side friction demand, superelevation, curve radius, tangent speed, vehicle type, curve deflection angle, tangent length, curve length, available stopping sight distance, grade and vertical curvature. They suggested that tangent speed has been identified by a number of researchers as being a key factor.

Although these various factors are known to influence curve speed, curve design guidance is based on the kinematics equation in which total lateral acceleration (or side force) of a vehicle negotiating a curve is calculated from superelevation and tyre surface friction. A vehicle entering a curve will have its tendency to skid off the road reduced by provision of a centripetal force. On a level road (i.e. no superelevation), this centripetal force is supplied by the tyre surface friction. For a superelevated curve, the centripetal force is provided by a combination of tyre friction and the normal force, which is based on the vehicle mass. There is therefore less reliance on friction for superelevated sections of road. This relationship is captured in Equation 1 which represents the design speed for a curve.

$$V^2 = 127R(e+f) \qquad \textbf{1}$$

Where

V	=	vehicle speed	(km/h)
R	=	radius	(m)
e	=	superelevation	(m/m)

f = side friction factor

When designing a curve, selection from different pairs of values for radius and superelevation are made that satisfy the above equation, subject to various constraints.

2.3.3 Assumptions in road curve design

There are a number of assumptions used in the road design process, including on the approach to curves. Given that curve design speed is based largely on speed and radius, assumptions linked to these factors were of particular interest. The assumptions underlying current Australian road design practice include that (Austroads, 2010):

- On short straights, drivers will already be constrained (i.e. by the previous curve) and drivers are likely to maintain their current speed.
- On longer straights, drivers will accelerate until they reach a maximum speed, and continue at this speed until around 75 m from the curve. The driver will then decelerate to a speed that is considered safe for the curve ahead.
- Upon entering the curve, the driver will decelerate further, commonly within the first 80m. Advice is also provided suggesting that for untransitioned curves, deceleration can be assumed up to the curve tangent point.
- On transitioned curves there is an expectation that drivers will complete deceleration prior to the curve. It is also stated that deceleration can be assumed up to the first half of the transition.
- Speed will remain at this level until the driver has a clear view of the straight or the next curve ahead.
- If there is a straight following the curve, the driver will accelerate.
- If there is a more severe curve ahead, the driver will decelerate further until the driver reaches a comfortable speed (the ‘section operating speed’).

In addition, the following values are provided in current Australian design guidance (Austroads, 2010):

- Assume an acceleration of 1 km/h for every 5 m of travel when accelerating from speeds below 70 km/h up to around 80 km/h.
- The maximum comfortable deceleration by drivers is assumed to be 2.5 m/s/s.

- The maximum recommended side force through curves for cars on dry sealed roads is assumed to be 0.35 g (this is based on the comfortable side force, and is less than the maximum side friction factor that would result in a vehicle skidding).
- For short length curves of small radius (neither term is defined) drivers tend to start and end in the centre of the lane, and just touch the centre or edge line midway through the curve. Drivers therefore take a wider radius than the actual curve radius. With an assumed vehicle width of 2 m, an assumed transitioned driver path can be calculated.

There are a number of published studies that indicate that some of these assumptions may be inaccurate. Donnell et al. (2009) identified that the occupant comfort values were derived in the 1940s, and are based on subjective comfort levels of blindfolded passengers. Harwood et al. (2003) reports that passenger vehicles are likely to lose control at around 0.7 g in wet conditions, and at around 1.0 g in ideal, dry conditions. The rollover threshold is typically around 1.3 g, meaning that cars tend to skid off the road before they rollover.

Montella et al. (2014) noted that much of the research on operating speed models is based on spot speed surveys (see Section 3.2.1). They suggested that because of the low resolution of the data collected (i.e. only at a small number of points on approach and through a curve) assumptions are typically made that speeds are constant through curves, and that deceleration and acceleration occur on the approach and departure tangents. They suggested that this assumption may not reflect actual driving behaviour through curves, and that collection of continuous data is required to better identify driver behaviour. It is likely that research that includes a higher degree of resolution would assist in refinement of speed models, and may also help identify other important risk factors and elements related to driving through curves.

These are very important issues as design assumptions that are not based on evidence may have significant implications for both the safety outcomes and the costs of construction. This issue deserves further attention

2.3.4 Summary

Extensive information exists on the design of curves, and much of this appears to be founded on an understanding of driver risk when negotiating curves. Side force and surface friction is at the core of curve design philosophy, and this is dictated by vehicle speed, curve radius and superelevation. Superelevation cannot be altered by road users. However, it is of interest that speed is selected by drivers, and the radius of the vehicle's trajectory through curves can be altered by driver selection of lane position.

As stated previously, the relationship between these variables is of great interest in understanding driver risk at curves. A detailed understanding of this relationship would appear to be a useful area for exploration when examining crash risk at curves.

The design guidance that does exist makes some assumptions including about the speed (including acceleration and deceleration) and lane position of vehicles. Although there have been attempts to validate the assumptions used, there are still significant gaps in the knowledge relating to this subject. This is in part due to the methodology available which tends to collect spot speeds at key points in curves rather than continuous data commencing on the approach and continuing through to the departure. More detailed information may help better define relationships between key design elements, and issues such as speed, lane position and crash occurrence. No information was identified on individual or group differences for different drivers within design guidance. This also represents a gap in knowledge.

2.4 The role of speed in safety

2.4.1 Introduction

It has been established that current design guidance for curves is based on the kinematics equation, which includes the interaction between speed, curve radius and surface friction. This part of the literature review is intended to assess current knowledge regarding the speed element and crash outcomes at curves in order to identify gaps in knowledge. This includes a review of research relating to speed and crash outcomes; speed at curves; and speed and inexperienced drivers.

Definitions

The terms speed and speeding are sometimes used interchangeably. Generally the term speeding refers to situations where a road user is exceeding the speed limit, however, this is not always the case. In some circumstances the term is used to indicate that a road user is travelling too fast for the conditions, although this is often ill-defined. When referring to published literature, the term used within the cited reference has been used within this study, and so the reader should be aware of this interchange of terms. In addition, speed in this context generally refers to the speed of a road user over a set distance at any given point in time (e.g. km/h at any point on the approach to a curve). It is instantaneous speed, and not average speed that is of major interest. This is because speed changes on any given journey, and it is often the maximum speed at key points of the road network that leads to the greatest increase in risk.

Incidence

Worldwide, it is suggested that speed contributes to around a third of all fatal crashes (OECD, 2006). Armour and Cinquegrana (1990) reported that speed is the probable or possible cause of a quarter of rural serious crashes in Australia that involved single vehicles, while Haworth and Rechnitzer (1993) reported that around 20% of fatal crashes in rural areas involved excess speed. It is sometimes suggested that such figures are an underestimate of the true extent of the contribution of speed to the rural crash problem (e.g. Kloeden et al. 2001; Patterson et al. 2000). This is because it is difficult for the police (who typically record such data) to positively identify the effect of speed in any given crash.

Results from an analysis of crash data from across Australia by Turner (2009) identified that based on police reports of crash causation, an average of 28% of all fatal crashes on rural roads were caused by speeding. The figure was as high as 40% in New South Wales and Tasmania, and as low as 5% in South Australia. This disparity may indicate differences in the influence of speed in crashes across Australia, although it is more likely to indicate a flaw in the approach taken in collecting data. As indicated previously, the police attribution of causation is often based on limited information. Much of the research on this topic uses similar crash data and methodology (whether this be from Australia or international). Because of this, the results of analysis using aggregated crash data should be treated with caution.

Link between speed and crash outcomes

Despite the limitations of typical analysis linking speed and crash outcomes (i.e. aggregated data collected by police) the evidence regarding this link is compelling and a direct causal link between speed and crash risk appears to have been firmly established. This evidence comes from a number of different sources as outlined below.

Firstly, the effect of speed on crash energy is predicted by basic physics through the kinetic energy equation (Equation **2**).

$$E_k = \tfrac{1}{2} m v^2 \qquad \mathbf{2}$$

Where

E_k	=	kinetic energy	(Joules)
m	=	Mass	(Kg)
v	=	Velocity	(m/s)

In simple terms, the amount of energy exchange for any given collision is increased substantially with speed given that velocity is squared in this relationship.

The relationship between speed and crash risk also has an empirical basis. Elvik (2004) concluded there is a causal relationship between speed and road safety based on a number of arguments, including that:

- “There is a very strong statistical relationship between speed and road safety. It is difficult to think of any other risk factor that has a more powerful impact on accidents or injuries than speed.
- The statistical relationship between speed and road safety is very consistent. When speed goes down, the number of accidents or injured road users also goes down in 95% of the cases. When speed goes up, the number of accidents or injured road users goes up in 71% of the cases.
- The causal direction between speed and road safety is clear. Most of the evidence reviewed in this report comes from before-and-after studies, in which there can be no doubt about the fact that the cause comes before the effect in time.”

Elvik et al. (2004) conducted an analysis of almost 100 separate speed studies covering 20 countries. The study included 460 estimates comparing a change in mean speed and the casualty rate. A meta-analysis was conducted on this combined data, and the results provide strong support for the ‘Power Model’ of speed. This shows that even small changes in mean speed can result in substantial increases in fatal crashes (an exponent of 3.6) and injury crashes (an exponent of 2.4). Table 2.1 shows this relationship in tabular form, while Figure 2.3 provides a graphical representation.

Table 2.1: Relationship between mean speed change and crash rate (from Elvik et al., 2004)

	Change in mean speed					
	Speed reduction			Speed increase		
	-10%	-5%	-1%	+1%	+5%	+10%
Change in:						
Deaths	-38%	-21%	-4%	+5%	+25%	+54%
Serious injuries	-27%	-14%	-3%	+3%	+16%	+33%
Other injuries	-15%	-7%	-1%	+2%	+8%	+15%
Property damage crashes	-10%	-5%	-1%	+1%	+5%	+10%

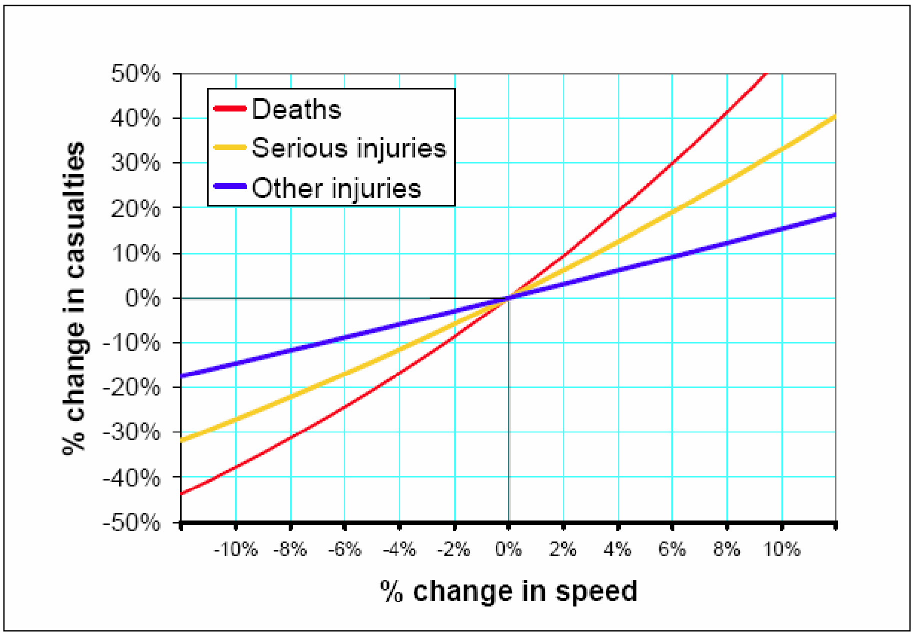

Figure 2.3: Relationship between mean speed change and crash rate (from Elvik et al., 2004)

Elvik and colleagues have conducted more recent studies to review the relationship between mean speed change and safety outcomes. In 2009 Elvik updated his 2004 meta-analysis (Elvik 2009) including results from 115 studies which contained 526 estimates of speed change and its safety implications. This review generally confirmed the strong relationship identified in the earlier work. However, the 2009 review identified that the safety benefits from changes in speed were less predictive for urban roads than previously identified (i.e. the safety benefits were not as strong for urban roads as previously thought). This was further confirmed by Cameron and Elvik (2010).

These findings are supported by a number of studies that have employed more sophisticated approaches to examining this issue. In an Australian case-control study on rural speed, Kloeden et al. (2001) identified that the risk of involvement in a casualty crash more than doubles when travelling 10 km/h above the average speed of non-crash involved vehicles and that it is nearly six times as great when travelling 20 km/h above that average speed as indicated in Figure 2.4.

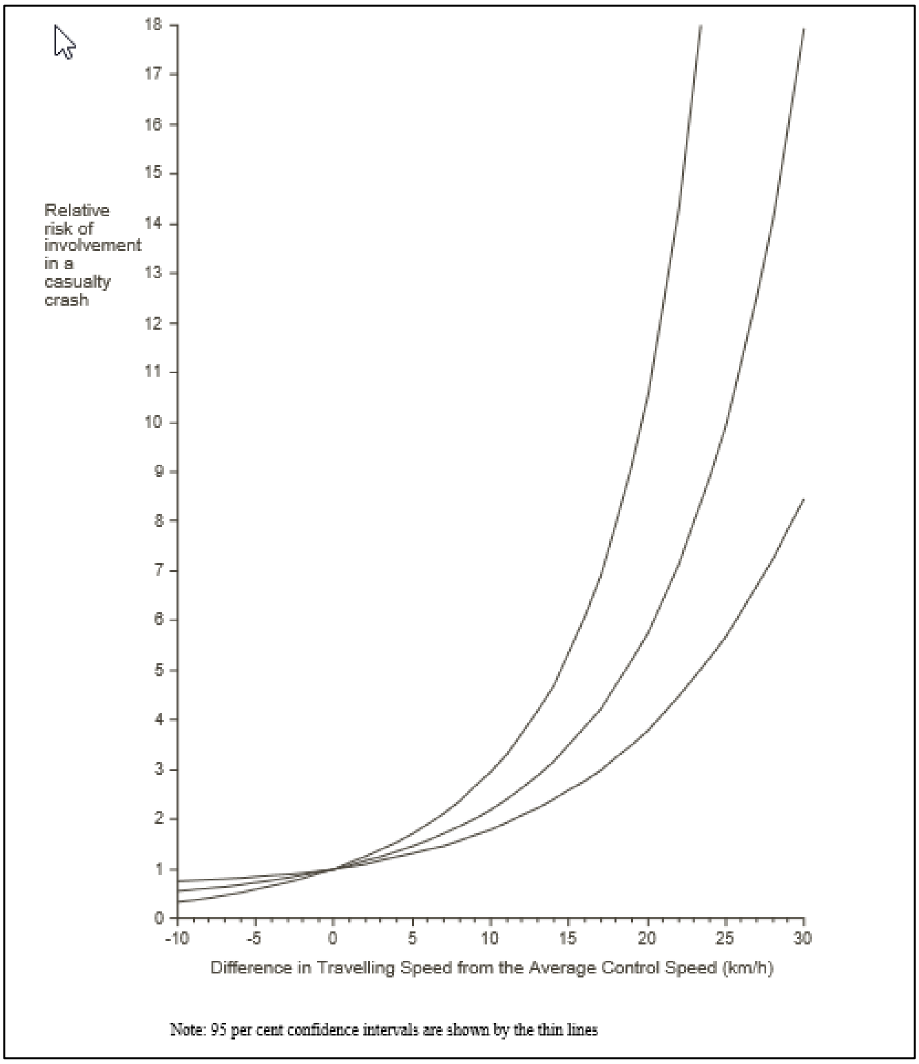

Figure 2.4: Speed and crash risk (from Kloeden et al., 2001)

There is further empirical evidence for the causal link between increases in speed and a subsequent increase in risk from a study by Sliogeris (1992) that involved a 'natural' experiment of this issue. In the late 1980s, the general speed limit for freeways in Victoria, Australia increased from 100 km/h to 110 km/h, but was then reduced to 100 km/h due to safety concerns. This offered an opportunity to study the safety effect of increases in speed limits for these types of roads. A 'before', 'during' and 'after' study was conducted on these roads spanning a 2.5 year period.

When the speed limit was increased to 110 km/h the casualty accident rate increased by around 25% and when the speed limit was decreased back to 100 km/h the casualty accident rate decreased by almost 20%. The study did not distinguish between safety performance on straights and curves.

Link between speed, infrastructure and crash risk

Taylor et al. (2002) analysed the relationship between speed and crashes on rural 60 mph (100 km/h) roads in the UK. Their study included a stratified sample, providing information on a wide range of roads. Six key variables were assessed, comprising crash rate, mean speed, minor intersection density, bend density, density of driveways and hilliness. Based on modelling, roads in their study were classified into four types, each with differing road quality. The groups comprised:

- Low quality roads: Roads which are very hilly, with a high bend density and low traffic speed (Group 1)
- Lower than average quality roads: Roads with a high access density, above average bend density and below average traffic speed (Group 2)
- Higher than average quality roads: Roads with a high junction density, but below average bend density and hilliness, and above average traffic speed (Group 3)
- High quality roads: Roads with a low density of bends, junctions and accesses and a high traffic speed (Group 4).

Results from this study showed that as speeds increased within each of these road classes, crash frequency also increased (Figure 2.5).

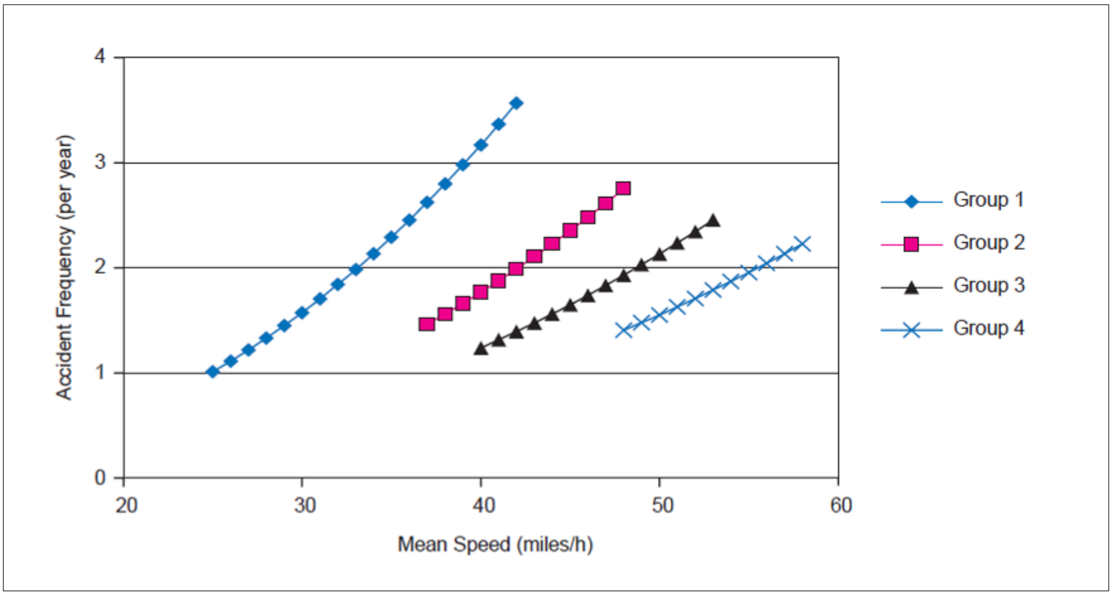

Figure 2.5: Relationship between accident frequency, speed and road quality (from Taylor et al., 2002)

Group 1 roads had the highest crash frequency, while Group 2 roads had around half the crash frequency, Group 3 roads a third, and Group 4 roads a quarter.

It was also found that with an increase in the density of sharp bends (defined as those with chevrons and/or warning signs) and in the density of minor intersections the total number of injury crashes increased rapidly (by 13% for each additional bend per kilometre, and 33% for each additional intersection per kilometre). Single vehicle crashes were particularly sensitive to an increase in sharp bends, with a 34% increase with each additional bend per kilometre).

This study clearly showed that there was an inter-play between crash frequency, mean speed, and road design characteristics. For this reason, the issue of road design in driver selection of speed is assessed in further detail (Section 2.5.1) as is the design of rural curves (Section 2.3).

It appears that there is a very clear relationship between speed and safety outcomes. This relationship has been identified from international research, as well as studies in Australia using a variety of methods, and the evidence base is very clear on this issue. With an increase in speed for any given road, there is a strong tendency towards a decrease in safety. There is also a link between speed and infrastructure in safety outcomes. The provision of higher quality infrastructure moderates the effect of higher speeds on crash risk. The following section looks more specifically at the role of speed in safety outcomes at curves.

2.4.2 The role of speed at curves

It has already been demonstrated that a large number of crashes occur at curves on rural roads and that speed has a significant role in these crashes. There is less research regarding why this crash type may be so significant, and the mechanisms that might contribute to these crashes. This section examines this issue in greater detail, including the incidence, crash types and risks associated with these crashes.

Incidence

Research from the United Kingdom (Richards et al. 2010) highlighted speed as a significant factor in crashes at curves. This study used a robust methodology, analysing in-depth crash data (i.e. where speeds were derived from skid marks or witness information) and crash data from police reports (considered less robust given previous comments about the sometime subjective nature of this method). From police reports it was established that cornering comprised around a third (32%) of all crashes involving excess speed (or exceeding the speed limit). This compared to 14% of ‘non-excess’ speed crashes. From the in-depth analysis it was identified that cornering comprised 42% of all excess speed crashes from the in-depth analysis (compared with 16% from ‘non-excess’ speed crashes). The study also assessed speed related crashes where the speeds were inappropriate, or where the driver was thought to be travelling too fast for the conditions. This indicated that more than half of all speed crashes (52%) were thought to be related to cornering (compared with only 10% of non-speed crashes). It was concluded that the majority of speed related crashes in the UK were from loss of control of the vehicle, usually at a bend.

Turner (2009) identified that speed was thought to be a major contributor to crashes at curves. This study reviewed the types of crashes on rural roads that were considered by police to be caused by speed. As already identified this is a relatively coarse measure of causality as often police do not attend the scene of a crash, or when they do, they may have a limited amount of information available to form an accurate judgement of crash causation. However, the most common crash types in order of occurrence were:

- off path on curve (i.e. running off the road while negotiating a curve)
- off path on straight
- vehicles travelling in opposing directions colliding
- overtaking.

Off path on curve was by far the most common crash type, with around 80% of all rural speed-related crashes. Compared with ‘non speed related’ crashes (i.e. where speed was not indicated as a contributing factor) this crash type is also over-represented. In non speed crashes, off path on curve crashes accounted for only 20% of crashes.

These results were replicated by Turner (2009) using New Zealand crash data where the same key crash types were identified, and where ‘cornering’ crashes represented almost 65% of all speed related crashes, while only contributing to around 30% of non speed crashes.

In a separate study of New Zealand data by Turner & Tate (2009) it was identified that speed was a factor in 37% of curve related crashes (based on an analysis of data between 2001 and 2005).

Similar results have been seen in international research. For example, Krammes et al. (1995) presented results from a study by Zeeger et al. (1991) which examined 104 fatal and 104 non-fatal crashes. Estimated speed was higher for the fatal crashes, and it was concluded that speed was a definitive factor in crashes, possibly in both the occurrence and severity. Hallmark and McDonald (2007) suggested that more than half of all curve crashes (56%) are the result of speed.

Crash types and risks

Based on their review of the literature Charlton & de Pont (2007) discussed three causative factors that may have an influence on crashes at curves. It is suggested that attentional demand may be higher at curves than on straight roads, and that this is exacerbated by higher speeds. Misperception of speed and curvature, especially on approach and at curve entry, was suggested as another factor in crashes at curves. Charlton & de Pont provided evidence to suggest that misperception of curvature is 'relatively common'. The third cause suggested by Charlton & de Pont is that motorists have difficulty maintaining lateral position through a curve, leading to a loss of control (discussed further in Section 2.6).

Wooldridge et al. (2003) also suggested that crashes may occur at curves when there is a disparity between the perceived safe speed of the curve, and the actual speed at which the curve can be safely negotiated. They suggested that driver expectation based on prior experience plays a large part in safe curve negotiation, and that fewer crashes occur at curves that conform to driver expectations.

Turner and Tate (2009) also suggested that driver expectation plays a part in the causes of curve crashes, and that this factor is intertwined with the consistency of alignment. They suggested that drivers travelling on a straight road will not expect a low speed curve, whereas drivers who are already travelling on curved roads are likely to expect further curves.

This issue of expectation and curve consistency appeared to be a useful mechanism to improve understanding of crashes at curves, but also to help categorise curves according to risk. There is a significant amount of research indicating that speed on approach to curves, and particularly the amount of speed reduction required through the curve (sometimes referred to as inconsistency in design) is a major predictor of crash risk (Bonneson et al., 2007; Cardoso, 2005; Fitzpatrick et al., 2000; Herrstedt & Greibe, 2001; Krammes et al., 1995; Montella et al., 2014; Pratt & Bonneson, 2008). The issue of approach and curve speed and the link to crash risk was also discussed in relation to road design in Section 2.3.

As examples, Fitzpatrick et al. (2000) analysed the safety effect of speed differential on tangents and through curves based on a sample of 5,287 curves. These were classified as good (those that required a 10 km/h reduction in speed from the approach tangent to the curve), fair (a 10 to 20 km/h reduction) and poor (greater than 20 km/h reduction). The crash rate increased dramatically for those curves requiring a greater speed reduction. Good curves had a crash rate of 0.46 crashes per 100 million vehicle km travelled; fair curves had a rate of 1.44; and poor curves had a crash rate of 2.76 (six times the crash rate of good curves). Further modelling of the data showed that the speed reduction variable was far more sensitive to crash outcomes than measures relating to curve radius.

As previously highlighted, Krammes et al. (1995) found that the mean crash rate on horizontal curves increased in a linear manner with mean speed reduction from the approach tangent to the curve. Using data collected at 78 curves of different designs, speed reduction (defined as the 85th percentile speed along the approach tangent, and the 85th percentile speed at the midpoint of the curve) was compared with crash performance. It was found that the required speed reduction was highly correlated with crash rates (R^2 of 0.91). A speed reduction of 30 km/h had a crash rate that was more than double that of a curve that required a 10 km/h speed reduction. These findings have been replicated in a number of more recent studies and reviews. For example, Bonneson et al. (2007) also suggested that there is a strong link between 85th percentile speed on the tangent preceding the curve, and 85th percentile curve speed. Pratt & Bonneson (2008) suggested that this risk is increased with higher speeds on the tangent, as the amount of energy transfer during a crash would be greater with higher initial speeds.

Knowledge of this relationship between speed reduction on approach to curves and crash outcomes has been used to help identify treatment strategies (the issue of effective treatment at curves is discussed further in Appendix A). Herrstedt & Greibe (2001) developed a model to identify risk for different types of bends. Their model is based on the approach speed to curves, and the curve design speed, and is used to allocate treatment packages at these locations.

This approach appears to be a robust means of determining risk at curves based on design elements.

It appears that the contribution of speed to crashes is significant, with estimates suggesting that speed contributes to 20–30% of fatal crash outcomes. Speed appears to be a particular problem at rural curves, with many crashes at these locations attributed to inappropriate speed. There is a strong relationship between crash risk, and the reduction in speed required to negotiate a curve. It is likely that more appropriate speeds at curves would lead to improved safety outcomes.

2.4.3 Speed and young drivers

Age has previously been identified as a factor in speed and crashes, with research consistently identifying that young drivers are more likely to speed, and to have speed-related crashes (e.g. Catchpole et al. 1994; Familiar et al. 2011; Fildes et al. 1991; Fleiter & Watson 2005; Harrison et al. 1998; Oxley & Corben 2002).

As an example (and as already identified in Section 2.2.3), Wundersitz (2012) examined the role of young drivers in crashes using the results from in-depth crash investigations. The review confirmed that the younger drivers were more likely to be involved in crashes on high speed roads; that decision making errors were the most common error type amongst the young drivers; and that of the decision making errors, the most common were excessive speed (22% of all crashes) and speeding for conditions (11%). Wundersitz also identified that young males tend to make more decision based errors such as speeding.

Based on a survey of US drivers, Shinar et al. (2001) suggested that younger drivers are more likely to report that they did not adhere to speed limits. The study also identified that male drivers were also more likely to report non-compliance with speed limits.

Catchpole et al. (1994) examined the crash involvement (based on police reports) of young drivers. They suggested that voluntary risk acceptance by young drivers, and particularly speeding, increases the difficulty of maintaining control of vehicles. They identified that for run-off-road crashes at curves, young drivers were significantly more likely to have been travelling at ‘excessive speed’ (either too fast for the conditions or 10% above the posted speed limit).

The earlier review of crash risk for young drivers (Section 2.2.3) revealed that this group had a higher crash rate than experienced drivers. It is likely that this increased risk is in part due to higher speeds for this group of drivers.

2.4.4 Summary

Speed, whether above the speed limit, or too fast for the conditions, plays a significant role in fatal and serious crash outcomes. There is considerable evidence about the direct link between speed and crash outcomes. With an increase in speed for any given road, there is a strong tendency towards a decrease in safety. There is also a link between speed, road design elements and risk. The provision of higher quality infrastructure moderates the effect of higher speeds on crash risk.

Speed has also been identified as a key contributor to crashes at curves, for drivers in general, but also for young drivers. The reduction in speed required on the approach and through curves has been shown to have a strong link to crash risk. This measure of speed reduction appears worthy of further analysis, but also serves as a useful means of categorising crash risk for individual curves.

Given the likely contribution of speed to crashes and the potential for improved safety through a reduction in speed, there is a need for a greater understanding of speed-related behaviours at rural curves, particularly at high risk curves. To further understand the relationship between speed at curves and crash risk the following section explores the ways that drivers select their speed, including speed through curves. Given the link between road design, speed and crash risk identified above, this section has a focus on how road-related factors influence speed.

2.5 Factors influencing driver choice of speed

In order to identify ways in which speeds can be better managed at curves, it is important to understand the way in which drivers select speeds. Information regarding selection of speed at curves was of greatest importance, but given the limited amount of research available on this issue, a broader assessment covering all road environments was initially undertaken. In addition, the main focus of this review was on ways that road-related factors influence speed selection, and this is discussed in detail in Section 2.5.1. However, there is a substantial amount of information on driver, vehicle and trip-related factors that influence speed. These include the following key findings:

- Younger drivers are more likely to speed (discussed in Section 2.4.3).
- Those who reported driving more frequently drive faster (Harrison et al., 1998).
- Those who had a tolerance of illegal behaviours (i.e. they believed various illegal behaviours to be ‘less bad’) drive faster (Harrison et al.1998).
- The perceived speed of other drivers and perceptions regarding enforcement are linked to speed (Harrison et al., 1998; Oxley & Corben, 2002).
- Newer cars, and higher performance cars are more likely to be identified as speeding (e.g. Familar et al., 2011; Oxley and Corben, 2002).
- Trip purpose, trip distance and number of passengers are all linked to speeding behaviour (e.g. Familar et al., 2011; Fildes et al., 1991; Fildes and Lee, 1993; Fleiter and Watson, 2005).

The following section explores the road-related factors that are associated with driver choice of speed.

2.5.1 Road-related factors

Methods used

Methods for determining road related factors that influence driver choice of speed include presenting motorists with images or videos and asking them to estimate speeds for different combinations of design elements; assessment using driver simulators; collection of data comparing speeds when different design elements are present; and before and after studies where one or more road elements are changed.

It is important to note that it is often difficult to isolate the effect of individual design elements on speed from such studies, as typically roads vary on two or more of these elements. For example, higher quality roads will be wider, have road markings, and be comparatively free from roadside hazards. A more robust approach is to conduct a 'before' and 'after' type analysis, or a simulator-based assessment where a single characteristic is changed, and speeds measured before and after this change (Austroads 2012). Such research relating to road design elements and speed is rare. However, the information below serves as a guide to speed based on various design elements.

Key design factors

A large number of studies have been conducted on road-related factors that influence driver choice of speed. The research evidence is relatively consistent in terms of identifying factors that contribute to speed choice by motorists.

Cairney (1986) conducted a trial that involved presenting different road scenes to subjects who were asked to estimate the speed limit, what a safe operating speed might be, and the speed they thought most traffic would be travelling for each environment. The road configuration (whether two or four lanes, and whether there was a narrow or wide median), and the land use (recreational, industrial, commercial or residential) were assessed. Cairney (1986) identified that estimates of speeds were quite sensitive to differences in the environment. Two lane roads and commercial land use were associated with the lowest estimates by subjects of a safe speed, while roads with wide medians and with recreational land use produced the highest estimates.

The same key factors were also identified by Jarvis and Hoban (1988). As part of a study to develop an expert system for the setting of speed limits they assessed important factors in selecting speed limits. This involved an assessment by an expert panel, and collection of data from 64 sites with varying road characteristics. The study suggested that abutting development and road cross-section were the major determinants that should be included in speed zoning decisions.

Fildes and Lee (1993) reported similar findings, indicating that road configuration (including the width of the road and number of lanes) had the greatest influence on drivers' choice of speed. The level of roadside development was found to be important but had a lesser influence. They proposed other road or environment factors of interest including curve radius and length, shoulder width, intersections or driveways, average traffic speed, delineation, weather, grade, volumes, parked vehicles, pedestrians and sight distance.

Similarly, Harrison et al. (1998) identified road based factors such as land use or population density, roadside development, road category and lane width, horizontal and vertical curves, and traffic density.

Oxley and Corben (2002) reviewed literature to determine factors that influence choice of speed. They identified a more comprehensive list of factors that included speed limit, curvature, grade, length of grade, number of lanes, surface conditions, sight distance, lateral clearance, number of intersections, built-up areas near the roadway, advisory and warning signs, traffic density and composition, speed of traffic, and presence of road lighting. It was suggested that speed limit was the most important factor, although it should be noted that there is typically a linkage between speed limit, and road use and cross-section so this is a somewhat circular argument.

Results from a study by Varhelyi (1996) were consistent with those from Oxley and Corben's (2002) finding that speed limit was the most important element in choice of speed. Amongst road and traffic environment characteristics thought to increase speeds were the design speed, road standard (when good) including lane width, number of lanes and roughness, visual guidance (speeds increase when delineation is good), and downhill gradient. Elements thought to reduce speeds were speed limits, bad road and weather conditions and increased traffic volumes.

Silcock et al. (2000) suggested that the physical dimensions and layout of the road, prevailing traffic conditions, and the perception as to whether the road was urban or rural in characteristics were important determinants of driver speed. Based on video footage of drivers in differing road environments, they found that in lower speed environments (30-40 mph), the speed limit was most often exceeded in situations where roads were wide and straight, where there was good sight distance, and little frontage activity. The report also identified the need to inform motorists of the reason for speed limits if these are not clear (for instance by providing supplementary plates on speed limit signs).

Elliott et al. (2003) identified a number of road design features that influence speed based on a review of literature. They listed factors similar to those identified above, but also included presence of a median, parked cars, presence of road signs (including speed camera signs and warning signs), road markings (including transverse and longitudinal markings, cycle lanes and bus lanes), gateways (transition points between rural and urban environments) and shared space designs (including the Dutch ‘woonerf’ and UK ‘Home Zone’ concepts). Elliott et al. also identified that combinations of treatments are likely to be more effective than individual treatments.

Quantifying the influence of design factors on speed

As well as studies that identify design elements that influence speeds, some studies have estimated the extent of speed change in response to changes in road elements. Varhelyi (1996) reviewed previous literature that put values on some of these road elements. For instance, research by Nilsson (1989, cited in Varhelyi, 1996) suggested that for every 1 metre increase in the paved width of a road, speeds increased by 0.4 km/h. Evidence from Yagar & van Aerde (1983) is cited that suggests for every 1% reduction in gradient, there is about a 2 km/h increase in speed. For roughness, a study by Anund (1992) is cited that suggests a 3 km/h reduction in speed with each additional IRI (International Roughness Index) increase of 1 mm/m.

Thoresen (1999) sought to isolate the effect of road width alone on speed. This study assessed a 1,000 km primary inter-regional two-lane highway which had seal widths ranging from about 6 m to 12 m. The study used a series of paired observations which allowed direct comparison of road sections based primarily on seal width. A regression analysis was conducted to identify statistically significant differences. Thoresen found that an increase in speed was associated with an increase in width. A regression analysis yielded a statistically significant coefficient of about 0.75 km/h per metre of seal width.

In a major review conducted as part of the ‘Managing the Speed of Traffic on European Roads’ (MASTER) project, Martens et al. (1997) assessed the effect of design elements on speed, providing information on a number of relevant factors. In some cases the effects of these elements were quantified. They cited a study by Van der Hoeven (1987) which identified a mean speed of 80 km/h for a pavement width of 6 m, while with a width of 8 m, speeds increased to 90 to 100 km/h. This finding seems inconsistent with the work reported above by both Nilsson (1989, cited in Varhelyi, 1996) and Thoresen (1999) which found much more moderate differences in speed based on road width.

Martens et al. (1997) also cited a study that indicated a minimal reduction in speed from a reduction in lateral clearance (the space that is visually available on either side of the side walk) from 30 m to 15 m (only 3%), while a decrease to 7.5 m resulted in a speed reduction of 16% (Van der Heijden 1978). They identified a further study that indicated a speed reduction of 13% when objects were placed directly alongside the road compared with 1 m from the edge of the road (Knoflacher & Gatterer 1981).

Martens et al. (1997) identified information which indicated that roughness had a quantifiable impact on speeds. They cited a study by Slangen (1983) that indicated a 14-23% reduction in speeds for roads with a rough surface. Similarly, they cited a study by Cooper et al. (1980) that found with improvements to the road surface following resurfacing, speeds increased by up to 2.6 km/h. Te Velde (1985, cited in Martens et al. 1997) reported that a rough road that followed a smooth section of road reduced speeds by 5%. It could be questioned as to whether this relationship is still valid given the age of the research and changes to vehicles, including improved suspension systems.

Other road design elements identified by Martens et al. (1997) but not quantified were roadside obstacles (the closer to the side of the road, the slower the speed, but typically only if the pavement width was less than 6 m), road curvature (where reductions in speed were partly influenced by reduced visibility along the road) and gradient (again, possibly due to reduced visibility).

Charlton and Baas (2006) conducted a review on road design elements and speed to identify ways to maintain speed reductions on an area-wide basis. In summarising literature on this topic, they suggested the values in Table 2.2 for speeds based on changes to road elements.

Table 2.2: Road elements and typical speeds (adapted from Charlton & Baas, 2006)

Road element	Mean speed (km/h)	85th percentile speed (km/h)
Carriageway width		
6.0m	80	Unknown
8.0m	90-100	Unknown
Number of lanes - urban arterial		
4	50	51
2	45	46
1	40	Unknown
Delineation		
Marked centre line	Unknown	72
No centre line	Unknown	51
Marked edge line	Unknown	77
No edge line	Unknown	64
Medians		
No median	55	61
Raised median	59	68
2-way turn lane	Unknown	71
Deflecting median	50	Unknown
Median width		
0	Unknown	69
3m	Unknown	87
6m	Unknown	97
Access density		
>29 per km	Unknown	74
<29 per km	Unknown	83
On street parking		
Parking	Unknown	51
No Parking	Unknown	77
Roadside hazards 3m from road edge		
Clear	Unknown	80
Yielding objects	Unknown	72
Yielding and rigid	Unknown	61
Isolated rigid (arterial)	Unknown	68
Continuous rigid (arterial)	Unknown	76

These values are based on a number of studies, some of which apply to rural roads, while others are from research on urban arterials. Information on local roads are also presented by Charlton and Baas, but has not been replicated here given the focus on higher speed rural roads in this investigation.

The findings from Charlton and Baas as well as other research identified in this section highlights that much is already known about design elements and how (and to what extent) these are associated with speed. The following text discusses how knowledge of these relationships can be used to influence driver choice of speed, including on rural roads.

Influencing speed of drivers through design

The information in the previous section provides the basis for guidance around road features that can potentially influence driver choice of speed. It is likely that some of these elements could be varied resulting in subsequent reduction in driver speeds.

Elliott et al. (2003) identified a number of features that can be used to influence driver speed based on a review of literature. As well as suggesting a number of behavioural approaches (e.g. increased perceived level of enforcement, and better knowledge of own travelling speed) they provided suggestions around design-related options, including:

- increasing cognitive workload (i.e. the complexity of the driving task)
- reducing the perceived benefit of speeding (for instance by designs that increase physical discomfort or stress when speeding)
- enhancing perceived danger/risk
- increased retinal streaming (placing elements in a driver's peripheral vision to increase the perceived speed)
- improving driver knowledge of current speed limits (through appropriate road features).

Based partly on information regarding drivers' choice of speed, the Netherlands has developed the concept of the 'self explaining road' (e.g. Schermers, 1999; SWOV, 2006; Theeuwes & Godthelp, 1992). This key element of their 'sustainable safety' approach suggests a need to make clear to motorists what is expected in terms of their driving behaviour, communicated by the design of the road itself. A clear function is assigned to each road based on a predefined hierarchy. In order to recognise the current road function, and to predict road elements, one study (World Bank, 2005) suggested the following three features are required:

- clear design, marking and signing

- recognisable road categories
- limit the number of design elements for each road category and make them uniform.

Charlton and Baas (2006) suggested that the uniform road categories and their features should act to clearly indicate to motorists the type of road that they are on, but should also act implicitly (or unconsciously) to control the behaviour of motorists. In terms of speed management, they suggested these features could include use of median and edge line treatments, access controls, road markings, pavement surfaces, and roadside furniture.

Based on these findings it is apparent that there are a number of road design elements that have an influence on driver choice of speed and it is generally known whether these act to increase driver speed, or decrease it. Abutting land use, road cross-section (including number of lanes, width etc.) and speed limit are often cited as the most influential elements in choice of speed, although it should be noted that there are strong linkages between these elements. A number of other elements also play an important role in speed selection. In some instances, information is available on the magnitude of likely change in terms of speed. Manipulation of these road design elements has been used to effectively manage speeds. The 'self explaining' road is an approach that uses knowledge of design and speed outcomes to achieve this. However, there is not perfect knowledge on these factors, their interactions, and influence on speed. A better knowledge of these principles is important both in understanding of crash risk at curves as well as in identifying likely solutions.

2.5.2 Driver selection of speed at curves

Although there is a reasonable amount of research on the types of factors that influence driver selection of speed in general (as discussed earlier in Section 2.5), there is less information specific to the selection of speed through curves. This section discusses both behavioural models and road design models relating to driver speed through curves.

Behavioural models

A variety of behaviour models have been proposed to explain how drivers negotiate curves. What is clear from these models is that the driving task is substantially different between straight roads and curved, both in terms of the driving demands and perceptual processes.

Based on a review of literature, Fildes (1986) suggested that the main source of information for drivers is through vision, with up to 90% of information processing through this means. In terms of driver perception of curvature, Fildes suggested that several theories have been developed. These were categorised into three main types:

- stimulus feature theories, or those theories that describe important stimulus properties, such as what drivers use when assessing a curve
- general theories to explain angle illusions
- specific accounts of processes, which were suggested as the most sophisticated accounts of perception, focusing on mechanisms involved in directly perceiving curvature.

From a review of these theories, it was concluded by Fildes that the inside edgeline of a curve is the most important element in assessing curves. It was further suggested that perceptual errors in the assessment of this edgeline can lead to errors in curve assessment. Fildes' own study (based on laboratory-based experimentation) suggested that curve angle (i.e. the degree of the bend) is most important in the assessment of curvature; far greater than curve radius. Because of this, in situations where the full curvature of the road is obscured (e.g. by a cliff face or vegetation), curvature judgement may be impaired, potentially leading to an under-estimate of curve severity.

Fildes and Jarvis (1994) reviewed curve negotiation and identified that the assessment of a curve begins well in advance of the curve. They concluded that on approach to a curve, drivers use brief glimpses (of 300-400 msec duration) that are scattered around the road surface. They suggested that the assessment process happens at least 100 m in advance of the curve. Fildes and Jarvis also report that there is a misperception by drivers when judging road curvature, with an 'inappropriate preference' for curve angle over radius.

Campbell et al. (2008) conducted an extensive review of literature on driver behaviour through curves. Their research included the development of a task analysis of driving behaviour. Based on this work, the authors identified four phases of driving behaviour as shown in Figure 2.6 (note that driving is undertaken on the right hand side of the roadway). Although four discrete tasks were identified, it was suggested by the authors that this grouping was used for convenience, and that the driving task does not neatly fit within these divisions.

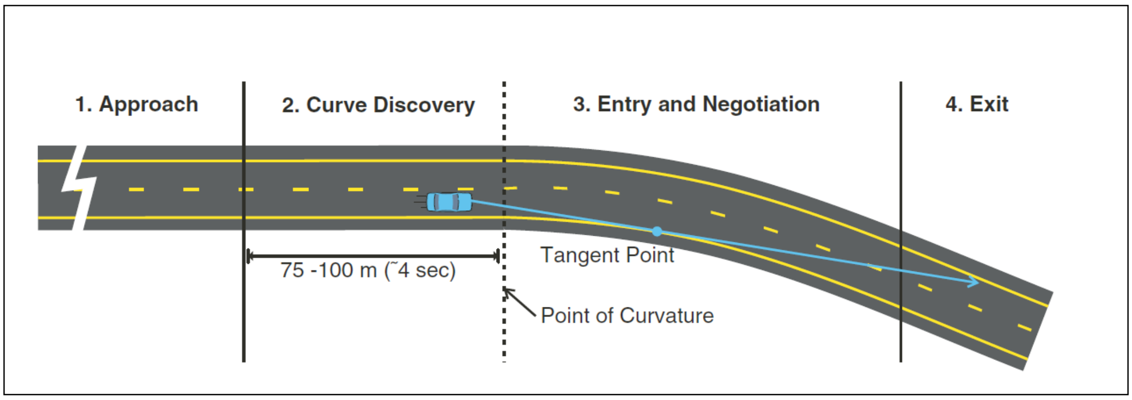

Figure 2.6: Segments of curve driving task (from Campbell et al., 2008)

The four stages of curve driving defined by Campbell et al. (2008) include the approach, curve discovery, entry and negotiation and exit. Given that these provide a useful framework for assessing parts of curves, details on each of these phases are provided below.

On ‘Approach’ the driving tasks include locating the bend, gathering speed information from signage, and making initial adjustments in speed. It is proposed that information is gathered from advisory speed or message signs, and that drivers have more time to read and interpret such information. Speed is influenced by previous roadway elements and signage.

‘Curve Discovery’ involves determining road curvature, assessing road conditions, making additional speed adjustments, and adjusting the vehicle path for curve entry. Sources of information including curvature perception cues based on ‘non-verbal’ (e.g. chevrons) and direct information (e.g. delineators) and roadway conditions are required, as drivers have less time to read and interpret information signs, and act upon these. Driver expectations and these curvature cues are the primary influencers of speed.

During ‘Entry and Negotiation’ speed is adjusted based on curvature and lateral acceleration, while proper trajectory and lane position are maintained. There are many eye fixations on the tangent point of the curve, and only ‘direct’ information is used. This must be either where the driver is looking (e.g. lane markings) or in their peripheral vision (e.g. raised reflective markers at night). It was proposed that the primary influencers of speed at this point are expectations and lateral acceleration.

‘Exit’ tasks included acceleration to an appropriate speed, and adjustment of lane position. Vehicle position information is required, and the posted speed or expectations is the main influence on speed.

It was proposed by Campbell et al. (2008) that the highest visual demands are just after the point of curvature (during the entry and negotiation stage), and that most of the time is spent assessing tangent point to keep the vehicle aligned with the roadway. However, it was thought that for less severe curves (this is defined by example as 3 degrees by the authors) more time was spent looking to the horizon than at the tangent point. Vehicle control demands are also highest at the curve entry and negotiation stage, with drivers constantly adjusting their position to stay within their lane. Campbell et al. suggested this is especially the case for shorter radii curves and smaller lane widths.

Campbell et al. (2008) suggested that direct cues such as lane width and the visual image of the curve are important for speed selection. Previous experience with the curve, and speed on preceding parts of the road also influence speeds. However, it was suggested that perceptual factors are the primary influence on speed. The apparent radius (i.e. the curve radius perceived by the driver) was suggested as being particularly important. It was thought that the apparent radius can be distorted by road and topographical elements to either make the curve appear less or more severe than it really was. Curves that were combined with vertical sag were said to appear flatter than they really were, and therefore lead drivers to select an entry speed that was faster than appropriate. They cited studies by Appelt (2000) and Hassan & Easa (2003) that suggested such curves were associated with higher entry speeds and greater crash rates. Alternatively, crest curves were said to appear less severe than they really were, resulting in slower entry speeds. Campbell et al. again cite Appelt (2000) and Hassan & Easa (2003) as supporting this hypothesis.

Campbell et al. (2008) highlighted other visual effects that may influence curve perception, while recognising that there is a lack of empirical evidence to support these. Factors included cross slope (a suggested flattening of curves for sag horizontal curves with greater cross slope and lane width); deflection angle, or the difference in angle between approach and departure tangents (curves appear sharper with greater deflection angle when holding the curve radius constant, especially for small radii horizontal curves); delineators (improves curve perception by providing drivers with more information); and spiral transition curves (potential to make the curve appear less severe, or increase difficulties in perception due to a less apparent onset of the curve).

Campbell et al. (2008) claimed that signage can provide a perception that a curve is more risky, but also stated that signage is not a primary source of information for speed selection.

Road design models and related studies

Predictions of driver speeds are a fundamental factor in the design of roads. This is particularly important at curves. If the predicted speed is lower than actual speeds, then the design of the road is likely to be unsafe. On the other hand, if the predicted speed is higher than actual speeds, the cost for constructing a road will be higher than is necessary. For this reason, this topic has been the subject of extensive research over many years. Although not directly designed to provide a comprehensive model of how drivers select their speed through curves, the operating speed models have been developed to identify the key elements that determine the speed of vehicles, particularly through curves. This issue is discussed in further detail in Section 2.3.

Turner and Tate (2009) conducted a study based on speed profiles of drivers (measured through an in-vehicle trip meter and data logger), road geometry data and crash data. Their dataset included 488 curves, and assessed the behaviour of 12 drivers over a 20 km route a total of four times in each direction. The results suggested that driver's choice of speed through curves was mainly determined by the minimum radius of that curve, and that this was a more important determinant of speed than design speed. The analysis also identified that other factors were likely to influence speeds, in particular the average 85th percentile speed over the previous 500 m.

Lee (1988) conducted a study to assess driver behaviour on curves by measuring the speeds at 10 m intervals using video footage of 400 vehicles travelling through a curve. Measurements were taken from a point 30 m along the tangent prior to the curve, and then at six more locations at 10 m intervals through the curve. The objective of this study was to examine the strategies used by drivers when perceiving curves, and the speed control undertaken while driving through the curve. Mean speed, 50^{th}, 85^{th} and 99^{th} percentile speeds were calculated for each of these points.

Lee (1988) identified three zones of driver behaviour on approaching the curve. The first zone (30 to 20 m prior to the curve) showed speed reductions. The second zone (20 m prior to curve to the start of the curve) showed an adjustment in speed that was fairly minimal, or to a point that was suggested by Lee as a comfortable level of speed. The third zone was termed the zone of comfortable driving by Lee, with minor adjustments to the 'near optimum' speed through the curve. This involved a minimum speed at a point around 20 m past the tangent point for most drivers, and increases in speed at a point 35 m from the tangent point. Comparisons of different percentile speeds identified various differences in groups of drivers. For example, the rate of reduction was greater in the first zone for the more cautious drivers (those travelling at or below the 50th percentile speed). Less cautious drivers did not slow as substantially at this point. In contrast, the less cautious drivers slowed to a greater extent in the second zone.

Levison and Kantowitz (2000) conducted a study that utilised GPS technology to determine driver speed. In this study 18 drivers drove a 42 km test route which contained 12 test sites with horizontal curves that were of interest. The continuous collection of data via GPS on approach and through each curve was thought to provide the type of database required to help understand the interaction between roadway geometry and driver behaviour, and was relatively successful in this task.

The study identified mixed results in terms of driver behaviour on approach to curves, with some speed profiles indicating a minimum speed at or before entry to a curve, while others indicated that around 15% of deceleration occurred beyond curve entry. The analysis did not allow conclusions about why such differences might occur.

Fildes (1986) concluded that research evidence varied in terms of deceleration on the approach to curves, with some reports indicating that most speed adjustments occurred on the approach to a curve, while others reported additional deceleration well into the curve. This study also suggested there was a lack of research on this issue in relation to different types of curves. It would be interesting to determine where the point of minimum speed is for different types of curves and to contrast this with information regarding where this minimum should be in order to minimise risk.

Bonneson and Pratt (2009) found that driver selection of speed through curves is based on a balance between safe and efficient travel. In their study speed data was collected at 41 sites using sensors adhered to the pavement on the tangent in advance of the curve, and at the curve midpoint. More than 6,600 passenger vehicles were observed during the trial. Information on curve radius, curve length, lane and shoulder width, superelevation and grade was also collected. A model was developed to predict curve speeds. Based on the hypothesis that there was a trade-off between safety and efficiency, one model term reflected the expected desire of drivers to maintain a minimum level of safety (i.e. the desire to avoid loss of control or rollover) while a second term reflected the desire to maintain speed, and to tolerate a slightly higher level of side friction on sharp curves to do so. The model was thought to accurately estimate curve speed based on tangent speed, radius, deflection angle, and superelevation rate. It was concluded that the increase in side friction demand that a driver is willing to accept is directly proportional to the energy required to slow the vehicle through a curve.

Further information on different road and road user elements relating to driver selection of speed can be found in Section 2.3. In that section, these elements are discussed in the context of road design.

Individual and group differences

There is a lack of literature on individual or group differences in driver speeds (as there is for other behaviours) on the approach and through curves. As discussed above, Lee (1988) did investigate this issue suggesting differences between more and less cautious drivers. Lee suggested that less cautious drivers did not slow as substantially as cautious drivers 30 to 20 m from the start of the curve, but rather slowed to a greater extent closer to the start of the curve. Mintsis (1998) suggested that individual differences in driver speed increased by level of curvature. Greater variation was identified for curves with a radius of less than 250 m. More information is needed on the behaviour of individuals and groups of drivers as they travel through curves, including differences in speeds adopted.

There are various behavioural models that have been developed to examine curve negotiation and selection of speed. The driving task is often split into phases relating to tasks required on approach and through curves. These phases provide a useful taxonomy for assessing behaviour through different parts of curve negotiation. Other behavioural studies identified key design elements that help drivers select an appropriate speed. Misperception of these elements may be responsible for inappropriate driver selection of speeds through curves. It is clear from the literature that gaps remain regarding the most important elements in driver selection of speed at curves.

The information that is available has been used to inform the development of road design models for curves. Information on road elements is used to predict driver speeds through curves, and this is an important aspect of road design. Road design as it relates to curves is explored in further detail in Section 2.3.

2.5.3 Summary

There is extensive information on the way that drivers select speed. Key elements include driver, vehicle and trip-related factors. Road design elements also have an important role in driver choice of speed. These act to increase or decrease driver speed, and in some instances, information is available on the likely change in terms of speed. Manipulation of these road design elements has been used to effectively manage speeds.

There is less information, but still a solid evidence base, on selection of speed through curves. Different approaches have been taken to examine this issue, leading to the development of behavioural models for speed selection, as well as development of design standards and guidelines (which are typically based on this behavioural foundation). The behavioural models that have been developed include assessment of the driving task at different stages on the approach and through curves. Perceptual errors, particularly relating to the severity of the curve, can lead to inappropriate choice of speeds through curves. Although there is a reasonable amount of evidence regarding driver selection of speed through curves, there also appear to be a number of gaps in knowledge related to this issue, with no definitive model of driver behaviour through curves.

2.6 Role of lane position in crashes at curves

2.6.1 Lateral acceleration, speed, radius and lane position

As identified in Chapter 1 and Section 2.2, crashes at rural curves often occur as a result of vehicles losing surface friction or drifting from their lane. Rivers (2006), in summarising prior research in relation to crash reconstruction, stated that each curve has a radius that when coupled with the drag factor for the roadway produces a critical speed above which a vehicle cannot safely negotiate. This is consistent with the material presented in Section 2.3 on curve design. Rivers also stated that if this speed was exceeded the vehicle will yaw, sideslip and leave the intended path of travel. This may result in the vehicle leaving the road or striking other vehicles. This issue may be exacerbated by driver actions through the curve. For example, Charlton (2007) suggests that friction demands through curves often exceed those anticipated by designers because drivers overshoot curves thereby producing a path through the curve that is sharper (i.e. a lower curve radius) than the actual curve.

Lateral acceleration (or side force) of a vehicle negotiating a curve is based on the speed of the vehicle (velocity) and curve radius as shown in Equation 3.

$$CA = \frac{v^2}{R} \qquad \textbf{3}$$

Where

CA	=	centripetal acceleration	(m/s^2)
v	=	Velocity	(m/s)
R	=	curve radius	(m)

This is a simplified account of this relationship as in reality, superelevation of the curve offsets some of the effect of lateral acceleration (discussed further in Section 2.3 in the context of curve design).

Figure 2.7 provides a graphical representation of the relationship between speed, curve radius and side force, derived from Equation 3. Examples are provided showing side force for curves with a radius of 50, 75 and 100 m at different speeds.

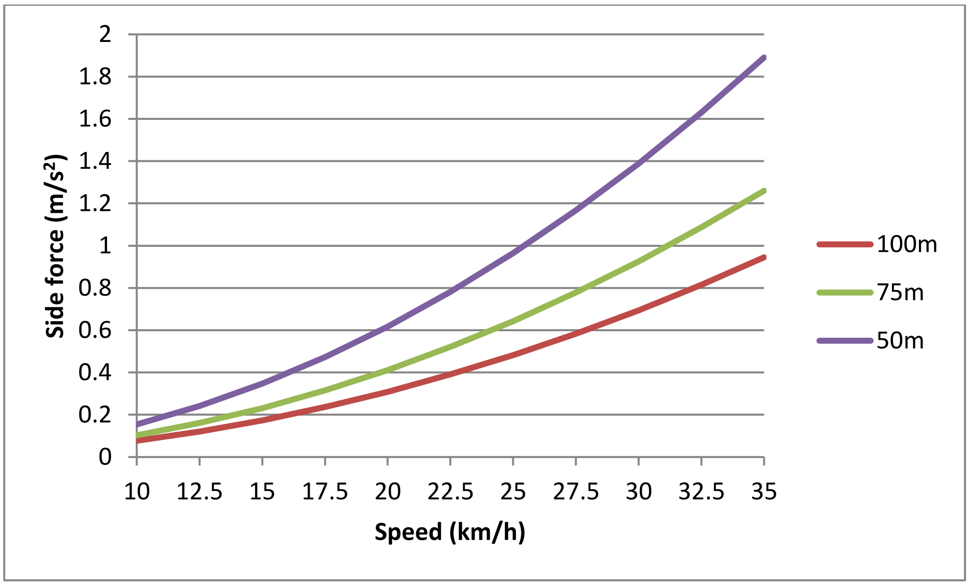

Figure 2.7: Relationship between speed, radius and side force at curves

It is clear from this figure that increases in speed for low radii curves can have a more substantial impact on side force than for higher radii curves. As an example, using Equation 3, for a curve with a radius of 50 m, the difference in side force for vehicles travelling at 20 km/h and 21 km/h is a 0.063m/s^2 increase in side force. The same increase in speed for a curve radius of 100 m is far less substantial with an increase of 0.031m/s^2. It is also clear that very small changes in curve radius can have substantial impacts on side force, especially at higher speeds.

Road designers dictate the radius of a curve, but it is possible for drivers to adjust this radius through their selection of lane position. The remainder of this section provides a review of lane position research at curves. Although there have been several studies undertaken on lane position through curves, there is a very limited understanding of the factors that influence choice of lane position, the link to driver selection of speed, and the influence this has on crash outcomes.

2.6.2 Previous research on lane position

A number of different methods have been employed to study lane position through curves, and the sophistication of these studies has improved substantially in recent years. An early attempt to measure lane position was undertaken by Glennon & Weaver (1971, cited in Fitzsimmons et al., 2013). They analysed behaviour at five curves by following vehicles through curves in a 'chase vehicle' and recording their driving position on video for later assessment. That study identified that vehicles 'cut the corner', reducing the sharpness of the curve by travelling in a straighter line through the curve.

Many of the studies since that time have assessed behaviour at individual curves using various data collection devices. Most popular has been pneumatic tubes set out in a 'Z' configuration, allowing calculation of lane position based on timestamps. Other methods include automated interpretation of video data (e.g. Weise et al., 1997), use of roadside sensors (e.g. Spacek, 2005) and data collected through instrumented vehicles, including as part of naturalistic driving studies (Hallmark et al., 2014).

Jamieson (2012) suggested that very little research has been conducted on the influence of lane position on crash occurrence, although there has been some good research on lane position behaviour. Based on a review of several studies, the following conclusions were drawn:

- drivers tend to straighten their path when travelling through curves
- the driving path is typically shifted to the inside of the curve, particularly as curve radius decreases (i.e. as the curves become sharper)
- encroachments occur across both edge and centrelines
- driver behaviour through curves is based on conscious and unconscious decision making, as well as a lack of information
- there are different curve tracking behaviours, and curve radius will vary for different drivers
- the side force can vary substantially between these different tracking behaviours (by a factor of two)
- speeds also vary by tracking behaviour
- combining these two factors (side force and speed) can mean that there can be very high friction demand in some scenarios
- loss of control at curves cannot be solely attributed to high speeds – lateral position should also be included.

All of these points are of interest, but the last two carry particular significance. It appears that very little is known about the combination of speed and lane position and their combined influence on crash outcomes.

In Jamieson (2012), field data was collected from seven curves, all with a radius of less than 300 m. Data was collected at key points (a minimum of nine per curve) using video collected from a vehicle that was reported to be parked in an unobtrusive location. A minimum of 100 vehicles were recorded at each site. Information on driver characteristics was not available, and therefore not included in the analysis. Jamieson categorised driving behaviour into four groups; those drivers who travelled in the centre of the lane (mid-lane); those who entered from the left and moved to the right towards the exit (left in – right out); those who entered from the right, moved wider through the corner, and moved left towards the exit (right in – left out); and those who cut the corner (cutting). Each of these behaviours is shown in Figure 2.8. The proportions for each of these four driving behaviours were not provided.

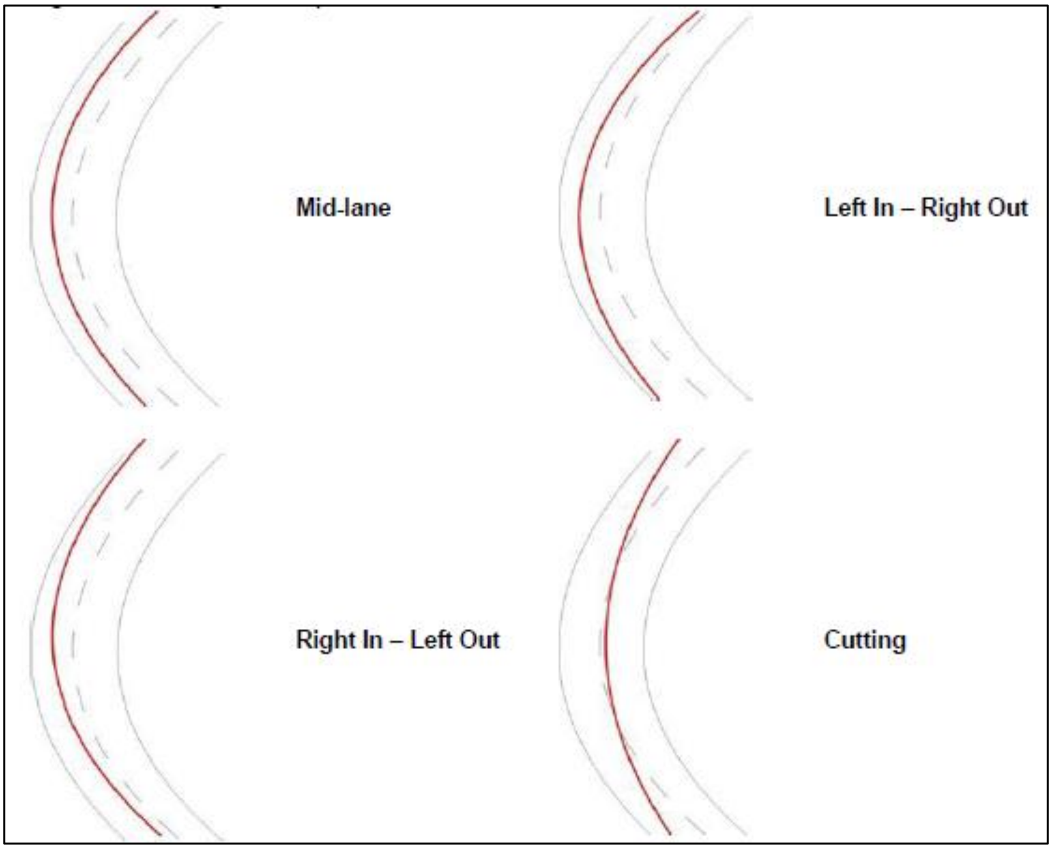

Figure 2.8: Four categories of lane position (from Jamieson, 2012)

Chrysler et al. (2009) suggested that drivers do not follow the centre of the lane through curves, but rather use a curve flattening strategy. They cite a study by Zador et al., 1987 who found that for left curves, drivers were closer to the centreline at the midpoint, while for right curves, they were closer to the edgeline (note driving on the right). They also cite a study by Filipe and Navin (1998) who identified that drivers cut the curve for small radius curves, but that this was not the case for large radius curves. It would be interesting to understand the importance of this strategy in terms of safety outcomes. Given knowledge regarding curve risk, and particularly the importance of change in speed between curve approach and the curve itself, it would also be interesting to examine different driver strategies for curves of different risk.

Chrysler et al. further cite a study by Pagano (1972) that developed a crash model for curves. It was found that variance in lane position between curve entry and the middle of the curve was one of the factors related to increases in crash rates (the other variable was the rate of deceleration in the first half of the curve). A similar result was found by Stimpson et al. (1977, cited in Chrysler, 2009) in a study of 32 road segments. They found that crash rates increased with distance of vehicles from the centre of the lane and with the variance of lateral placement.

Chrysler et al. used piezoelectric sensors (thin pressure-sensitive cables that generate an electric current when subjected to pressure) placed on the road in a ‘Z’ configuration to measure lane position at four sites. Curve flattening behaviour was identified for both left and right curves. With the introduction of curve chevrons, it was found that drivers adopted a different lane position, with drivers shifting less from the centre of the lane. Variance in lane position was also reduced with the introduction of chevrons, as were encroachments onto or across the edge or centreline. The same result was found with the introduction of post-mounted delineators. It is unclear whether these changes resulted in decreases in risk.

Hallmark et al. (2013) suggested that the relationship between speed and lateral position in curves is not well documented or understood. They collected data at three sites using pneumatic tubes in a ‘Z’ configuration. Information on lane position and speed was collected at the curve beginning, middle and exit. The data collected was analysed to identify situations where there was a ‘near lane crossing’, which was defined as being within six inches (15 cm) of the lane marking. Although results for many of the locations were not statistically significant, there was evidence that those travelling 5 mph (8 km/h) or more above the advisory speed were more likely to have a near lane crossing (2.4 to 4.5 times more likely).

Hallmark et al. (2014) analysed naturalistic driving data (i.e. data collected while subjects drove their own vehicles) for over 3000 drivers across a three year period. This information was linked to the Roadway Information Database, which contains detailed information on the road environment including design parameters. Comprehensive data was available for 148 curves.

Hallmark et al. (2014) identified that drivers begin reacting to the curve 164 to 180 m in advance of the curve (defined as the point of curvature), depending on curvature. Drivers reacted sooner to curves with larger radii, a seemingly counter-intuitive result.

An analysis indicated that lane position within a curve was influenced by lane position on approach to that curve. It was suggested that drivers may be more vulnerable to lane departure at different points within the curve due to differences in lane position. Drivers tended to move more to the right at the centre of the curve for right curves (note that driving occurred on the right hand side of the road), while drivers were at the furthest point from the centerline for left curves at the beginning of the curve. The study also identified that distraction had an influence on lane position when driving through curves, with drivers shifting from the centre of the lane when distracted.

Spacek (2005) suggested that attempts to understand the relationship between driver behaviour, the road environment and crashes often fail if they are based only on speed and that an understanding of lane position (or 'track behaviour') is also required. Two types of lane position behaviours were described. 'Normal' behaviour was where drivers kept to the centre of the lane (as is assumed in most road design guides), while 'extreme' behaviour was where drivers deviated strongly from this position. Spacek suggested that this extreme behaviour can happen consciously, as when drivers cut the corner to reduce side force. It can also happen unconsciously, as when the driver underestimates the curvature. Corrections within the curve may lead to increases in side force, and therefore decreases in surface friction.

Spacek collected data using an array of 12 'measuring posts'. These were camouflaged as regular edge marker posts, but using infrared were able to detect vehicle speed and position. Data was collected at eight curves, with curve radii of between 65 and 220 m. Based on earlier work conducted by AGVS (1980, cited in Spacek, 2005), six curve driving behaviours were defined as shown in Figure 2.9 (note that driving was undertaken on the right hand side of the road). The collected data was analysed to determine lane position based on these categories.

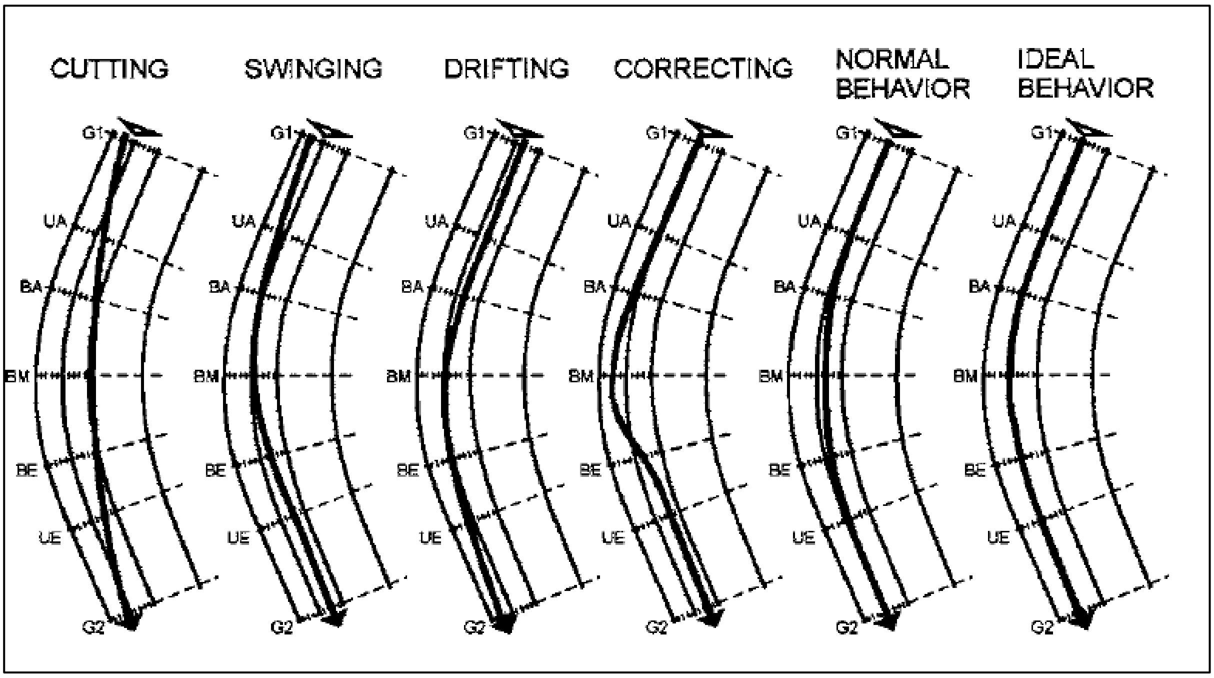

Figure 2.9: Six categories of driving style (from Spacek, 2005)

Findings from the evaluation included that drivers generally maintained a position that is further from the edgeline than from the centreline. For left curves, drivers tracked closer to the centreline than for right curves. For right curves, they tended to track closer to the centre of the lane.

Tracking behaviour varied substantially by curve. Each of the track types identified in the figure above were seen in one or more of the curves. Ideal behaviour was seldom seen, while 'normal' behaviour and 'cutting' were the most common.

The highest vehicle speeds were seen for cutting for left hand curves, and 'swinging' (see Figure 2.9) for right hand curves. Spacek stated that although these behaviours were assumed to be used in an attempt to minimise side force, these tracking behaviours were still associated with the highest levels of side force. A number of cases were identified where these two behaviours were aborted part way through the curve (e.g. if there was an oncoming vehicle). This resulted in corrective actions that produced high levels of side force.

An analysis including different design elements indicated that normal and ideal tracking behaviours were most common when the following factors were present simultaneously:

- curve radius between 120 and 230 m (the maximum curve radius in this study)
- clothoid parameters between approximately 0.33 and 0.5 R
- circular arc lengths equating to at least 5 s pass-through time

- lane width of between around 3.4 to 3.5 m at the centre of the curve.

Spacek's conclusion that speed alone is not adequate to describe driver safety through curves is worthy of further exploration. Measures relating to lane position should be explored in further detail. Information on this and other elements of driver behaviour (including speed) might help explain risk through curves.

Fitzsimmons et al. (2013) analysed speed and lane position at two curves (one rural and one urban) using pneumatic tubes in a 'Z' configuration. Drivers showed lane cutting behaviour for the rural curve in both left and right directions, and the authors suggested that this allowed drivers to maintain a higher speed through curves. It was also found that more vehicles adjusted their speeds around the centre of the curve, while the greatest amount of adjustment for lane position occurred just after the middle of the curve.

2.6.3 Summary

Research on lane position at curves has consistently shown that drivers tend to cut the curve, most likely in an attempt to maintain higher speeds through curves. The response differs by curve direction. There appear to be several different categories of lane position through curves, and these can result in substantially different side forces, and hence surface friction. A key conclusion is that there is little information on the optimum lane position for curves of different risk. In addition there is a lack of information on the linkage between speed and lane position, and the combined effect that this has on crash outcomes. Similarly, there is very little information on lane position for different groups of drivers, and no research was identified that examined differences between inexperienced and experienced drivers. These issues appear to be worthy of further exploration.

2.7 Responses to the curve crash problem

There is an extensive amount of research on the approaches that may be used to improve safety at rural curves. These include responses relating to changes to the road design or environment; vehicle-based interventions; and road user measures, including enforcement, education, training and publicity. A review of these might highlight the mechanisms by which these work (for instance through speed reduction or more appropriate lane position) and how effective these mechanisms are. A full review can be found in Appendix A, while a summary is provided below.

In terms of the engineering based solutions, options include:

- advanced warning signs

- chevron alignment markers
- speed advisory signs
- vehicle activated signs
- other delineation devices (e.g. line marking, guide posts)
- transverse rumble strips
- perceptual countermeasures
- route based curve treatments.

These tend to operate by informing motorists of the presence and severity of a curve with the objective of ensuring that motorists select a speed that is appropriate for that curve. It is interesting to note that with the exception of line marking, none of the interventions act to inform motorists of the most appropriate lane position through curves.

Vehicle factors also play a role in crash occurrence at curves, and so changes to vehicles can also act to reduce severe crash outcomes. Issues such as tyre tread depth, provision of electronic stability control (ESC), braking performance, road departure warning systems, vehicle handling and stability may all play a part in the likelihood of vehicles losing control at curves. Vehicle features also play a key role in the severity of crashes when they do occur, with airbags, seatbelts and other safety features all likely to reduce the severity of injuries sustained. Some of these technologies act without the knowledge of drivers to help improve safety (such as ESC), while others provide active guidance to inform motorists (such as lane departure systems or in-vehicle curve warning systems). Future systems may take more active control of vehicles to reduce or present crash occurrence.

Enforcement by police is often used as a mechanism to ensure safe vehicle speeds, and this may have some impact on the safety of drivers through rural curves. When coupled with effective education and training programs, this can have a positive benefit on crash occurrence and outcomes. There appears to be great potential in combining these approaches to improve safety outcomes, including at curves.

One thing that is clear is that despite considerable research, and widespread use of these different approaches over a number of decades, the safety problem at rural curves remains a serious issue. New solutions, whether these be based on the road environment, vehicle or road user (or a combination of each) will be required to address this significant safety issues. As previously discussed, much research has concentrated on speed at curves in isolation. It may be that a better understanding of speed and lane position in combination will provide a better understanding of behaviour and risk at curves, and that this may in turn lead to more targeted solutions.

2.8 Summary and gaps in knowledge

2.8.1 Summary

Curves on rural roads have an elevated level of crash risk compared with other road environments producing a substantial number of crashes. Crash types at curves include vehicles running off the road, rollover, or drifting into oncoming lanes resulting in head-on collisions. Young and inexperienced drivers are involved in a disproportionate number of road deaths and injuries and have crash rates of around three times greater than experienced drivers at rural curves. Speed and lane keeping errors have both been identified as issues for this group.

A review of the approach used in curve design identified that side force and surface friction are at the core of curve design philosophy, and that these factors are influenced by vehicle speed, superelevation and curve radius. It was also identified through the literature review that there are a number of important assumptions used in the design of curves relating to these variables. Vehicles exceeding certain thresholds for side force will drift from their lane, lose control or rollover. Curve superelevation and design radius are out of the influence of vehicle operators as they negotiate curves. However, speed is controlled by road users. In addition, the radius of a vehicle through a curve can be adjusted by the lane position adopted.

Excessive speed has been identified as a key contributor to rural crashes, with more than half of all curve crashes attributed to this cause (Hallmark and McDonald, 2007). There is an extensive amount of research indicating this link between speed and safety outcomes, including at curves. There is also very clear evidence about elements that influence driver selection of speed through curves. There is also consistent evidence indicating that risk at curves is directly related to the approach speed prior to the curve, and the minimum speed required to negotiate that curve. Where the difference in these two speeds is high, crash risk also tends to be high. This metric has been used for classifying high and low risk curves in a number of studies (Bonneson et al., 2007; Cardoso, 2005; Fitzpatrick et al., 2000; Herrstedt & Greibe, 2001; Krammes et al., 1995; Montella et al., 2014; Pratt & Bonneson, 2008) and appears to be a robust method for classification of curve risk.

Less clear is the influence of lane position on safety outcomes at curves, or lane position and speed in combination. It is clear that there are different lane position driving strategies through curves, and these may be used by drivers to reduce side force when negotiating curves.

Solutions used by road engineers to address safety at curves have focused largely on methods to reduce speeds on approach or through curves. Very little information was identified on methods to provide better guidance regarding the appropriate lane position (with line marking being the exception).

Despite a large amount of research on the topic of crash risk at curves, the problem still continues as a serious one. It appears that a better understanding of issues relating to curve design and crash risk might help identify more effective solutions for managing risk at these locations.

2.8.2 Gaps in knowledge

Despite extensive research on these topics, a large number of gaps in knowledge were identified in the review of the literature. It is not possible to explore all of these gaps in this thesis, so an assessment was made of gaps relating to curve design elements and crash risk.

A clear gap in knowledge identified by several studies (e.g. Hallmark et al. 2013; Spacek 2005), is that speed has often been analysed in isolation in relation to curve risk. Based on the review of literature, key design elements that can be varied by road users at curves include speed (which includes acceleration and deceleration) and lane position. Both of these factors are closely linked to curve risk through their influence on side force. It appears that these issues have not been analysed in combination previously.

Despite an understanding of factors that contribute to curve risk, there appears to be little previous research that assesses and contrasts the key elements identified above (speed, side force and lane position) in relation to this risk. More specifically, there appears to be little research that compares curves of different risk (e.g. high risk and low risk) on these metrics.

In addition, the evidence is clear that there are different risk outcomes for inexperienced and experienced drivers. Although there is some research on risk for inexperienced drivers, there is a gap in knowledge around differences in the key elements (speed, side force and lane position) in regard to these different driver groups. In addition, there is little information on the key elements for these driver groups at curves with different risk (e.g. high and low risk curves).

Much of the previous research has relied on detailed study of a small number of curves to examine elements such as speed or lane position, or limited data collection for a larger number of curves. These methods have left gaps in knowledge relating to the issues of interest (speed and lane position), and assumptions in road design relating to these issues appear to remain relatively untested. New research methodologies now allow more thorough analysis of driver behaviour through curves.

Based on these gaps in knowledge, key research questions are provided in the following section while the methodology used to assess these is described in the following chapter.

2.9 Key research questions and hypotheses

The broad assertion presented in Chapter 1 is that an assessment of speed in combination with other factors at curves will provide a more comprehensive understanding of driver behaviour at curves. This may in turn lead to a better understanding of risks and therefore possible solutions for improving safety at these locations.

Based on the literature review a number of gaps in knowledge were identified as discussed in Section 2.8. It is clear that there is a lack of knowledge regarding the key curve design factors in combination. Some of these factors are 'set' at the time curves are designed and constructed (curve radius and superelevation), but others are dynamic in that road users can adjust these on approach and through curves. Dynamic factors include speed and side force, while vehicle radius can be adjusted by vehicle lane position. The research seeks to address these gaps by analysing driver speed, side force and lane position through different types of curves. Longitudinal acceleration and deceleration (both a function of speed) are also important elements to be assessed. Lane position in terms of distance to edge of lane, and lane crossing behaviour are of interest.

A closer examination of these factors provides the broad framework for the experimental phase of this research. Specific research questions and hypotheses relating to these are provided below.

2.9.1 Research question 1: Differences between high risk and low risk curves

There is a gap in knowledge regarding differences in the dynamic curve design factors at high and low risk curves. Comparing the behaviour of drivers through high risk curves and low risk curves should help identify elements that could be linked to risk. This research question generates the following hypotheses.

Hypothesis 1a:

H_o: there will be no difference in driver speeds through high risk curves compared to low risk curves.

H_A: driver speeds will be different through high risk curves compared to low risk curves.

Hypothesis 1b:

H_o: there will be no difference in longitudinal acceleration and deceleration through high risk curves compared to low risk curves.

H_A: longitudinal acceleration and deceleration will be different through high risk curves compared to low risk curves.

Hypothesis 1c:

H_o: there will be no difference in side force through high risk curves compared to low risk curves.

H_A: Side force will be different through high risk curves compared to low risk curves.

Hypothesis 1d:

H_o: there will be no difference in lane position through high risk curves compared to low risk curves.

H_A: lane position will be different through high risk curves compared to low risk curves.

2.9.2 Research question 2: Differences between inexperienced and experienced drivers

The second research question relates to differences in driver outcomes related to the curve design variables comparing two groups of drivers – those who are inexperienced and those who are experienced. It is clear from the evidence base that inexperienced drivers have higher risk through rural curves, and so comparing behaviours of these drivers with more experienced drivers might identify key issues that contribute to risk. This research question generates the following hypotheses.

Hypothesis 2a:

H_o: there will be no difference in speed through curves for inexperienced drivers compared to experienced drivers.

H_A: speed will be different through curves for inexperienced drivers compared to experienced drivers.

Hypothesis 2b:

H_o: there will be no difference in longitudinal acceleration and deceleration through curves for inexperienced drivers compared to experienced drivers.

H_A: longitudinal acceleration and deceleration will be different through curves for inexperienced drivers compared to experienced drivers.

Hypothesis 2c:

H_o: there will be no difference in side force through curves for inexperienced drivers compared to experienced drivers.

H_A: side force will be different through curves for inexperienced drivers compared to experienced drivers.

Hypothesis 2d:

H_o: there will be no difference in lane position through curves for inexperienced drivers compared to experienced drivers.

H_A: lane position will be different through curves for inexperienced drivers compared to experienced drivers.

2.9.3 Research question 3: Differences between inexperienced and experienced drivers through high and low risk curves

The third research question relates to whether there are differences in the behaviours of different driver groups (inexperienced and experienced) for high and low risk curves. Based on the findings from the literature review, it is hypothesised that the greatest differences in the key design factors between inexperienced and experienced drivers would occur at the high risk curves. This research question generates the following hypotheses.

Hypothesis 3a:

H_o: there will be no difference in speed through high risk curves for inexperienced drivers compared to experienced drivers.

H_A: speed will be different for drivers through high risk curves for inexperienced drivers compared to experienced drivers.

Hypothesis 3b:

H_o: there will be no difference in longitudinal acceleration and deceleration through high risk curves for inexperienced drivers compared to experienced drivers.

H_A: longitudinal acceleration and deceleration will be different through high risk curves for inexperienced drivers compared to experienced drivers.

Hypothesis 3c:

H_o: there will be no difference in side force through high risk curves for inexperienced drivers compared to experienced drivers.

H_A: side force will be different through high risk curves for inexperienced drivers compared to experienced drivers.

Hypothesis 3d:

H_o: there will be no difference in lane position for high risk curves for inexperienced drivers compared to experienced drivers.

H_A: lane position will be different through high risk curves for inexperienced drivers compared to experienced drivers.

2.9.4 Research question 4: Curve design assumptions

The final research question relates to the assumptions used in curve design. Previous methodologies have not allowed collection of comprehensive data that allows testing of some of the assumptions relating to road design and driver behaviour through curves. Given the importance of these assumptions on safety outcomes at curves, where possible it would be useful to determine whether assumptions relating to factors such as vehicle deceleration, side force and lane position are accurate. Given the need to collect data on these factors, where possible it would be useful to test the assumptions used in curve design. This research question generates the following hypothesis.

Hypothesis 4:

H_o: the assumptions used in curve design reflecting deceleration, side force and lane position behaviours are valid.

H_A: the assumptions used in curve design reflecting deceleration, side force and lane position behaviours are not valid.

3 METHOD

3.1 Introduction

This chapter provides information on the method adopted in this study. The key hypothesis of this thesis is that better knowledge of speed and lane position in combination will provide a better understanding of driver risk at curves. The study involved the collection of data on these key driver behaviours and outcomes through curves on a predetermined route using both experienced and inexperienced drivers. The behaviours of interest included driver speed, acceleration/deceleration (which are a derivative of speed) and lane position. Both of these elements are related to side force.

The approach involved testing of multiple drivers through a number of high and low risk curves. The literature review identified that curve risk could be determined based on approach speed to curves and minimum speed through curves. The review also identified that inexperienced drivers had a much greater level of risk through curves, and it is suggested that a comparison of the key behaviours for this group when compared to experienced drivers might provide greater insights into risk factors at curves, especially when examining high risk curves.

The chapter includes information on the experimental design, including:

- options for data collection
- factors influencing route selection
- sample design
- planned statistical analysis.

Information is also provided on:

- the selected route
- the curves that were included in the study
- subjects
- equipment used
- testing procedure
- data extraction process.

3.2 Experimental design

3.2.1 Different methods for assessing behaviour at curves

It is apparent from the review presented in Chapter 2 that there are a variety of methods that have been used in assessing behaviour of road users through curves. Different methods that may be used to address the key research questions and hypotheses are addressed in this section.

The approaches used in previous research varied, usually depending on the focus of the study (i.e. the type of behaviour being assessed), but they typically involved one or more of the following data collection methods:

- roadside assessment
- car following studies
- simulator study
- instrumented vehicle
- naturalistic driving behaviour.

Roadside assessment

Collection of speed data based on roadside assessment has been undertaken for many decades. Austroads (2009c) suggested that the passage of time between two points a measured distance apart can be easily recorded, and that high levels of accuracy are attainable. The simplest technique involves manually calculating speed through use of a stopwatch. Options include the use of painted markings at the start and finish point of a measured distance, or the use of an Enoscope (also referred to as a ‘flash box’, this is an ‘L’-shaped box, with mirrors configured at a 45° angle. Boxes are placed at the start and finish point of a measured length of road. An observer is positioned between these, and is able to determine when a vehicle crosses from the ‘flash’ of colour seen in the Enoscope). A stopwatch is used to measure the time taken to travel between the two points, and given the distance is known, the average speed can be calculated. Similarly, observers with walkie-talkie radios have been used to record travel time over a set distance (e.g. Sinclair & Knight Consulting, 1972).

In more recent times, technology has evolved, and collection devices have replaced the stopwatch. Pairs of sensors are often placed on the roadway a measured distance apart. Sensors are most commonly pneumatic tubes (for temporary sites) or inductive loops embedded in the road (for long term collection). However, other sensors can be used, and recently the use of infrared detectors (either at temporary or permanent sites) has become more common (for example The Infrared Traffic Logger or 'TIRTL' system, developed in Australia). Austroads (2007) reports on technology that uses changes in the earth's magnetic field due to the passage of a vehicle to detect vehicles.

Collection devices are able to determine the speed of individual vehicles given the distance between the sensors (whether these be tubes or infrared beams). Many of these devices are able to store this information for later retrieval and analysis. However, some devices are still operated manually, and this might involve the recording of speeds on a data collection sheet for later data input and analysis.

In addition to speed data, information such as traffic volumes and type of vehicle can also be collected by some of these devices (the latter based on axle configuration). As described in Section 2.6, detectors placed in a 'Z' configuration are able to determine the lane position of vehicles.

Radar and lasers have more recently been used to collect speed data with high degrees of accuracy (Austroads, 2009c).

With the advent of video technology, a number of studies have used concealed cameras to record information on speed and behaviour. The video data is assessed following collection to determine the target behaviours (including speed and lane position). The camera can be placed on the roadside, or used from a height above the roadway (e.g. Skutil & Orlowska 1982 used aerial photography, while Yashiro & Kotani 1986 used a kiteballoon). Often markings are temporarily placed on the road to allow some form of calibration (e.g. for speed or lane position), and then removed from the road for data collection.

Austroads (2009c) reported that extraction of information from video recording was time consuming, and therefore tedious and expensive. Software has been used to analyse data in an automated manner to determine behaviours (e.g. Weise et al., 1997), taking away much of the processing time required.

Due to the fixed nature of devices used for roadside data collection, most studies utilising laser, radar or video involve only a small number of sites. Manual analysis of video data is also very time consuming if this is required (e.g. accurate measurement of lane position). There are also concerns expressed by some (Austroads, 2009c) that drivers may become aware of such detection devices, and alter their behaviour, perhaps assuming that these are for enforcement purposes. In addition, it is difficult to obtain information about individual drivers within vehicles (such as driver age or experience) using roadside collection methods. Lastly, it is difficult to track the behaviour of an individual driver through a series of curves when using this method.

Car following studies

Car following studies have also been undertaken in order to collect data on speed and lane position (e.g. Glennon & Weaver, 1971; cited in Fitzsimmons et al., 2013). A test vehicle follows a randomly selected vehicle as it travels through a curve or series of curves. The actions of the test vehicles are captured on video for later interrogation.

The car following method shares some of the issues with roadside data collection. Although it is possible to collect data for a larger number of sites, the manual analysis of data can be very time consuming where this is required (e.g. for lane position). It can also be difficult to obtain information about individual drivers (e.g. age or driving experience).

Simulator studies

Driving simulators have been used to assess all manner of issues relating to driver behaviour. Several conferences and special editions of journals have been dedicated to this topic. In one such special edition, Allen et al. (2011) introduced papers on the use of simulators to explore driver fatigue, use of touch pad technologies in vehicles, assessment of rumble strips to reduce lane departures, motorcycle rider behaviour, and driver behaviour in response to advanced driver assistance technologies.

Simulators offer a controlled environment where one or more variables can be systematically varied to determine the influence on driver behaviour while holding other factors constant. This can be achieved within a safe environment (i.e. subjects are not exposed to normal driving risks). Given this safe environment, driving simulators are a key method when it comes to assessing dangerous driving behaviour, including issues such as use of alcohol and other drugs, fatigue or distraction (Helman & Reed, 2015).

A further advantage of simulators is that a large number of curves can be assessed in a short period of time and a large amount of data can be collected. The order in which curves are presented to drivers can be randomised, thereby reducing any learning effect.

A criticism of simulators is that subjects will be aware that they are not driving in a real traffic situation, and so their behaviour will differ from real-world driving. To address this issue a number of studies have assessed the validity of simulation for research for a variety of driver behaviours including speed. Much of the discussion on validity for speed research differentiates between relative validity and absolute validity. Relative validity refers to the order or rank of observations. With appropriate relative validity it is assumed that one condition will result in a higher speed outcome in the simulator just as it will in real life. With absolute validity, the order plus the extent of the difference will be the same in the simulator as in real life. It appears that although relative validity is easy to achieve with simulators, there is less reliability for absolute validity when it comes to speed. Godley, Triggs & Fildes (2002) found low reliability for absolute speed, while Bella (2009) found mixed results, including for curve entry speeds. Access to reliable simulators can also be a barrier to use of this method.

Instrumented vehicles

An instrumented vehicle is one that is fitted with a variety of sensors, and some form of data logger to record this information. With improvements in technology, a wider variety of information is now able to be collected and with a greater degree of accuracy. Imberger (2009) reviewed in-vehicle technology available at that time, identifying the following elements that could be obtained or measured:

- vehicle location
- position in lane
- acceleration, braking and cornering
- fuel consumption, emissions, axle load
- speed
- distance to vehicle in front
- use of vehicle indicators, brake pedal, accelerator pedal, clutch, seatbelt, tyre pressure etc.
- engine RPM
- steering wheel angle
- speech and movement of driver (through video)
- eye movement
- events outside the vehicle.

The simplest equipment includes a GPS unit and data logger. Using this equipment, accurate collection of data on speed is possible for journeys across road networks. Additional sensors can also be used to gather data, with increasing levels of sophistication. Global Positioning Systems (GPS) have been increasingly recognised as a useful tool in traffic surveys from the early 1990s (e.g. Zito 1993). The technology has been used for a range of traffic studies, including for journey time and travel time surveys (Clark & McKimm 2003; Zito & Taylor 1994), the effects of a congestion charge (Jun et al. 2006) and road traffic noise mapping (Asensio et al. 2009). The technology has also been used for road safety related research (e.g. Levison & Kantowitz 2000; Turner & Tate 2009; both of whom assessed the impact of road geometry on driver choice of speed using this technology).

GPS technology is becoming increasingly common for the collection of speed data and may become a leading method for such collection into the future. This could be particularly so with the rapid uptake of GPS enabled mobile phone technology (see e.g. Levick 2010).

Instrumented vehicles have been used by several researchers for collection of information on driver speed (e.g. Levison & Kantowitz 2000; Turner & Tate 2009). Obvious limitations include that subjects are often required to drive an unfamiliar vehicle, and that they are aware that their behaviour is being monitored.

Naturalistic driving studies

The most sophisticated method for collection of information on driver behaviour is a naturalistic driving study, or NDS (e.g. Hallmark et al., 2014). This involves equipping the subject's own vehicle (or a 'loan' vehicle provided on a long-term basis) with the instrumentation required (similar to that described for an instrumented vehicle). The benefit of the approach is that drivers over time will be expected to drive naturally, as they normally would in their vehicle had it not been equipped with instrumentation. Data is then uploaded from each vehicle for future analysis. With enough subjects and exposure (i.e. driving time) high risk events (including crashes at curves) will be recorded, and data made available on the contributing factors.

Although a sophisticated method for the collection of information on driver behaviour, a naturalistic study requires a large number of drivers and a long period of time in order to collect an adequate amount of data for useful analysis. This typically results in high costs. Management and analysis of the collected data is also a significant logistical issue, as a huge amount of information is generated.

Summary

There are a wide variety of methods available for the collection of information on driver speed and lane position behaviour through curves, all of which have been shown to be effective research tools. The use of a naturalistic study methodology would appear to be the most robust approach. If enough data were available, it would be possible to extract situations where drivers lost control of their vehicle through a curve, and to analyse relevant information related to this event. This would allow assessment of relevant driver variables, including those related to driver age and experience and normal driving behaviour, as well as those leading up to the event. It would also be possible to determine road design elements at each location that might be related to the crash (these variables have already been collected for large parts of the road network as part of the US NDS). Similarly, it would be possible to determine vehicle-related factors. The high cost of this type of study limited the ability to use this as a methodology for this current research. In addition, the data from NDS research was not available for analysis.

The use of a driving simulator would also offer a good opportunity to collect a large amount of relevant data. However, there is doubt about the robustness of absolute measures of speed which would be required for a study of driver behaviour through curves. In addition, no validation studies could be found that provided a robust assessment calibrating lane position in a simulator to real-world driving. Similarly, it is unclear whether the experience of side force, which was considered an important measure in this study, has been validated in a simulator compared to reality.

Because a large amount of information was required for a large number of curves, an instrumented vehicle was identified as the most practical option. Recent research has tended towards this methodology. As with any methodology there are some limitations to this approach. The key disadvantages include lack of driver familiarity with the vehicle and the impact of being part of an experiment. These disadvantages can be partly overcome by providing a period of time for familiarisation before data collection begins. These limitations are discussed in further detail in Section 5.3. This approach is preferable to roadside surveys, which are typically used at only a few locations and allow collection of data at a limited number of points. Recent advances mean that on-board instrumentation can collect data on a larger number of variables at a higher resolution (i.e. more data points for each curve) than is possible with roadside surveys.

3.2.2 Factors influencing route choice

Route conditions that were of importance for this experiment were identified to help identify a suitable test route. The selected route needed to be of sufficient length to allow for familiarisation with the vehicle and the experimental set up, and to collect the required data. Other key factors were that the test route needed to:

- include a high speed environment with high risk and low risk curves
- be easy to negotiate so that subjects could easily follow the route without deviating or getting lost

- have low traffic volumes so that other vehicles had minimal influence on subjects.

As already discussed, high risk curves are defined (based on the literature review) as those that require a large reduction in speed on approach and through curves. The route that was eventually selected met these criteria, and is described in Section 3.3.

3.2.3 Sample design

The study design required testing of differences in behaviours and outcomes (speed, acceleration/deceleration, side force and lane position) between high and low risk curves; and between inexperienced and experienced drivers. Curve risk was determined using the difference in approach speed and the minimum speed through the curve based on previous research (Bonneson et al., 2007; Cardoso, 2005; Fitzpatrick et al., 2000; Herrstedt & Greibe, 2001; Krammes et al., 1995; Montella et al., 2014; Pratt & Bonneson, 2008) and as discussed in Section 2.4.2.

Inexperienced drivers were classified as those with less than three years driving experience, while experienced drivers were those with greater than 15 years driving experience. The inexperienced driver group was selected based on the work of Catchpole & Edgar (1999) who identified an elevated level of risk, including risk at curves for this group.

The minimum sample size for both subjects and curves was selected based on previous examples of research that achieved statistically significant results (e.g. Levison & Kantowitz 2000; Turner & Tate 2009). A power analysis was also conducted, although given the lack of research on differences in means and standard deviations between groups of curves and drivers, this was based on assumptions.

It was assumed that differences between groups of drivers (i.e. inexperienced and experienced) would be smaller than differences between groups of curves (i.e. high and low risk), and so this more conservative variable was used to calculate the minimum sample size. It was assumed that the difference in mean speeds between driver groups would be 2 km/h, and that the standard deviation would also be 2 km/h. It was calculated that around 15 drivers would be required in each group (with the assumption of 80% power and a 95% level of significance). This calculation accorded well with the sample size used in previous research of this type.

As described in the literature review, speed and lane position behaviour are dynamic, and subject to change through different parts of a curve. In order to allow a meaningful analysis, curves needed to be categorised into different segments. Based on the literature review, and particularly the work by Campbell et al. (2008) the following parts of curves were defined:

- data for the 40 m prior to curve commencement was classed as the 'approach' (based on the finding by Lee, 1988 that identified speed reduction occurred in the zone lying 20 to 30 m prior to the curve)
- the point at which the radius fell below 1000 m was the 'start'
- the segment between the start (where the radius fell below 1000 m) and point of curve minimum (or curve mid-point) was the 'to minimum'
- the point of minimum radius was 'minimum'
- the segment between the minimum and curve end (but excluding both of these points) was the 'departure'
- the point at which the curve finished (i.e. the final point before the curve radius exceeded 1000 m or the curve direction changed) was the curve 'end'.

A large number of curves were available on the test route (101 in each direction, or 202 in total). A selection process was used to determine the 20 highest risk curves, and 20 low risk curves. This process is described in Section 3.4.

3.2.4 Planned statistical analysis

Statistical analyses were conducted for each of the hypotheses. These tests compared driver behaviour for high and low risk curves and for inexperienced and experienced drivers. The tests were performed to determine whether differences were significant (i.e. due to more than just chance). Differences between groups were expected to provide useful information on behaviours and risks associated with driving through curves.

The more conservative two sided t-tests were applied comparing group outcomes for each of the research questions. This is because in many cases, the direction of relationships could not be predicted based on previous research and existing theory. The analysis was conducted using IBM SPSS Statistics v22. The equation for the two sided t-test is as shown in Equation 4.

$$t_{statistic} = \frac{(\bar{X}_1 - \bar{X}_2)}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \qquad 4$$

where

$\bar{X}_1$ = mean speed in before period

$\bar{X}_2$ = mean speed in after period

S_1^2 = variance in speed in before period

S_2^2 = variance in speed in after period

n_1 = sample size in the before period

n_2 = sample size in the after period

Because of the large number of groups in some of the tests, tests were adjusted for all pairwise comparisons using the Bonferroni correction. The formula for this is shown in Equation 5.

$$\alpha' = 1 - (1 - a)^k \qquad \textbf{5}$$

Where

a = critical P value

k = number of tests

Results are presented where the significance level is less than 0.05 (p<.05).

3.3 Description of route

The Mt Dandenong Tourist Road in Melbourne’s outer eastern suburbs was selected as the test location. The location of this route relative to the Melbourne CBD is provided in Figure 3.1.

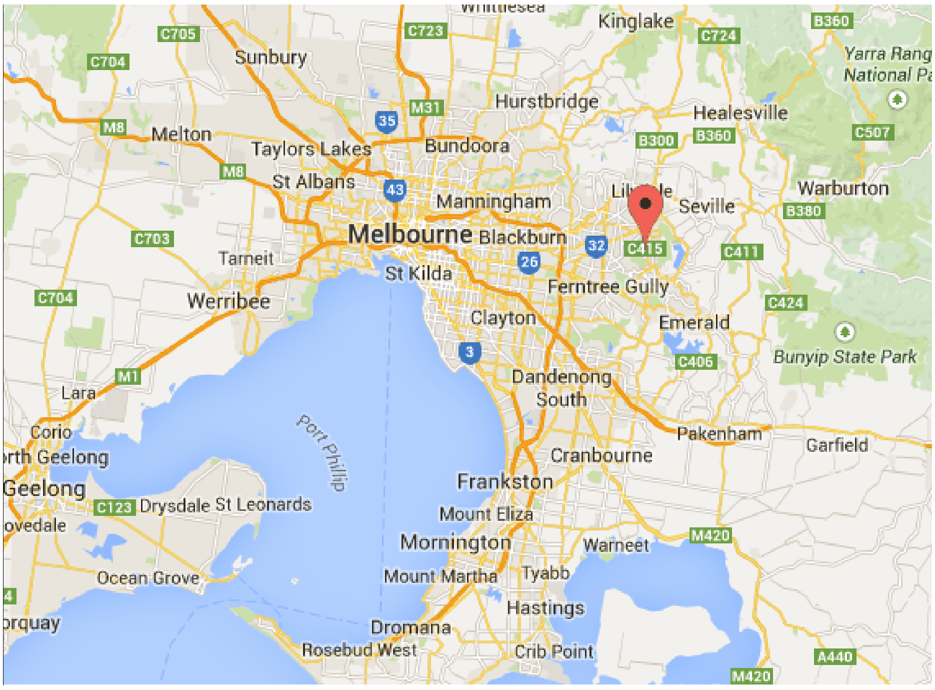

Figure 3.1: **Route location relative to CBD (from Google Maps)**

Subjects commenced their journey at ARRB's offices and travelled for approximately 13 km along an urban arterial road to the start of the test route. Journey time to the start of the route was generally between 16 to 18 minutes. The test route itself was 22 km in each direction, taking approximately 30 minutes, or around an hour in total. The journey to the start of the route, route negotiation, and return to the office took a total of around 1 hour and 35 minutes. The test route was easy to follow as it was all on one road. Subjects could easily negotiate a roundabout at the end of the route, and follow the same road to return to the office. The whole route is shown in Figure 3.2.

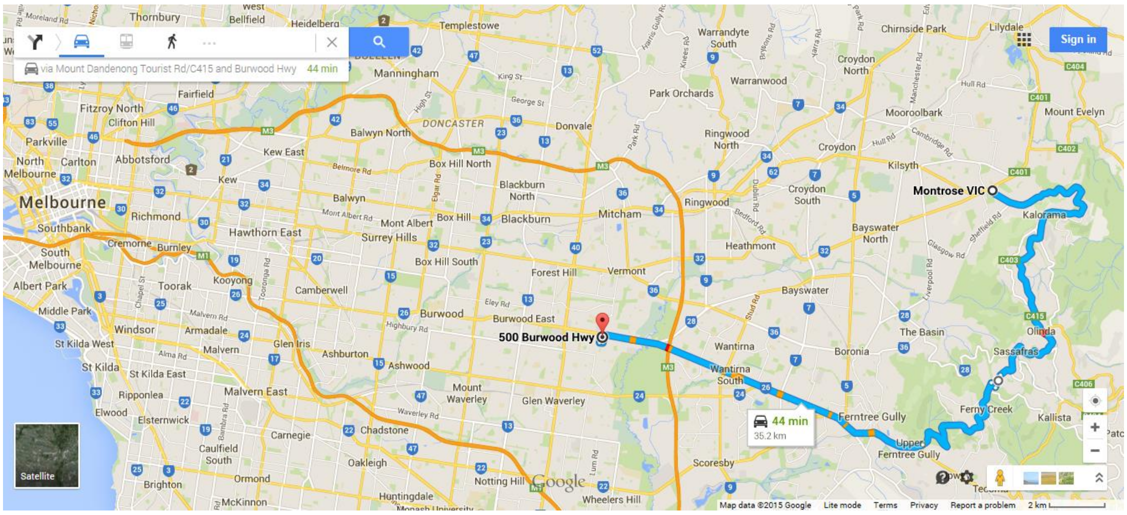

Figure 3.2: **Map of route (data recorded in both directions; from Google Maps)**

The test route (i.e. excluding the urban arterial portion) is shown in Figure 3.3.

Figure 3.3: Experimental section of route (data collected in both directions; from Google Maps)

The test route was hilly, and involved a mixture of speed environments. In some locations it passed through small townships, while in others it was quite rural. Given the mixed nature of development along the route, the speed limit varied between 60 km/h and 80 km/h. Only the higher speed portions of the route were included in the data analysis.

The route was a 'C' class road (the C145) managed by the state road authority (VicRoads). According to VicRoads (2015) C roads in Victoria generally indicate that the roadway has two sealed lanes (one is each direction) and has shoulders. Such roads provide a link between population centres and also link these population centres with the primary transport network.

The C145 has two sealed lanes in each direction, with limited extent of sealed shoulder. A sealed shoulder is sometimes provided at higher risk locations, such as the inside of left hand curves.

The entire route was marked with edge and centrelines, although in several locations this was faded. The lane widths were around 3.5 m, typical of a route of this type. There are numerous roadside hazards, including trees and utility poles. The route is popular with cyclists and motorcyclists. A typical image from the route is shown in Figure 3.4.

Figure 3.4: Typical environment from experimental route

The route has had various safety improvements, including provision of lower speed limits, edgelines, guideposts, curve warning signs, chevrons and advisory speed signs at many curves, intersection warning signs, shoulder sealing and roadside barriers (including motorcycle barriers). Safety improvements have been implemented in an inconsistent manner (i.e. curves with similar risk profiles have been treated in different ways). However, the route is typical of many rural areas.

There were a large number of curves along the route, some of which were severe with high speed approaches. There were 101 curves for each direction of travel, giving a total of 202 curves over the whole route. The start of a curve was defined as the point on the road where the curve radius fell below 1000 m, or where the curve changed direction (from a left curve to a right curve; or from a right to a left curve) when the radius was already below 1000 m. The end of a curve was defined as the point at which the curve radius increased above 1000 m, or where it changed direction. A radius of 1000 m was selected as current Australian road design guidance (Austroads, 2010) suggested that larger radius curves may be considered as straights (i.e. curve radius no longer influences speed), with guidance only provided up to this radius.

There was a reasonably low level of traffic on the route, particularly in off-peak periods. According to VicRoads (2014) the average annual daily traffic (AADT) on the route was around 1600 vehicles in the centre of the route, but higher at the southern end (around 3000) and northern end (around 4500). Around 5% of traffic was comprised of commercial vehicles.

3.4 Curve selection

The experiment called for a comparison between driving behaviours and outcomes at low risk curves and high risk curves. Based on the review of literature relating to curve risk (see Section 2.4.2), and consistent with current road design guidance (Austroads, 2010) curve risk was defined as the difference between the approach speed and the minimum speed within the curve. Both values were calculated based on design speed as described in Section 2.3.2. Consistent with this research, the approach speed was based on the mean speed over the preceding 500 m approaching the curve. The minimum speed within the curve was simply the lowest speed point through the curve. There were concerns that given this route had a high number of curves, the 500 m definition for approach might produce some lower speeds and therefore lower differences in speeds between approach and curve minimum. A shorter approach was also tested (200 m) but found to produce similar risk profiles for curves as the 500 m approach. The 500 m definition based on previous literature was therefore retained.

Risks were calculated for all curves, and the 20 highest risk curves selected. Twenty of the lowest risk curves were also selected. Note that some of lowest risk curves were excluded due to issues including being in a lower speed limit environment. Roughly half of each were curves in the northbound direction (nine high risk and 10 low risk) while the others were southbound (i.e. on the return journey; 11 high risk and 10 low risk). Information on geometric characteristics including design speed for each of the high risk curves can be found in Table 3.1.

Table 3.1: Details for high risk curves

Direction of travel	Curve #	Curve length	Minimum radius	Curve direction	Minimum curve speed*	Mean speed prior*	Speed difference
NBD	4	160	44	Right	39.4	81.57	42.17
NBD	10	90	17	Left	27.6	99.05	71.45
NBD	13	240	78	Right	51.5	108.36	56.86
NBD	16	300	67	Left	49.6	90.75	41.15
NBD	18	370	50	Left	43.8	85.65	41.85
NBD	29	240	75	Right	52.75	119.24	66.49
NBD	30	190	63	Left	50.47	101.55	51.08
NBD	34	190	46	Right	42.54	106.98	64.44
NBD	35	160	73	Left	52.42	91.71	39.29
NBD	81	190	77	Left	55.26	94.83	39.57
NBD	84	320	62	Right	46.92	85.19	38.27
SBD	98	160	41	Left	39.14	97.79	58.65
SBD	92	130	21	Right	28.93	102.59	73.66
SBD	89	230	80	Left	54.49	111.35	56.86
SBD	79	280	62	Left	48.78	90.53	41.75
SBD	72	200	62	Right	47.73	95.05	47.32
SBD	59	230	89	Right	54.02	105.73	51.71
SBD	33	190	56	Right	45.03	101.49	56.46
SBD	7	100	63	Left	51.09	107.92	56.83
SBD	6	110	93	Right	56.09	114.51	58.42
	Mean	204	60.95		46.878	99.59	52.71

* These figures are based on design speed (see Section 2.3) and not measured speed

Details on the low risk curves can be found in Table 3.2.

Table 3.2: Details for low risk curves

Direction of travel	Curve #	Curve length	Minimum radius	Curve direction	Minimum curve speed*	Mean speed prior*	Speed difference#
NBD	24	260	167	Left	71.15	73.16	2.01
NBD	26	100	260	Left	82.73	91.16	8.43
NBD	36	90	208	Right	74.8	79.39	4.59
NBD	42	140	133	Right	63.37	65.58	2.21
NBD	44	90	303	Left	86.29	81.91	-4.38
NBD	49	80	272	Left	87.2	87.68	0.48
NBD	54	120	282	Right	88.29	93.35	5.06
NBD	70	110	152	Right	67.4	71.97	4.57
NBD	71	100	339	Left	89.91	88.56	-1.35
NBD	82	90	204	Right	73.68	80.05	6.37
SBD	90	240	382	Right	92.38	95.04	2.66
SBD	88	100	410	Right	94.93	87.24	-7.69
SBD	87	350	163	Left	71.67	77.85	6.18
SBD	66	90	197	Left	72.5	78.45	5.95
SBD	58	90	318	Right	86.73	86.25	-0.48
SBD	47	90	524	Left	105.91	89.87	-16.04
SBD	46	110	224	Left	78.41	80.67	2.26
SBD	31	100	339	Right	87.92	91.94	4.02
SBD	24	100	250	Left	85.1	91.61	6.51
SBD	20	90	216	Left	76.43	76.00	-0.43
	Mean	127	267.15		81.84	83.39	1.55

* These figures are based on design speed (see Section 2.3) and not measured speed

A negative value indicates that vehicles are likely to be accelerating on the approach to the curve.

Information for each curve was added to an SPSS data file and included as variables in the analysis.

3.5 Subjects

Two groups of drivers were selected for inclusion in the study. In order to reduce variance (i.e. to eliminate an additional factor that may influence the results), only male drivers were included. Males were selected as they are a higher risk group (see Section 1.1). In addition, gender as a variable would either double the study sample size, or potentially increase the variation in the results thereby reducing the power of the comparisons

The first group comprised inexperienced male drivers defined as those with less than three years driving experience, but holding a valid licence (i.e. not on learner plates). The second group comprised experienced male drivers. The drivers had at least 15 years of driving experience, but were also required to be aged less than 60. This is because there is evidence that safety begins to decrease for older drivers (e.g. Catchpole et al., 2005).

Subjects were recruited through a number of methods. These initially included an email to internal staff at ARRB, as well as contacts at VicRoads, local council and RACV. Social media were also used, including advertisements on several websites, Twitter, and Facebook. These methods were particularly useful for recruiting younger drivers. Basic information was provided on the task required, the expected duration of the trial, and the compensation for involvement.

Once advertised, further recruiting occurred through ‘snowballing’ – a technique whereby further recruitment was undertaken through personal contact of those already taking part. A ‘passive’ snowballing technique was used, meaning that no pressure was placed on subjects to recruit others, but instead they were made aware of the opportunity to invite others to join the experiment.

Those wishing to take part in the trial responded through email or by phone. A set of initial screening questions was used to make sure that subjects met the selection criteria. This included a check on month and/or years since obtaining a driving licence, gender and confirmation that subjects did not live near to the test route or regularly drive this (to minimise driver familiarity with the route). Those who met these conditions were asked to select a suitable time to take part in the experiment.

A total of 40 subjects was included in the experiment, made up of 20 inexperienced and 20 experienced drivers.

The average age for inexperienced drivers was 21.1 years, with ages ranging from 18.49 years to 31.95 years. The average driving experience was 1.28 years, ranging from 0.17 years (2 months) to 2.58 years.

The average age for experienced drivers was 43.67 years, ranging from 32.99 years to 57.01 years. The average driving experience was 21.1 years, ranging from 18.49 to 31.95 years.

Analysis of drivers indicated that experienced drivers were involved in substantially more driving per week than inexperienced drivers. The vast majority of experienced drivers drove more than 5 hours per week (80%) compared to only half of inexperienced drivers.

When comparing the amount of driving undertaken on rural roads, there were again quite substantial differences. Experienced drivers tended to have had more recent driving experience in the most recent month on rural roads. Half of all experienced drivers had driven on rural roads in the previous month, while only 35% of inexperienced drivers had driven on these roads. The majority of inexperienced drivers had no driving experience on rural roads in the previous month (55%) compared to just 15% of experienced drivers.

There was a set period when the experimental vehicle was available. The first subject was tested on 25 January 2013 while the last was tested on 22 February 2013.

3.6 Equipment

The same vehicle was used for the duration of the experiment by each of the subjects in order to minimise variability in the experiment. Vehicles of different types would have added more complexity to the experiment and the analysis. The vehicle was a 2008 Subaru Outback station wagon with four speed automatic transmission. This vehicle had a four cylinder petrol engine with a 2.4 litre engine capacity and produced 170 hp at 6,000 RPM.

A number of data collection devices were fitted to the vehicle, and data was also drawn from the vehicle CAN bus (this is the device that allows different parts of the vehicle system to communicate internally and externally). These allowed collection of data on speed, lane position, presence of vehicles in front, GPS location, video images (view in front), side force, and details on road geometry (curve radius, grade etc.). Each of the devices and the data collected is described below.

3.6.1 Data acquisition unit

A Hawkeye 1000 data acquisition unit was used as the primary data collection device (Figure 3.5; ARRB Group, 2016).

Figure 3.5: Data acquisition unit

This device integrated the other data collection devices and operated by collecting a time stamp (with 0.5 ms accuracy) from each of the other data collection devices (excluding the Mobileye device discussed below). This allowed for easier and more accurate alignment of data post survey.

The connected devices included a Garmin GPS unit which was secured to the roof of the vehicle (Figure 3.6). This collected data on location every second (dependent on signal availability) with a position accuracy of 15 metres RMS.

Figure 3.6: GPS unit fitted to vehicle

A rotorpulser (or Distance Measuring Instrument, DMI) was fitted to the right rear wheel of the vehicle as shown in Figure 3.7. This device measured distance travelled, collecting eight pulses per vehicle tyre revolution. The worst case accuracy of this device is 0.1%, however, given the system was calibrated under test conditions by trained staff, it is assumed that the accuracy will be better than this. Combination of the GPS and DMI provides very accurate vehicle location.

Figure 3.7: Rotopulser device fitted to vehicle

A Gipsi-Trac road geometry measuring device (ARRB Group, 2016) was also installed. Figure 3.8 shows the Gipsi-Trac device fitted to the rear compartment of the test vehicle.

Figure 3.8: Gipsi-Trac device fitted to vehicle

The Gipsi-Trac device combined information from a gyroscope system, an accelerometer, distance sensors (described above) and GPS (also described above) to calculate information on road grade, cross slope, horizontal and vertical curvature amongst other variables. It utilised ‘dead-reckoning’ which allows for the collection of position data even in situations where there is no GPS coverage (such as tunnels and around high-rise buildings). This was important for the test route, as GPS data was not always available due to overhanging trees and topography (GPS reception is often lost in hilly terrain as line-of-sight to satellites is not possible). This system was developed by ARRB, and has been used extensively to collect road geometry information around Australia and overseas. The accuracy of the collected data is 0.2% (0.11 degrees) for grade; 0.2% (0.11 degrees) for cross slope; less than 0.5% for horizontal curvature; and 0.2% for vertical curvature.

Lastly, a Basler Scour video camera was secured to the front windscreen using suction cups (Figure 3.9) and linked to the data acquisition device. This collected video images in a forward direction from the perspective of the front passenger seat. Images were collected in full colour at 1920 x 1080 pixel resolution with a 68 degree lens.

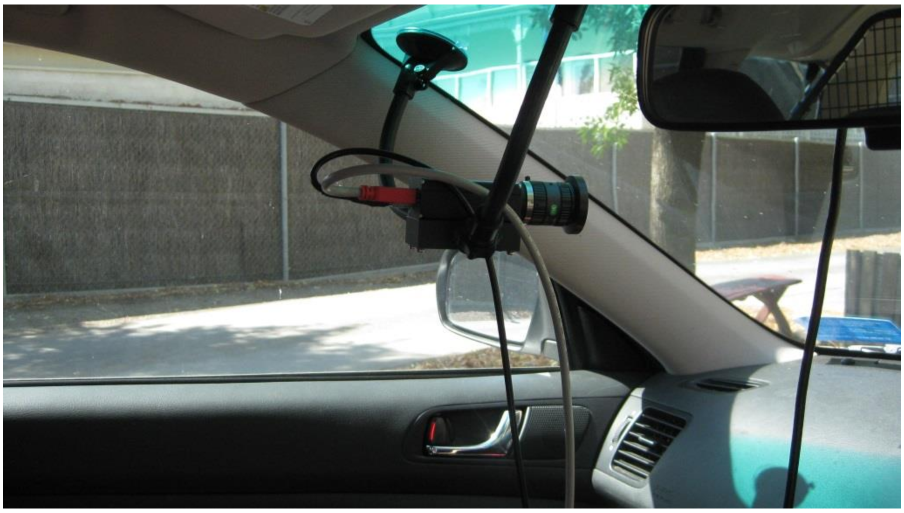

Figure 3.9: **Video camera fitted to front windscreen**

3.6.2 Mobileye C2-270 device

A Mobileye C2-270 device (www.mobileye.com) was used to collect information on vehicle headway and lane position. This unit is not normally used as a data collection device, but rather is advertised as a ‘collision detection system’. This equipment is used as a ‘post production’ safety device for vehicles, meaning that it is typically fitted to a vehicle after it is purchased.

In its normal mode of operation it has the ability to alert drivers that they are following too closely to other vehicles; are departing their lane; or that they are about to collide with a pedestrian or cyclist. Similar systems utilising the same technology are produced by Mobileye for a number of vehicle manufacturers, and are either fitted as standard, or as an optional safety feature. The system uses video-based technology to detect vehicles and line marking in order to provide these alerts. Information was collected via a camera mounted internally on the front windscreen (see Figure 3.10).

Figure 3.10: Mobileye device fitted to front windscreen

When combined with data on speed (drawn from the vehicle CAN), algorithms are used to determine the distance to the vehicle in front, and distance from the device to the centre and edgeline marking. These markings need to be present, and of reasonable quality to allow accurate measurement. The device makes an assessment of line marking quality, and this information is used when determining lane position. Figure 3.11 shows an example of a low quality centreline (from the perspective of this image) and edgeline (for vehicles travelling towards the camera lens). In both cases a confidence level of '0' was determined, meaning that the lane position data was not usable.

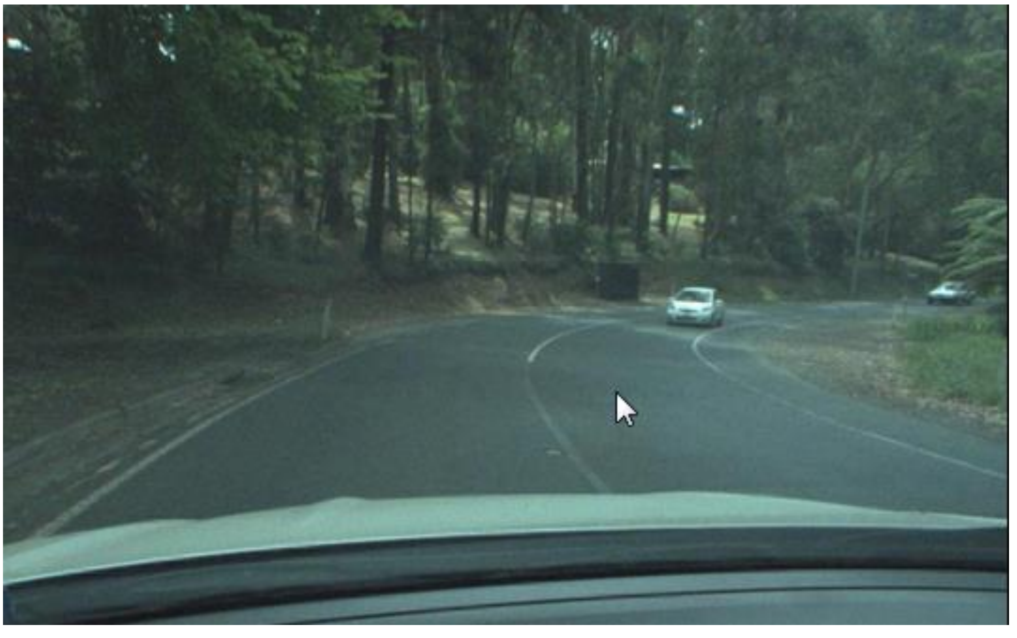

Figure 3.11: Curve 84 (NBD) showing faded centreline and edgeline

Based on communication with the hardware developer, it was determined that the data collected by the device could be sent to a laptop computer rather than used to provide alerts to vehicles. Additional firmware was developed and installed by Mobileye that allowed export of the data collected by the system. A software application was developed by an ARRB technical assistant to manage the collection of this data. It was then merged with data collected from the other devices.

Installation of the hardware system involved a detailed calibration and testing procedure. Distance to left edgeline and right centreline is calculated 10 times per second, and recorded in metres. Accuracy of this measurement was tested against actual measurements and found to be highly reliable. Accuracy of this system parameter has recently been tested by Hoover et al. (2014). This validation was undertaken on both straight and curved test routes, and identified that the Mobileye C2-270 system obtained 100% accuracy for all environments.

Data from each of the devices was collected by a laptop computer in raw data format. This data collection process required the development of a software application (produced by the technical assistant) that recorded data from each of the collection devices. The routine for starting the different devices was quite complex, involving 44 steps despite some degree of automation. However, these steps ensured that the data collection process had commenced correctly and in a format that could be merged later. At the end of each drive the data was downloaded and exported to a network drive.

Testing of all of the equipment was undertaken to ensure that the data was being exported in a manner that could be analysed. All devices had previously been validated, with the error or variance for each provided above. Spot checks were made of data to ensure measurements were in accordance with these specifications.

3.7 Procedure

Prior to the commencement of the experiment, ethical approval was gained from the University of Adelaide Human Research Ethics Committee (ethics approval number H-2012-136). A Job Safety and Environmental Analysis (JSEA) was also undertaken for both pilot and experimental phases. This was to help ensure that risks and hazards were minimised.

Several pilot test runs were conducted to test equipment and the testing procedures. This was to ensure that the data collection process was working as anticipated, and that subjects had a clear understanding of the tasks. Detailed feedback was received from participants resulting in some refinement of the process before full testing commenced. Note that neither this data nor the participants were used in the main study.

For the main experiment, subjects were greeted on arrival either by the researcher or the technical assistant. A brief introduction regarding the experiment was provided to each subject. A participant information sheet (see Appendix B) was also provided, which subjects were asked to read. This included details of the study, explaining that it was concerned with the safety of drivers on rural roads but avoiding mention of the behavioural issues of interest. Subjects were informed that they would be required to fill in various forms. Subjects were informed that the time to complete the route would not be recorded and was not of interest to the study and that they should drive at their own pace. Subjects were asked when travelling on the rural part of the route to ensure that they keep adequate distance to the vehicle in front. If they were following a slow moving vehicle, they were asked to pull over where it was safe to do so, and allow the vehicle in front to move well ahead.

Subjects were informed that participation in the study was entirely voluntary, and that they were free to withdraw at any time. Subjects were informed that their details would be kept confidential. Details of the ethical approval were also provided. A consent form was signed indicating that subjects were willing to take part in the experiment (see Appendix B).

The driver details form was completed by each subject (see Appendix C). This included driver licence information, contact details, date of birth, time since licence was obtained, type of vehicle normally driven (including whether this was a manual or automatic), amount of driving undertaken in a normal week, and amount of driving undertaken on country roads in the last month and last year.

The route was then described to the subject, with clear written instructions and pictures of key landmarks provided for subjects to take with them (see Appendix D). As identified earlier, the route was quite simple involving a ‘U’ turn from the start location, a left turn on to the test route, a ‘U’ turn at the roundabout at one end of the test route, a right turn at the end of the test route and then the drive back to the office (no turns required). Subjects were then given time to familiarise themselves with the vehicle and to adjust mirrors etc. ‘P’ plates were fixed to the vehicle if required by the driver’s licence category.

The trial initially commenced with four subjects in a day, but this was found to be too hard to manage, so a maximum of three subjects per day was used for the rest of the investigation. The times selected for inexperienced and experienced drivers were allocated to ensure an equal spread of start times. This was intended to minimise any effect caused by different times of the day, such as periods of higher traffic volumes. The morning and afternoon peak periods were avoided to minimise the effect of congestion. All testing was undertaken during the day, and on weekdays only.

On return to the office, the drivers were met as they parked the test vehicle. They were then debriefed, with notes taken regarding any unusual events that occurred during the drive. They were then told the main objective of the study (relating to driver behaviour including speed and lane position through curves). Data was then extracted from the laptop computer for processing.

3.8 Data extraction and processing

Data extraction from the different collection devices was a complicated process. Relevant data was downloaded from each device and converted to Microsoft Excel format where required. Video images were extracted into jpeg format. A key part of this process involved the synchronisation of the Hawkeye and Mobileye data. This was achieved utilising time stamp information and vehicle speed collected from each device. The devices were started within 30 to 60 seconds of each other giving a relatively short time period to search. A macro was developed by the technical assistant to graph the speeds recorded by each device. By adjusting the offset time for the devices it was a relatively simple task to identify with accuracy the points at which speeds matched thereby synchronising the devices. The different data files were then merged using another macro (also developed by the technical assistant). A separate document was created for each subject. One line of data represented a snapshot of data at 10m intervals (the currency used by the Hawkeye device). This provided data at intervals of around half a second on typical high speed parts of the experimental route (i.e. two data points per second), and around one per second for lower speed sections.

Data cleaning was then undertaken on each data file. This involved identifying parts of each dataset that did not meet certain criteria. Relevant data was identified using video images and through assessment of key variables. Each of the following variables had been identified prior to the experiment as having a potential influence on behaviour, and data was therefore excluded from the experimental phase.

Following distance was a critical variable. If subjects were following closely behind other vehicles it is likely that their behaviour would be influenced by the vehicle in front. The presence of a vehicle was easily checked through the Mobileye device.

Information was gathered on whether any vehicle was detected (including cars, motorcycles and trucks), and the ‘time’ between vehicles (estimated in seconds). This data was also supplemented and validated by video images of the road ahead. The typical value used in speed surveys to ensure free running speeds is four seconds (Austroads, 2009c). The Mobileye appeared reliable in detecting vehicles in front at a four second headway. At this distance, vehicles were ‘flagged’. When following distance reduced to 2.5 seconds or less, the actual following distance was recorded by the device. However, a more conservative approach was undertaken for this study. For the rural experimental route, any section of the road where a vehicle was visible to the subject was excluded.

Rain had the potential of influencing driving behaviour, possibly slowing drivers when either visibility was obscured or there was a perception of increased risk. For this reason, periods of rain were excluded from the dataset. The definition of rain for the purpose of this experiment was when windscreen wipers were used.

Obstructions on or near the road were also likely to influence driver behaviour, and so instances where this occurred were excluded from the study. This included temporary roadworks, vehicles parked on the roadside, cyclists and pedestrians.

Data on vehicle speeds was monitored for situations where speeds dropped below 20 km/h. Video images were reviewed, and some data excluded where this reduction in speed was the result of vehicles pulling off the road. This typically occurred when drivers were being impeded by other vehicles as per instructions (see Section 3.7).

There was equipment failure with the Mobileye device for two experienced drivers (E19 and E20) and one inexperienced driver (Y01). This equipment failure meant that lane position data was not collected for these three subjects. This did not have an impact on other data collection, as devices operated independently of each other.

Subjects were debriefed following their drive, including questions on any unusual events. Two drivers deviated from the route, driving beyond the roundabout at the end of the test route. Both subjects soon realised this mistake, returning to the route. This did not adversely affect the testing procedure. Other subjects were recorded stopping at shops and performing an emergency braking procedure (a vehicle entering the road unexpectedly). This data was highlighted in the dataset, and excluded from the eventual analysis.

Informal feedback from subjects indicated that it took some time to become familiar with driving the test vehicle. None of the subjects identified that they owned or drove a make and model the same as the experimental vehicle. However, feedback from subjects from the debrief session indicated that it took around 15-20 minutes to become fully comfortable to drive this vehicle. This meant that most drivers reported that they felt comfortable by the time they reached the start of the test route.

The collected data was supplemented by some calculated data fields. This included vehicle acceleration based on distance travelled over time. Information on the point of first acceleration in each curve by each driver was manually determined. Information on lane position was also derived. This involved combining the information on distance to edge and centreline with the level of confidence in the data collected (a feature of the Mobileye system). Only where there was a high level of confidence in the collected data was the information used. The level of confidence appeared to be closely related to the quality of the painted edge or centreline. Where these markings were faded, the device seemed unable to estimate the distance with the required level of accuracy.

Data were then arranged in individual files by subject. Each file included the data for the whole drive (including the urban arterial portion and the test route). Data on the individual curves of interest were then extracted through a further macro (developed by the technical assistant). Information on the process for curve selection is discussed in Section 3.4. This macro was used to identify the GPS location for the start of each curve point. The length of each curve was then calculated manually. The macro then extracted the data for each subject and for each of the curves. The information on curve location and subject was retained in the data file allowing analysis by these variables. The information on the curve start point for different subjects was validated by comparing video images for a sample of subjects. The curve start point based on GPS location proved to be an accurate method for ensuring the same curve start point was selected for each subject.

As described in Section 3.2, data was categorised manually by the point within the curve based on the following categories:

- curve approach (data for the section prior to curve commencement)
- curve start
- the segment between the start and point of curve minimum
- the point of minimum radius was ‘minimum’
- the segment between the minimum and curve end
- the curve end point.

Note that in the results section data is broken down into each of these separate categories. However, when referring to a curve, the data comes from all points combined, including the 40 m of approach data.

The dataset was then exported to SPSS for final analysis. At this stage, information from other data sources was also added. This included information from the driver survey. It also included information on each of the curves, obtained through separate analysis (see Section 3.4). This included curve length, points within the curve (40 m prior to the curve, curve start, start to curve minimum, curve minimum to tangent), curve direction (left or right), and curve risk (calculated based on curve approach speed and minimum curve speed as discussed in Section 2.4.2).

4 RESULTS

4.1 Introduction

This chapter provides an analysis of the data collected through the experimental phase of research. It includes tests to determine results relevant to the key research questions. More specifically, the data was analysed to determine speed and lane position while driving through curves. The hypotheses were each tested using statistical analysis (as described in Section 3.2.4) and results presented. As discussed in Section 2.9, key research questions from this analysis were:

- differences between high risk and low risk curves, including:
  - speed at key points through the curve
  - longitudinal acceleration/deceleration
  - side force (particularly at the minimum curve point)
  - lane position
- differences between inexperienced and experienced drivers, including:
  - speed at all points through the curve
  - longitudinal acceleration/deceleration
  - side force (particularly at the minimum curve point)
  - lane position
- combinations of these factors (e.g. inexperienced driver behaviour through high risk curves)
- a check against curve design assumptions.

Information is provided on the mean values for driver speed, acceleration/deceleration, side force (the horizontal component of side force only, taking account of superelevation) and lane position. Information is also provided for these factors at key points throughout the curves. These points are defined in Section 3.8 and include curve approach, start, to minimum, minimum (curve mid-point), departure and end. It should be noted that because each curve was of a different length, the figures presenting results by points throughout curves are not identical. Rather, some points ('start', 'minimum' and 'end') represent just one point within the curve, while others are an average over a fixed distance (e.g. 'approach' is an average over 40 m) or a variable distance ('to minimum' and 'departure' may represent averages over between

50 m and 150 m each). Although these points differed between curves all comparisons between drivers were based on exactly the same points at each curve.

Exploratory analysis was undertaken to gain a basic understanding of the data. This included analysis of individual drivers and individual curves to better understand the data, and the variance within individual groups (i.e. inexperienced and experienced drivers; high risk and low risk curves). These results are also used to compare against some of the assumptions used in curve design.

For presentation purposes the results from the analysis are divided into the following sections:

- high risk versus low risk curves
- inexperienced versus experienced drivers
- inexperienced versus experienced drivers for high and low risk curves
- individual differences and design assumption validation
- results in relation to research hypotheses.

In order to provide context to the results, it is useful to understand the safety implications from changes to each of the measures (speed, acceleration, side force and lane position). As discussed in Section 2.3, Elvik (2004) reported that a 1% increase in mean speed generally equates to a 5% increase in fatal crashes. Although this relates to mean speed across a variety of road types and is generally based on before and after analysis from some specific change (e.g. a speed reducing treatment) the figure serves as a useful guide when interpreting the speed results.

Although no specific guidance on safe levels of acceleration or deceleration was identified in the literature review, the maximum comfortable deceleration by drivers is assumed to be 2.5 m/s/s based on current design standards (Austroads, 2010).

Previous research findings (see Section 2.6) provide information on critical side force values where drivers begin to lose surface friction. The maximum recommended side force through curves for cars on dry sealed roads is 0.35 g (Austroads, 2010). This is based on the comfortable side force, and is less than the maximum side friction factor that would result in a vehicle skidding. Harwood et al. (2003) reported that passenger vehicles were likely to lose control at around 0.7 g in wet conditions, and at around 1.0 g in ideal, dry conditions. The threshold for vehicle rollover is typically around 1.3 g, indicating that cars will most likely skid off the road before they rollover.

Lane position was reviewed in Section 2.6, and it was clear from previous research that little is known about the impact of lane position on crash outcomes. However, Jamieson (2012) did report that vehicle side force varied substantially (by a factor of two) with differing lane position. As indicated above, side force does have a direct impact on safety outcomes.

4.2 High risk versus low risk curves

A key objective of this research was to determine differences in behaviour for high risk and low risk curves for each of the key measures. This section presents results for speed, acceleration/deceleration, side force and lane position in relation to curve risk.

In this section (as with each of the following sections), where differences are referred to in the text, all differences are statistically significant ($p<.05$) unless indicated otherwise. As described in Section 3.2.4, results have been adjusted for all pairwise comparisons within each test using the Bonferroni correction. Although corrections have been applied within tests, they have not been adjusted between tests.

As previously discussed, high risk curves are defined as having a high difference in approach design speed, and design speed at the minimum curve radius, and low risk curves had little difference between approach speed and curve minimum.

4.2.1 Speed

As expected, mean speeds through high risk curves were substantially lower than through low risk curves (52.3 km/h compared with 58.5 km/h). This difference in speed occurred on approach and at all points throughout the curve, as indicated in Figure 4.1.

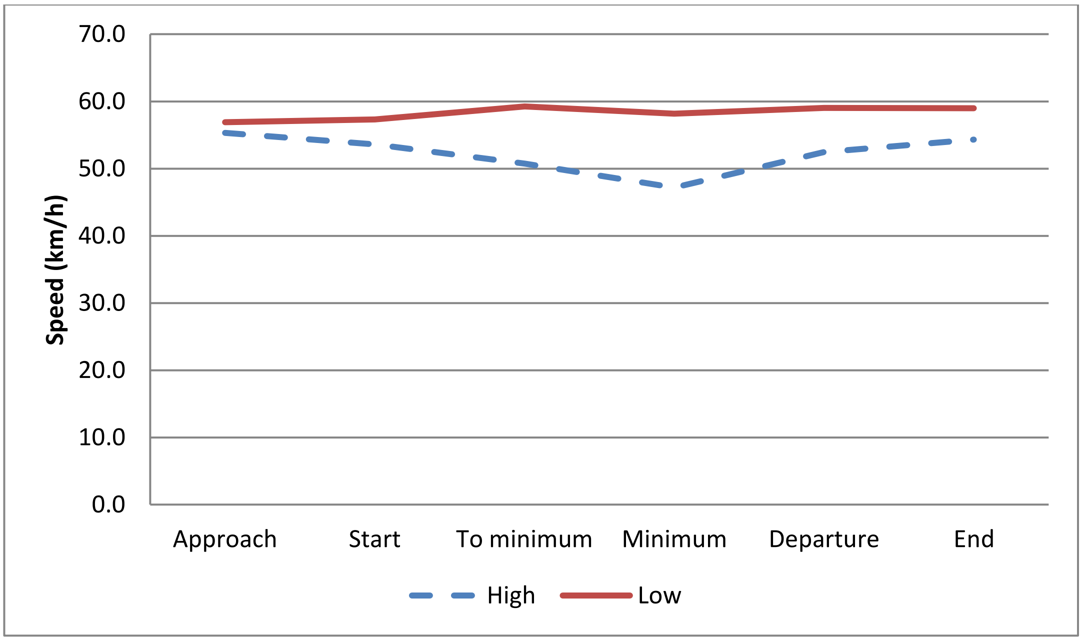

Figure 4.1: Speed at different points through high and low risk curves

For high risk curves, speeds were at their lowest at the point of minimum curve radius (47.2 km/h, a difference of 7.9 km/h compared to the approach to the curve). The situation was different for the low risk curves, where speeds increased on approach to the curve, slowed through the minimum point (58.2 km/h at the point of minimum radius, only 1.3 km/h slower when compared to the approach), before increasing again.

Speeds were similar on the approach to high risk and low risk curves (55.3 and 56.9 km/h respectively). Speeds at the curve end exceeded the approach speed for low risk curves, but were still increasing to this level for high risk locations (59 km/h and 54.3 km/h respectively).

Variance in speed was greater for high risk curves, and this occurred at all points through the curve (Table 4.1). This was particularly so at the curve minimum point (standard deviation of 7.7 km/h for high risk curves compared with 5.8 km/h for low risk curves). This finding accords with previous research and is discussed further in Section 4.5.1,

Table 4.1: Mean and Standard Deviation in speed for high and low risk curves

	High risk curves		Low risk curves	
Curve point	Mean	Standard Deviation	Mean	Standard Deviation
Approach	55.3	6.4	56.9	5.3
Start	53.6	6.3	57.3	5.3
To minimum	50.7	6.9	59.2	6.8
Minimum	47.2	7.7	58.2	5.8
Departure	52.5	7.2	59.0	5.7
End	54.3	6.7	59.0	5.8

4.2.2 Acceleration/deceleration

Longitudinal acceleration and deceleration rates varied by curve risk, with a net deceleration through high risk curves and a net acceleration through low risk (-0.114 compared with 0.247 m/s/s).

More meaningful is an analysis of acceleration by points within curves. The differences between high and low risk curves at all points were statistically significant. Figure 4.2 shows that for low risk curves, drivers accelerated throughout the curve, but that the amount of acceleration decreased through the curve. By the end of the curve, subjects were maintaining a steady speed. For high risk curves, deceleration commenced well in advance of the curve (exceeding the 40 m buffer used in this analysis). This deceleration peaked at the start of the curve, and remained high on approach to the curve minimum. Deceleration continued beyond the curve minimum indicating that vehicles had not fully slowed at the curve minimum point. Drivers then switched to acceleration on the departure and this acceleration continued beyond the end of the curve.

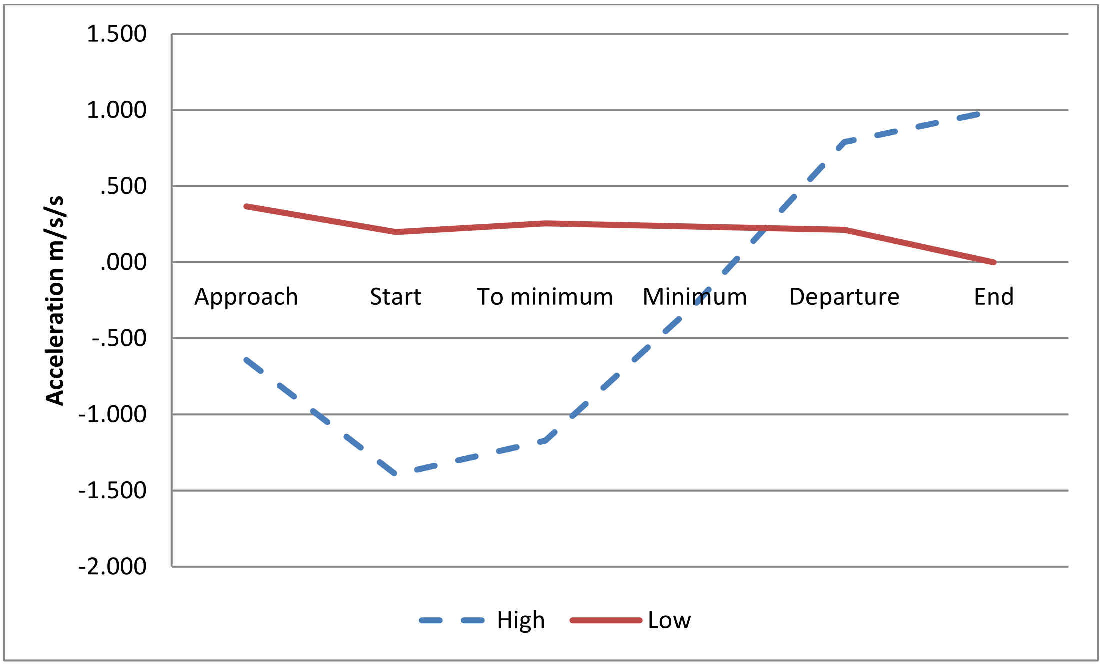

Figure 4.2: Acceleration at different points through high and low risk curves

Variance in acceleration/deceleration was greater for high risk curves and this occurred at all points within the curve (Table 4.2). For example, the standard deviation at curve minimum was 1.4 m/s/s for high risk curves, and 0.87 m/s/s for low risk curves. This issue is discussed further in Section 4.5.2,

Table 4.2: Mean and standard deviation in acceleration/deceleration for high and low risk curves

	High risk curves		Low risk curves	
	Mean	Standard deviation	Mean	Standard deviation
Approach	-.643	1.581	.367	1.204
Start	-1.394	1.836	.200	1.051
To minimum	-1.172	1.719	.256	1.114

Minimum	-.279	1.399	.235	.873
Departure	.789	1.341	.213	.955
End	.994	1.885	-.001	.973

4.2.3 Side force

As expected, side force (measured in terms of side force in g's) is greater for high risk curves compared to low risk curves. In terms of mean values for all curves in each group, the side force for high risk curves was 0.114 g compared to 0.044 g for low risk curves. More meaningful are the results for different points on approach and through curves, and this is shown in Figure 4.3.

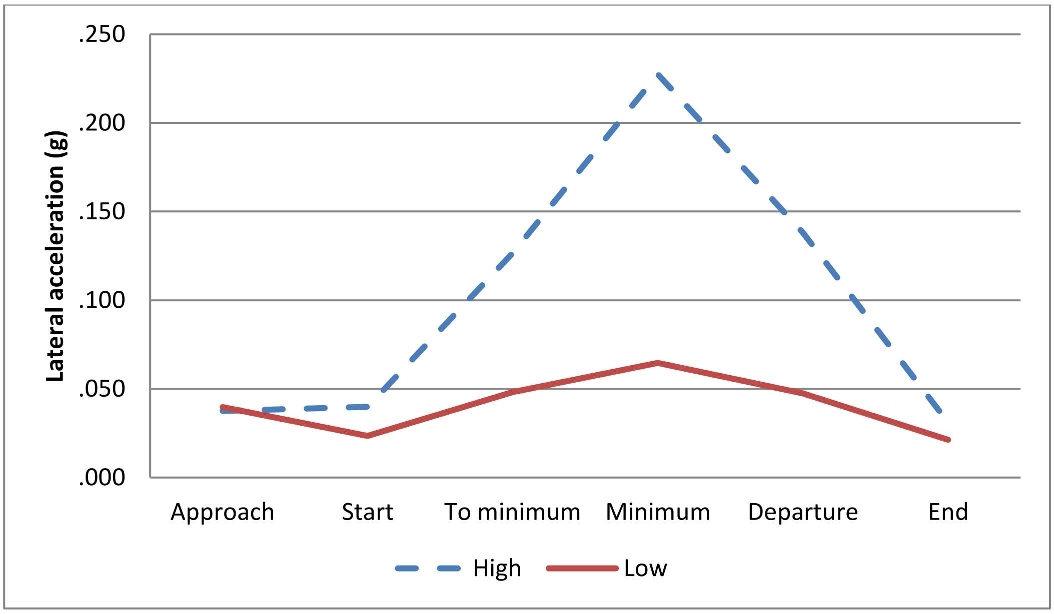

Figure 4.3: Lateral acceleration at different points through high and low risk curves

Side force is greater at most points for high risk curves, peaking at the minimum curve point (0.23 g). The side force on approach for high and low risk curves was not significantly different, but was for all other points through the curve, including the curve end.

Variance for lateral acceleration was greater for high risk curves (Table 4.3). For example, at curve minimum, the standard deviation of lateral acceleration for high risk curves was 0.086 g compared to 0.041 g for low risk.

Further details on lateral acceleration for individual curves, and individual drivers through curves can be found in Section 4.5.3 and Appendix E.

Table 4.3: Mean and Standard Deviation in lateral acceleration for high and low risk curves

	High curve risk		Low curve risk	
	Mean	Standard deviation	Mean	Standard deviation
Approach	.037	.041	.040	.043
Start	.040	.039	.023	.020
To minimum	.127	.097	.048	.035
Minimum	.227	.086	.065	.041
Departure	.138	.095	.047	.036
End	.031	.033	.021	.018

4.2.4 Lane position

Results of early analysis identified that the distance to the edgeline and centreline produced similar results, and it was not of value to present both of these side by side. For this reason, only results for the distance to the edgeline are presented here.

Overall, subjects drove closer to the edgeline for low risk curves when compared with high risk (0.73m from the edgeline compared with 0.81m respectively). However, as also identified in the early analysis distances to edgeline and centreline are meaningless unless presented for left and right curves separately.

There are clear differences for left and right curves when comparing high and low risk curves (Figure 4.4).

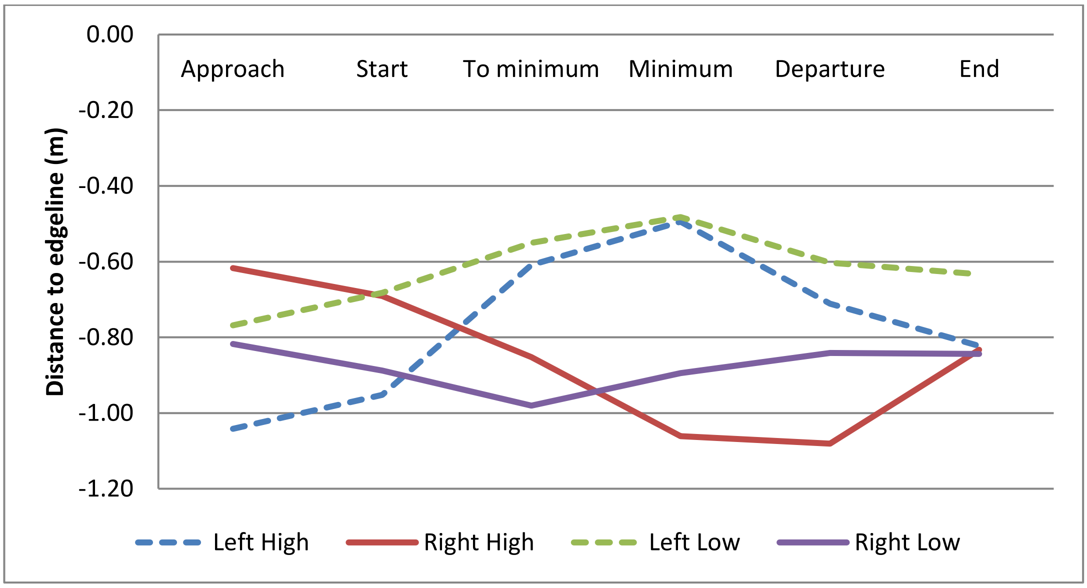

Figure 4.4: Distance to edgeline at different points through left and right and high and low risk curves

For left curves, there is a substantial difference in lane position on approach (0.27 m difference), through the curve start (0.27 m), and on approach to curve minimum (0.06 m), with subjects substantially further from the edgeline for high risk curves. Distance at curve minimum is the same, and then subjects move further from the edgeline on departure (0.11 m) and at curve end (0.19 m) for high risk curves.

For right curves, subjects were substantially closer to the edgeline on approach for high risk curves (0.15 m closer). This continued at curve start (0.2 m), and then prior to the curve minimum (0.14 m), this switched, with greater distance from the edgeline through high risk curves at the curve minimum (0.17 m further from the edgeline). This difference increased on departure (0.24 m), until by curve end, the position through high risk and low risk curves was the same.

Variance for high risk curves was greater than for low risk curves on approach (0.39 m compared to 0.33 m) and at curve minimum (0.43 m compared to 0.37 m), but was similar at other points within the curve (Table 4.4).

Table 4.4: Mean and standard deviation in distance to edgeline

	High risk curves		Low risk curves	
Curve point	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
Approach	-.81	.39	-.79	.33
Start	-.81	.33	-.77	.35
To minimum	-.73	.37	-.75	.39
Minimum	-.74	.43	-.66	.37
Departure	-.86	.36	-.68	.34
End	-.83	.29	-.73	.32

In addition to the results on distance to the edgeline, an analysis on lane position relating to 'lane crossing' behaviour was also undertaken. Lane crossing was defined as situations where the driver crossed either the edge or centreline. Note that in situations where the quality of the line marking was not good, data on lane position was not available. It is very likely that where lane crossing behaviour occurs frequently there will be a deterioration in the lane marking. This means that the results presented are likely to be an under-representation of actual lane crossing behaviour. The data also only shows the first location for each curve where lane crossing occurred (i.e. if drivers crossed the edgeline on approach and departure, the behaviour will only be recorded on approach. Similarly, if drivers crossed the edgeline on approach, and stayed across the edgeline, this would be counted just the once).

There were differences in lane crossing behaviour between high and low risk curves. There were more incidents of lane crossing for high risk curves. Lane crossing occurred in 150 curves (19% of curves) compared with 89 for low risk (11% of curves).

For left curves (Figure 4.5) there was a higher incidence of crossing the centreline on approach to curves for high risk curves. For right curves, there was a greater degree of crossing the edgeline on approach, and crossing the centreline within the curve for high risk curves (Figure 4.6).

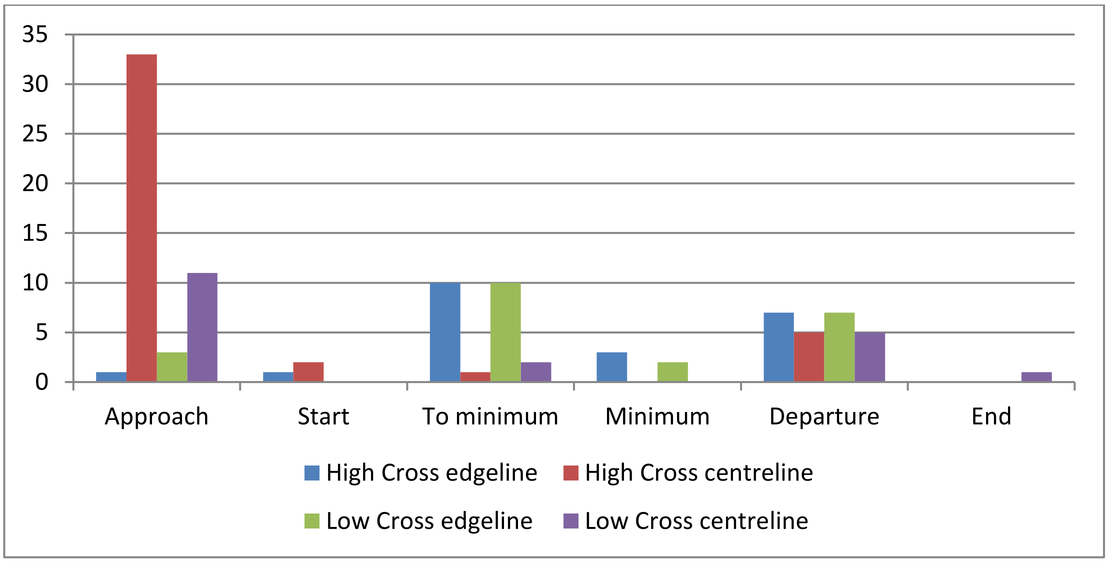

Figure 4.5: Incidence of lane crossing for left curves

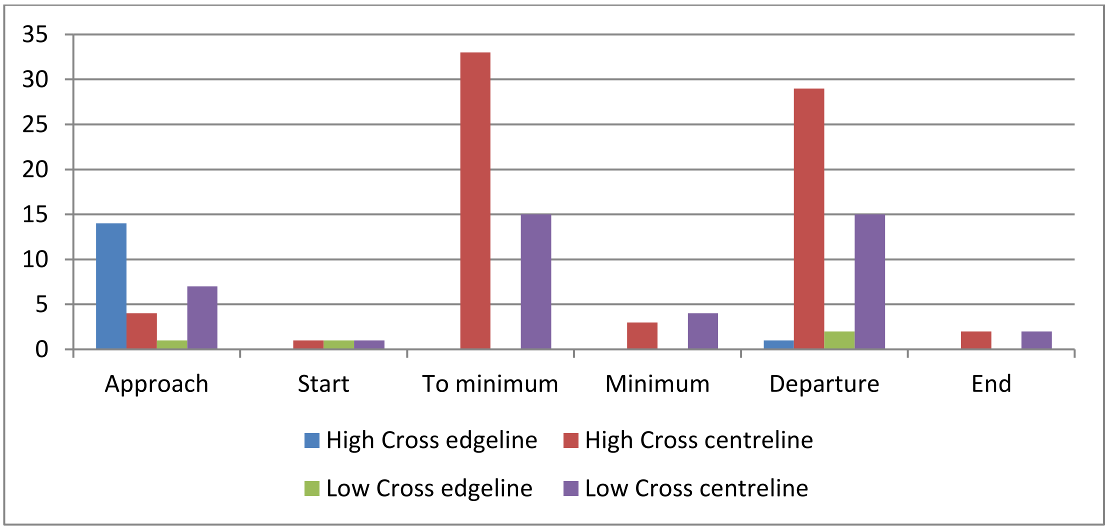

Figure 4.6: Incidence of lane crossing for right curves

4.2.5 Summary for high risk versus low risk curves

A key research question related to difference in driver behaviour for high versus low risk curves. The key behaviours of interest were speed, acceleration/deceleration, side force and lane position (including lane crossing behaviour). There were substantial differences between low and high risk curves. For high risk curves:

- speeds were lower at all points through the curve
- acceleration and deceleration were greater
- deceleration commenced earlier (prior to approach)
- deceleration continued beyond the minimum point for high risk curves
- side force was greater with a significant peak at curve minimum
- lane position was different. For right curves, drivers started closer to the edgeline on approach, but moved further from the edgeline on departure. For left, drivers approached further from the edgeline, and moved further from the edgeline on departure
- there was a greater degree of lane crossing
- variance was greater for most behaviours.

The implications of these results, particularly in relation to the key research questions, are discussed in Section 5.1.1.

4.3 Inexperienced versus experienced drivers

The following set of analyses compares driver behaviour for inexperienced and experienced drivers.

4.3.1 Speed

The analysis showed that against expectations, experienced drivers were faster than inexperienced drivers through curves (55.3 km/h versus 54.4 km/h). Although statistically significant, the difference is not substantive (0.9 km/h). This difference between groups was consistent at all points of the curve as indicated in Figure 4.7, with a difference of between 0.9 and 1.0 km/h at all points through the curve.

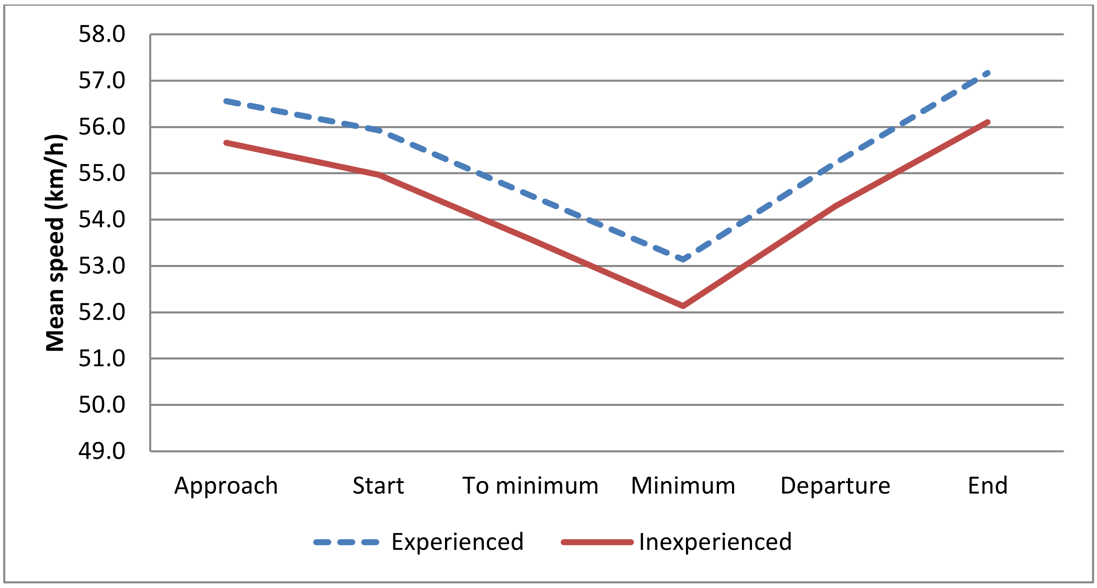

Figure 4.7: Speed at different points through curves for experienced and inexperienced drivers

4.3.2 Acceleration / deceleration

Acceleration rates were compared for inexperienced and experienced drivers. For mean acceleration through curves, there was no difference for the two groups (0.025 m/s/s for inexperienced, and 0.042 m/s/s for experienced). Acceleration rates were almost identical as shown in Figure 4.8, with no statistically significant differences at any points through the curve. Left and right curves were also compared, but again there were no significant differences between groups.

Figure 4.8: Acceleration at different points through curves for experienced and inexperienced drivers

4.3.3 Side force

Side force, measured in 'g' is almost identical for inexperienced and experienced subjects when combining all points of the curve (0.085 compared with 0.086 g respectively; n.s).

The difference for different points through curves is also insubstantial, with no points being significantly different. This is graphically illustrated in Figure 4.9.

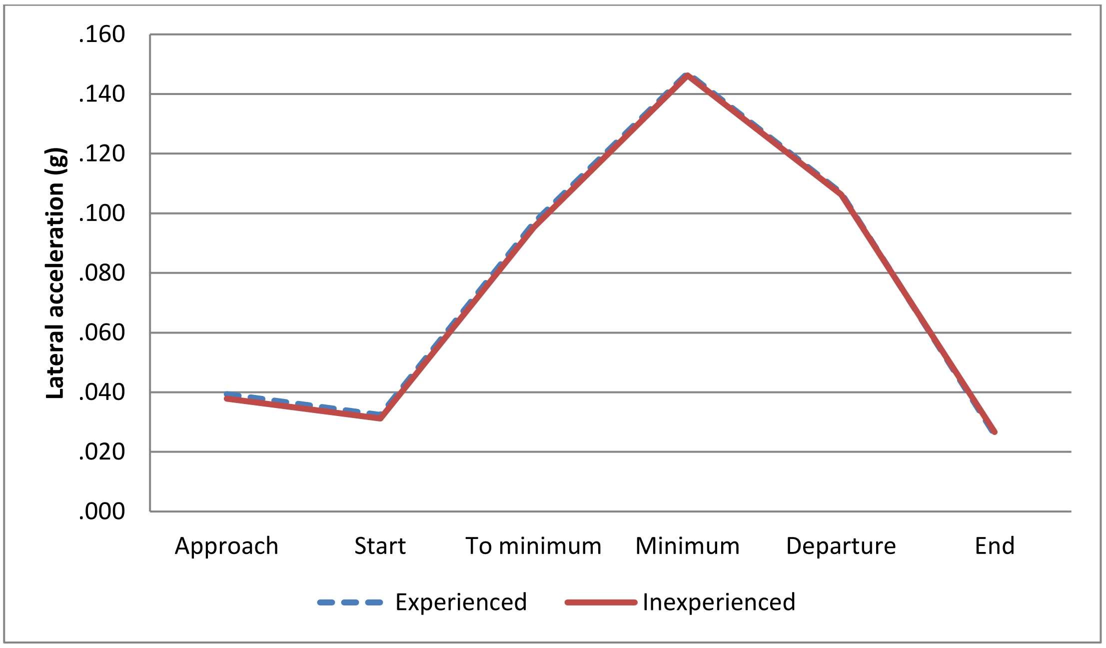

Figure 4.9: Lateral acceleration for inexperienced and experienced drivers

When comparing side force on left versus right curves, for left curves there was no difference between inexperienced and experienced drivers. For right curves there was a statistically significant difference, although again the difference is not substantive (0.094 g for inexperienced, and 0.098 g for experienced).

4.3.4 Lane position

Lane position (distance to edgeline) was statistically and substantively different for inexperienced and experienced drivers. For all curves combined, experienced drivers travelled further from the edgeline when compared to inexperienced drivers, but the difference was not substantive (0.78 m compared to 0.76 m). When comparing left and right curves, differences remained significant for left curves (0.71 m for experienced drivers and 0.67 m for inexperienced) but not for right curves (0.88 for experienced and 0.87 m for inexperienced).

Figure 4.10 shows lane position for left curves, while Figure 4.11 shows the same information for right curves.

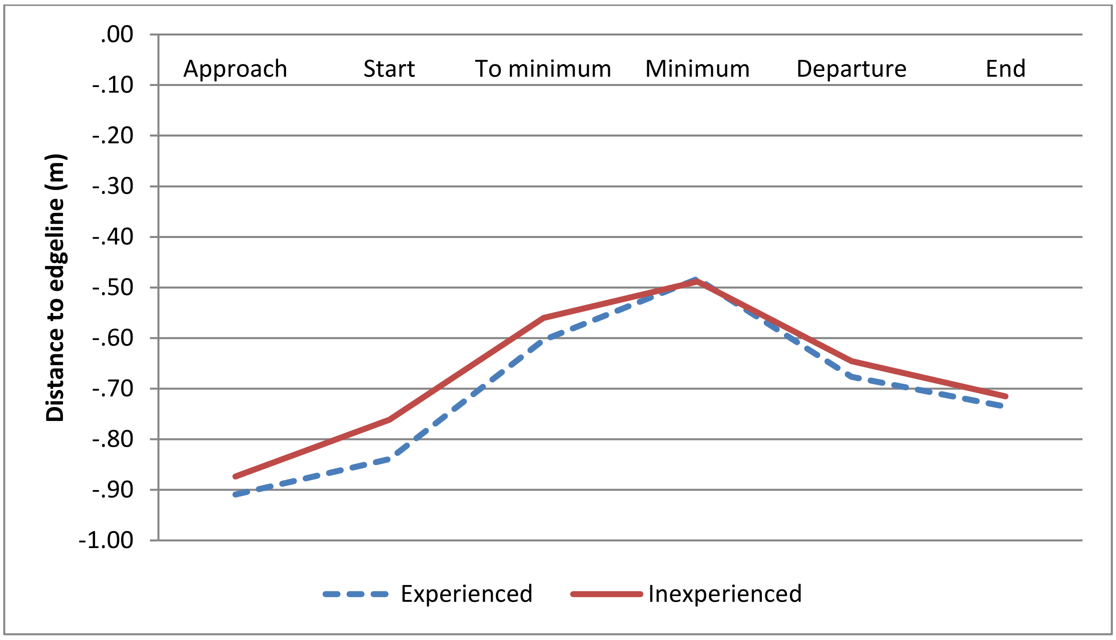

Figure 4.10: Lane position for inexperienced and experienced drivers for left curves

For left curves there were significant differences for curve approach, start, to minimum and departure. In each case experienced drivers were further from the edgeline than inexperienced drivers. The difference was most substantive at curve start (experienced drivers were 0.08 m further from the edgeline).

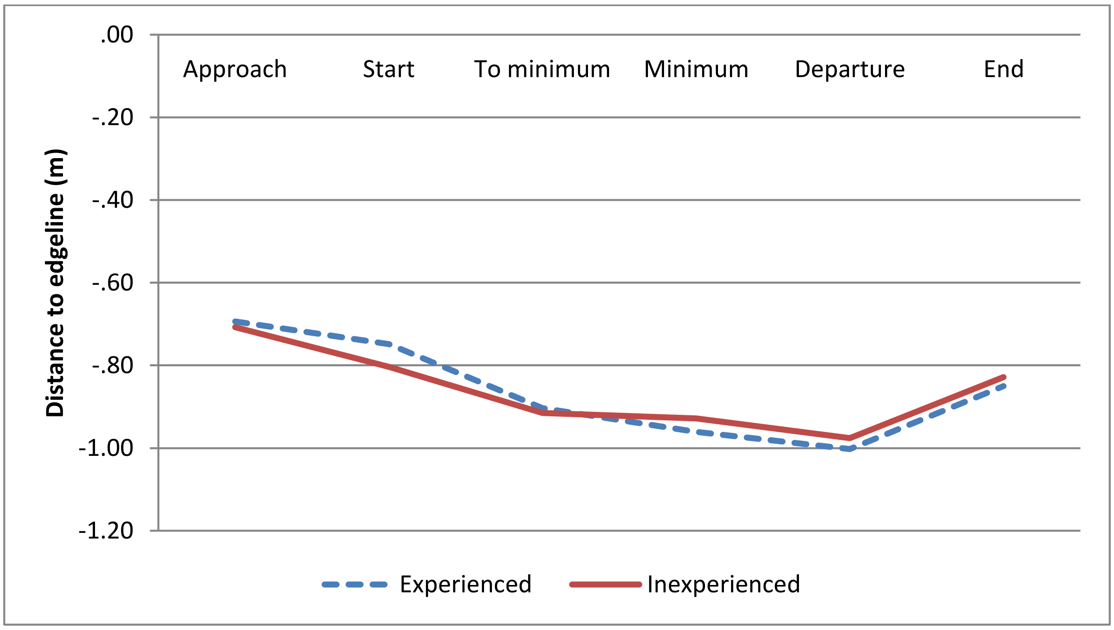

Figure 4.11: Lane position for inexperienced and experienced drivers for right curves

For right curves the differences between experienced and inexperienced drivers were not significant at any point.

Table 4.5 shows lane crossing behaviour for inexperienced and experienced drivers. There were a greater number of incidents involving inexperienced drivers crossing both the edgeline and centreline. Lane crossing occurred for 13% of curves for experienced drivers, and 17% for inexperienced drivers.

Table 4.5: Incidence of lane crossing behaviour for inexperienced and experienced drivers

	Experienced	Inexperienced
Cross edgeline	24	39
Cross centreline	76	100

Table 4.6 provides this same information for left and right curves. Again in each case there was a greater incidence of lane crossing by inexperienced drivers.

Table 4.6: Incidence of lane crossing behaviour for inexperienced and experienced drivers for left and right curves

		Experienced	Inexperienced
Left	Cross edgeline	17	27
	Cross centreline	26	34
Right	Cross edgeline	7	12
	Cross centreline	50	66

4.3.5 Summary for inexperienced compared with experienced drivers

Differences were not as pronounced as expected when comparing inexperienced and experienced drivers:

- inexperienced drivers were more conservative in their speeds than experienced, although the difference was not substantive
- there was no real difference for acceleration/deceleration
- there was no real difference for side force, and indeed the results were remarkably similar
- there was a substantive difference in lane position for left curves with experienced drivers further from the edgeline at all points except at the curve minimum and curve end. Differences in lane position were not statistically significant for right curves

- there was a far greater degree of lane crossing for inexperienced drivers, for both left and right curves.

The implications of these results are discussed in Section 5.1.2.

4.4 Inexperienced versus experienced drivers for high and low risk curves

This section combines results for both driver experience and curve risk.

4.4.1 Speed

Results for inexperienced and experienced drivers through high and low risk curves are shown in Figure 4.12.

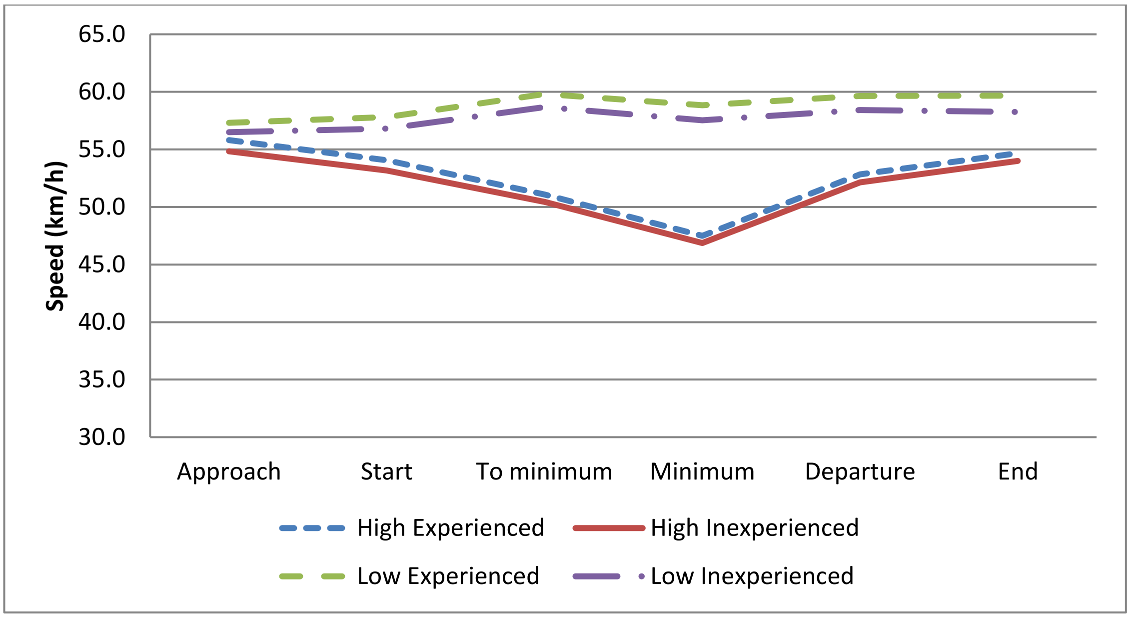

Figure 4.12: Speeds at different points through curves by experience and curve risk

Experienced drivers were faster through both high and low risk curves. The difference was significant and reasonably consistent at all points of low risk curves. Differences in speeds were more substantial than for high risk curves, and ranged from a difference of 0.8 km/h on approach to 1.4 km/h at curve end.

The difference between inexperienced and experienced drivers through high risk curves was less substantial. The difference was significantly higher for experienced drivers on approach; to minimum; and on departure. The differences were not significant at curve start; minimum or at curve end.

There were differences in speed behaviour between left and right curves. Figure 4.13 shows the results for left curves. Speeds for low risk curves showed a consistent trend, with experienced drivers travelling consistently (and significantly) faster (ranging from 1.4 km/h on approach to 1.9 km/h at curve end). The situation was different for the high risk curves. Experienced drivers were significantly faster on curve approach (by 1.0 km/h), but there was no significant difference at other points through the curve.

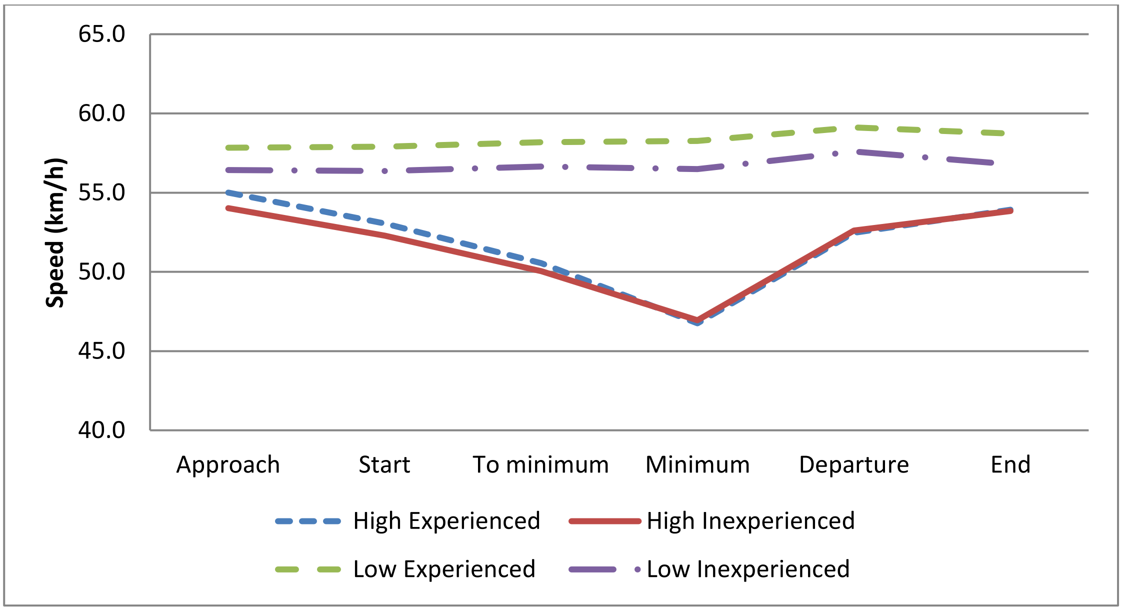

Figure 4.13: Speeds through left curves by driver experience and curve risk

For low risk right curves (Figure 4.14), experienced drivers were significantly faster than inexperienced drivers at two points through the curve (to minimum and departure, by around 1 km/h for each), but not at other points.

For high risk right curves, experienced drivers tended to be faster, and this difference was significant at several points (approach, to minimum and departure). The difference was greatest at departure (1.6 km/h). Although the differences were in some cases statistically significant, they were not substantive.

Figure 4.14: Speeds through right curves by driver experience and curve risk

4.4.2 Acceleration/deceleration

When comparing the two groups over high and low risk curves, there was no difference for high risk curves (-0.10 m/s/s for inexperienced, and -0.13 for experienced). There were differences for the low risk curves, with inexperienced drivers showing lower levels of acceleration when compared with experienced drivers (0.21 compared with 0.28 m/s/s).

Acceleration at different points of the curve was similar for both groups of drivers over high risk curves, as shown in Figure 4.15. There appeared to be greater deceleration for experienced drivers at the curve start, but the differences between groups were not significant. Acceleration for low risk curves was also very similar for the two groups, although there were significant differences at two points. There was greater acceleration for experienced drivers at approach (0.44 compared with 0.3 m/s/s) and when travelling to minimum (0.31 compared with 0.2 m/s/s).

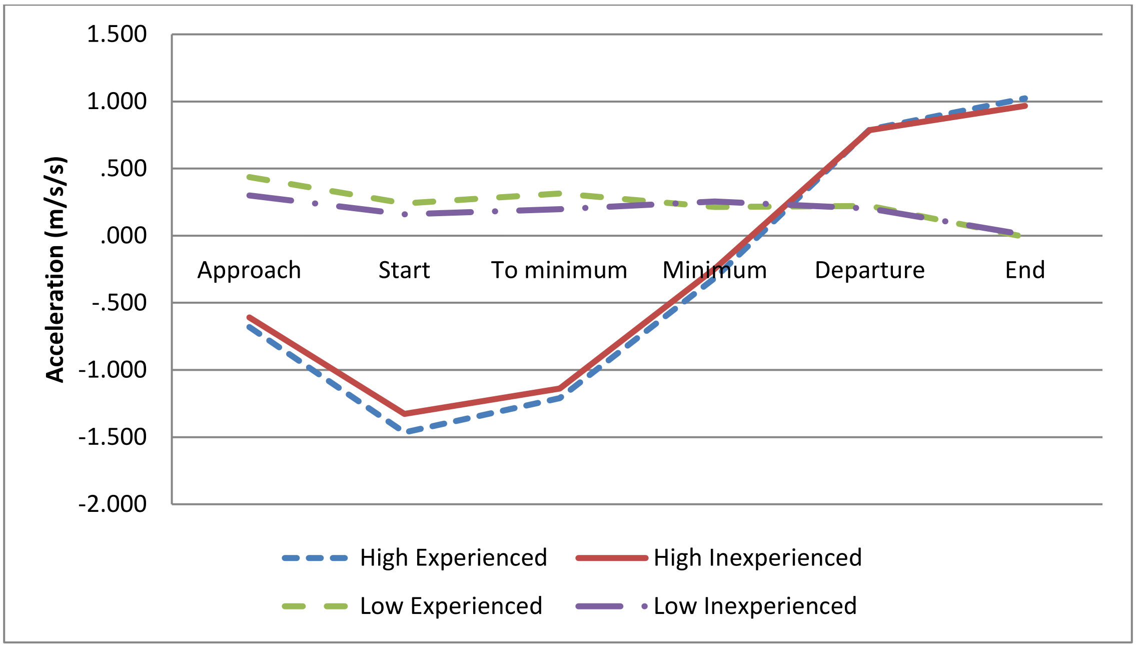

Figure 4.15: Acceleration through curves by inexperienced and experienced drivers

For left curves (Figure 4.16) there appeared to be slightly higher deceleration by experienced drivers on the approach and at curve minimum, but this was only significant when travelling to the minimum point (-0.97 compared with -1.12 m/s/s). Deceleration had finished for inexperienced drivers at the curve minimum, but continued for experienced drivers, although this difference is not significant.

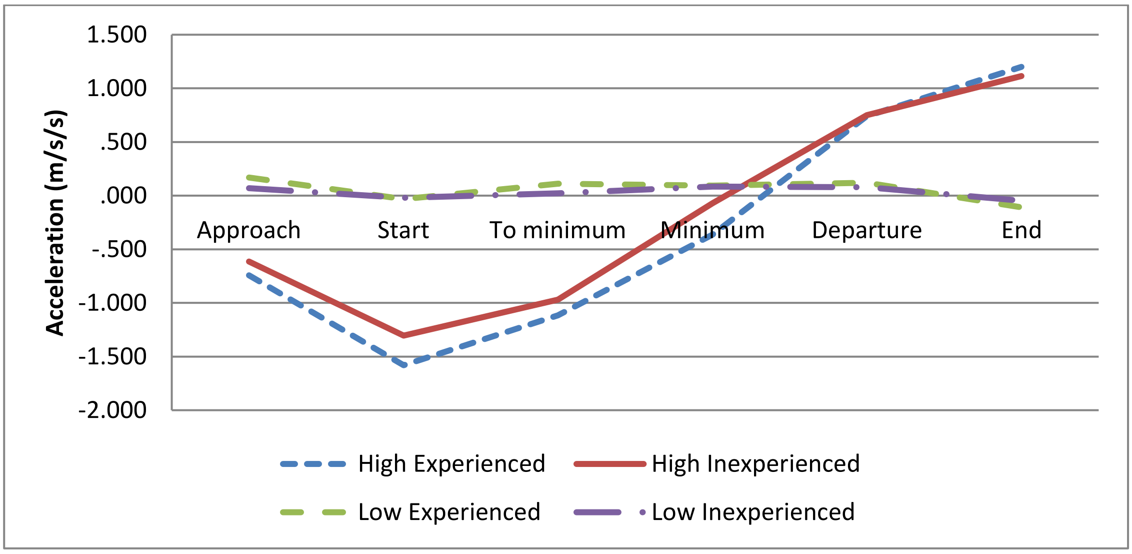

Figure 4.16: Acceleration for left curves for inexperienced and experienced drivers

The deceleration rate was similar for both groups for right curves (Figure 4.17), and continued for both groups at curve minimum. There were no significant differences for high risk curves. For low risk curves, experienced drivers accelerated at a faster rate on approach (0.78 compared with 0.56 m/s/s) and approaching curve minimum (0.54 compared with 0.37 m/s/s) when compared to inexperienced drivers.

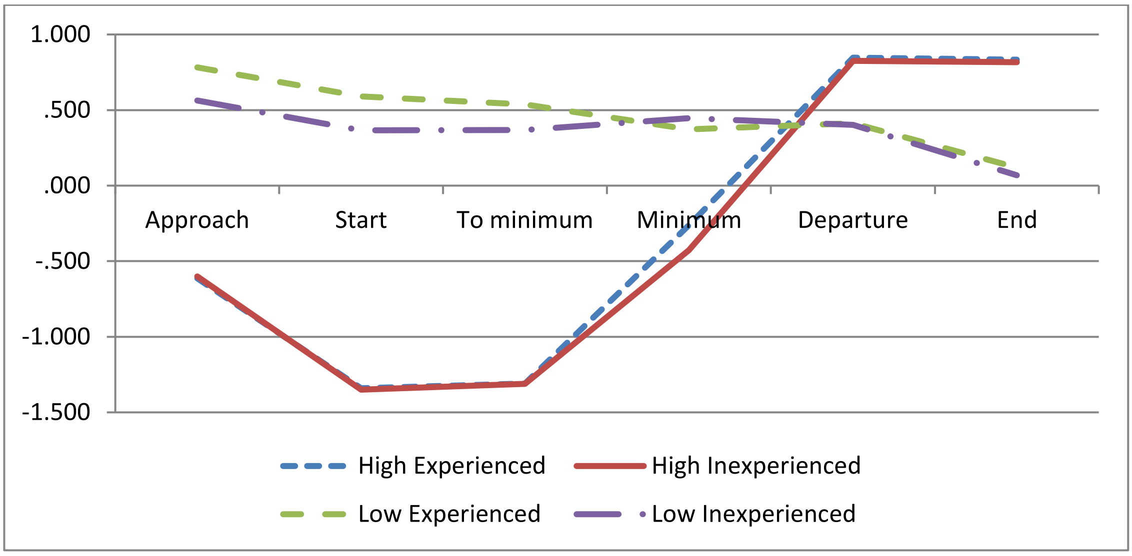

Figure 4.17: Acceleration for right curves for inexperienced and experienced drivers

4.4.3 Side force

When disaggregated by curve risk, there was an apparent difference in side force for low risk curves, with inexperienced drivers exhibiting less side force than experienced (0.043 g compared with 0.045 g). Although the difference is statistically significant, it is not substantive, with the difference being imperceptible to road users. There was no difference in side force for high risk curves.

Analysis comparing side force by curve risk showed there were no differences between inexperienced and experienced drivers through different points in the curve. The only exception to this was that inexperienced drivers showed lower side force on departure of low risk curves, although this difference was not substantive (0.046 g compared with 0.049 g).

When combining curve direction and curve risk it was seen that there were several statistically significant differences, but in all cases these differences were not substantive. There was no difference between driver groups for high risk left curves, but for other curves, inexperienced drivers showed lower side force than experienced drivers (0.121 g versus 0.126 g for high risk right curves; 0.037 g versus 0.039 g for low risk left curves; and 0.051 g versus 0.053 g for low risk right curves).

There were no substantive differences at different points through curves for left curves (Figure 4.18) or for right (Figure 4.19). However, there were some points where differences were statistically significant.

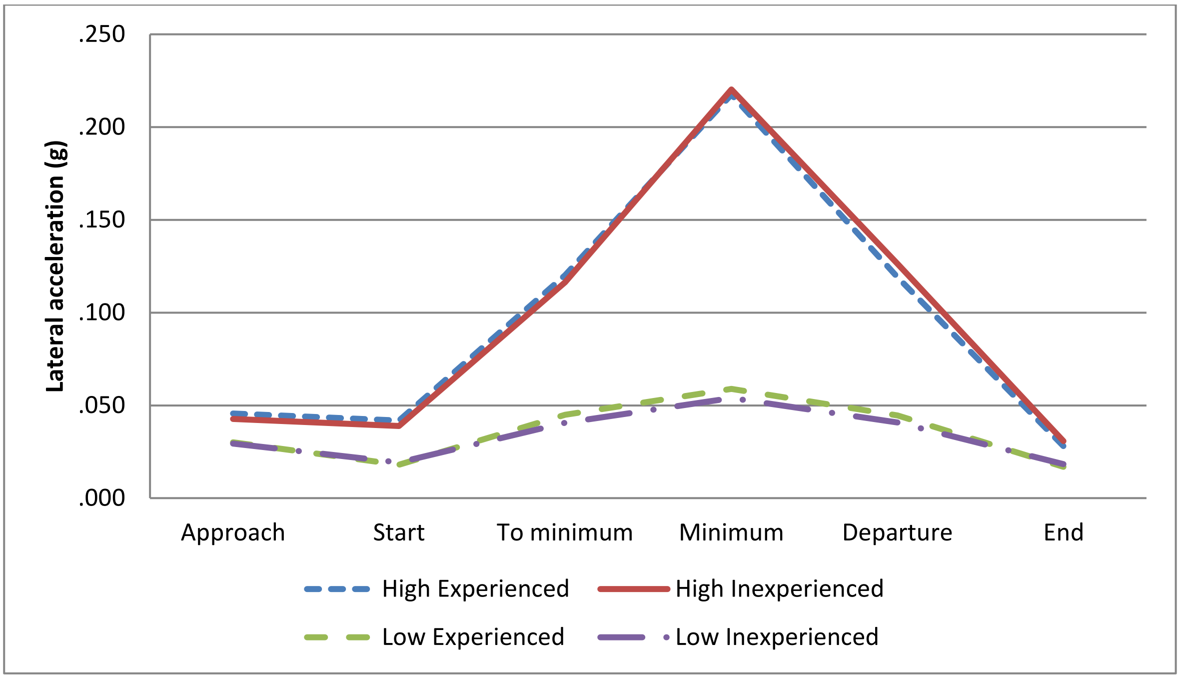

Figure 4.18: **Lateral acceleration through left curves for inexperienced and experienced drivers**

For left curves there were minor but significant differences for high risk curves at departure (0.126 g for inexperienced and 0.119 g for experienced), while for low risk curves there were differences when travelling to minimum (0.041 g for inexperienced and 0.045 g for experienced) and departure (0.041 g for inexperienced and 0.045 g for experienced).

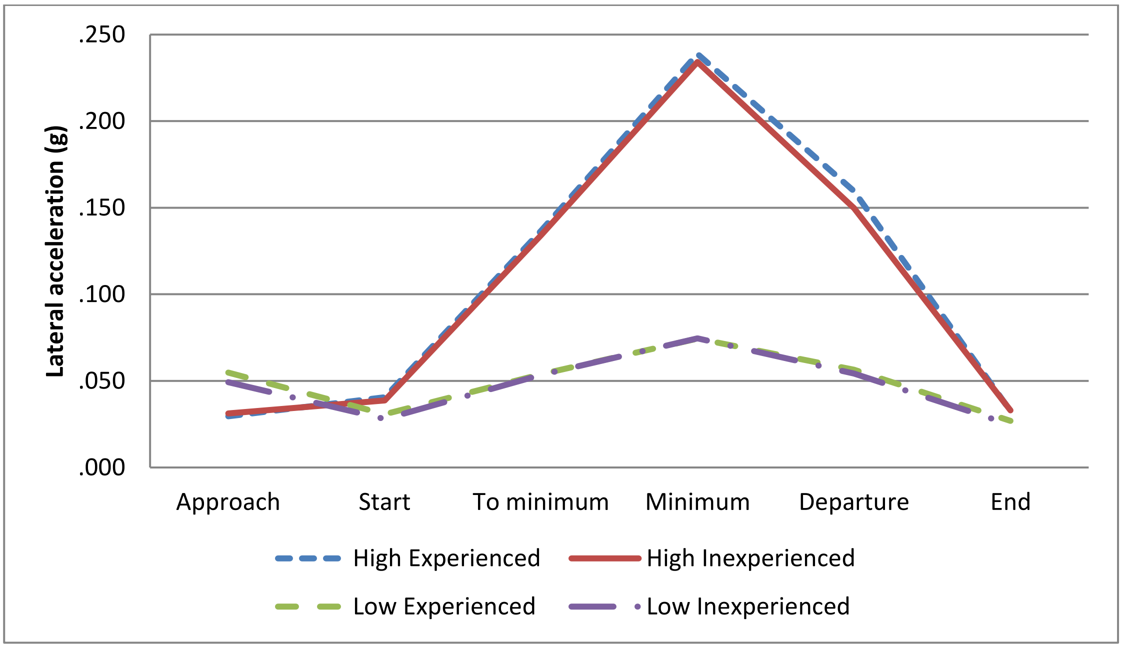

Figure 4.19: **Lateral acceleration through right curves for inexperienced and experienced drivers**

For right curves there was one significant difference, with lower side force for inexperienced drivers on departure of high risk curves (0.15 g compared with 0.16 g for experienced).

4.4.4 Lane position

Inexperienced drivers were closer to the edgeline than experienced for high risk curves (0.79 m compared with 0.83 m), but this difference did not occur for low risk curves.

When comparing left and right curves, the distance was in each case different. For high risk curves, inexperienced drivers travelled closer to the edgeline than experienced for left (0.73 m compared with 0.78 m) and right curves (0.86 m compared with 0.88 m). For low risk curves, inexperienced drivers were closer to the edgeline for left curves (0.62 m compared with 0.64 m) but the reverse situation occurred for right curves (0.9 m compared with 0.87 m).

Results for lane position through the curve showed significant and substantive differences between inexperienced and experienced drivers. Figure 4.20 shows the distance for left curves, while Figure 4.21 shows the results for right curves.

For left curves, there were no significant differences in lane position for low risk curves. The situation is different for high risk curves. Experienced drivers were further from the edgeline at all points except at the curve minimum and curve end. The differences were substantive on approach (1.07 m compared with 1.02 m); at the curve start (1.01 m compared with 0.9 m); on approach to curve minimum (0.65 m compared to 0.58 m); and on departure (0.73 m compared with 0.69 m).

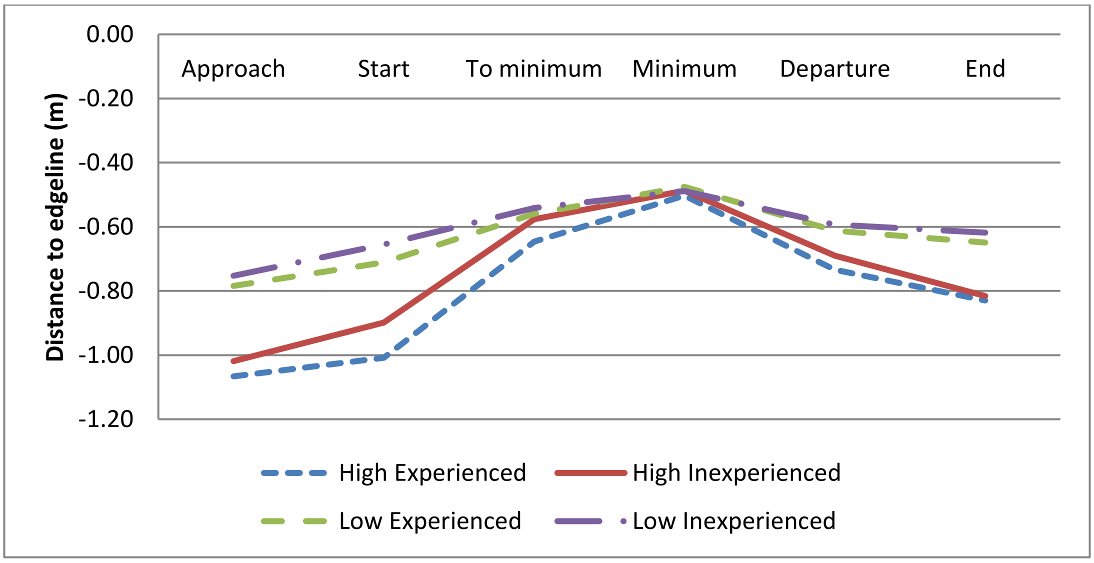

Figure 4.20: Distance to edgeline for left curves

For right curves, the behaviour is also quite different. Experienced drivers again 'cut the curve' and recover their lane position more quickly on departure.

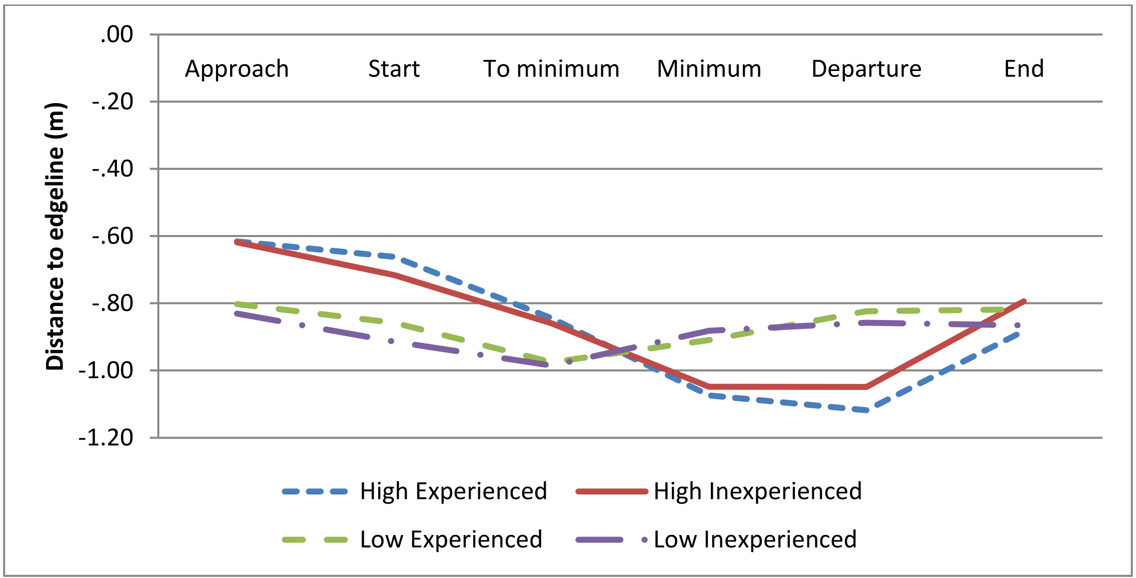

Figure 4.21: Distance to edgeline for right curves

For right curves, there was no difference in position for low risk curves. However, for right curves, the difference was statistically significant and substantive at several points. Although the difference at the curve start appeared large (0.66 m for experienced drivers compared with 0.72 m for inexperienced drivers) the difference was not significant. However, the difference was significant on curve departure (1.12 m compared with 1.05 m) and at the curve end (0.88 m compared with 0.79 m).

Table 4.7 shows lane crossing behaviour for inexperienced and experienced drivers, through high and low risk curves. Behaviours for high risk curves were broadly similar, although inexperienced drivers tended to cross the edgeline on a greater number of occasions. For low risk curves, there was quite a marked difference in behaviour. Inexperienced drivers crossed the edge and centreline on substantially more occasions.

Table 4.7: Incidence of lane crossing behaviour for inexperienced and experienced drivers

		Experienced	Inexperienced
High risk curves	Cross edgeline	15	22
	Cross centreline	58	55
Low risk curves	Cross edgeline	9	17
	Cross centreline	18	45

4.4.5 *Summary for inexperienced compared with experienced drivers through high and low risk curves*

Although there were differences when comparing inexperienced and experienced drivers through high and low risk curves, these were not as pronounced as expected. Key findings were that:

- inexperienced drivers were more conservative in their speeds than experienced drivers through both high and low risk curves, although the difference was not substantive
- speed of inexperienced drivers were slower for right curves (although not substantively), but the same for left curves
- there was no detectable difference for acceleration/deceleration
- there was no detectable difference for side force, and indeed the results were remarkably similar
- there was a substantive difference in lane position, especially on the high risk curves. For left curves, experienced drivers were further from the edgeline at all points except at the curve minimum and curve end. For right curves, experienced drivers were further from the edgeline on departure
- there was a greater amount of lane crossing by inexperienced drivers, and this was particularly so for crossing the centreline at low risk curves.

The implications of these results are discussed in Section 5.1.

4.5 Individual differences and design assumptions

An extensive amount of data was available on driving behaviour through each curve, and for individual drivers. This data was assessed to provide context regarding individual driver behaviour through high and low risk curves. This included a review of video footage for each driver and development of speed profiles through individual curves and for individual drivers.

The results presented here are intended to help support the key objectives for this research relating to behaviours at high and low risk curves, and for inexperienced and experienced drivers. This section also includes an assessment of driver variability. The data also offered the opportunity to test whether road design assumptions relating to driver behaviours of interest in this study are met by this sample of drivers. As with previous sections, results are provided on driver speed, acceleration/deceleration, side force and lane position.

4.5.1 Speed

Table 4.8 shows the speed for all drivers at each of the curves. Speeds are taken at the minimum point within each curve, and are separated into high and low risk curves. Information is provided for mean, maximum and minimum speeds and standard deviation for each curve.

Table 4.8: Speed results for individual curves at curve minimum – high and low risk (km/h)

High risk curves					Low risk curves				
Curve	**Mean**	**Maximum**	**Minimum**	**Std.dev**	**Curve**	**Mean**	**Maximum**	**Minimum**	**Std.dev**
10F	52.2	63.1	45.3	4.0	12F	58.0	71.4	50.6	4.9
11F	51.3	60.5	37.0	4.8	13F	56.1	70.1	47.8	5.2
1F	42.9	49.6	32.2	4.0	14F	55.9	71.3	50.8	4.2
22R	45.6	53.3	35.9	4.8	15F	53.6	66.3	47.2	4.5
23R	36.4	52.1	25.5	4.9	16F	56.1	65.8	49.0	4.1
24R	55.0	66.7	41.4	5.5	17F	56.4	68.8	47.3	4.8
25R	50.1	57.7	44.3	3.4	18F	56.7	69.2	49.1	4.1
26R	44.1	49.2	34.1	4.0	19F	60.7	76.7	53.4	5.7
27R	53.8	64.8	42.2	4.7	20F	59.6	73.4	44.3	5.3
28R	48.6	58.0	38.3	4.3	21F	61.5	81.5	51.6	5.4
29R	50.7	59.3	39.8	4.4	31R	70.2	82.9	62.1	5.4
2F	30.1	39.8	20.7	4.1	32R	58.4	68.2	49.5	4.2
30R	53.8	63.9	41.6	5.4	33R	57.7	70.4	50.9	4.7
3F	50.7	58.5	40.6	4.6	34R	57.4	69.0	47.9	5.0
4F	46.5	56.6	30.7	5.8	35R	55.4	65.7	46.8	4.8
5F	42.5	50.3	29.8	5.1	36R	56.1	66.2	46.6	4.6
6F	49.5	58.3	41.1	4.2	37R	56.2	65.2	50.4	3.8
7F	49.2	60.6	38.2	4.8	38R	58.6	74.2	53.0	4.2
8F	42.1	50.9	30.9	4.7	39R	58.2	69.0	50.3	4.1
9F	47.5	63.9	40.1	5.4	40R	59.1	81.0	52.7	5.9
Mean	47.1	56.9	36.5	4.6	Mean	58.1	71.3	50.1	4.7

It is clear that there is a great degree of variability between curves, and between drivers on each curve. As already indicated, speeds were lower for high risk curves. The standard deviation at curve minimum was similar for high and low risk curves (4.6 for high, and 4.7 for low). However, closer analysis of other points of the curve (e.g. on approach to minimum) indicated higher variability for high risk curves (5.2 for high risk, and 4.6 for low).

The raw data for speed (as a mean for the entire curve) can be found in Appendix E.1. This presents information on speed by curve and driver. The variation in speeds between curves and drivers can be seen clearly from this data.

Speed profiles were generated for individual curves and for individual drivers. The analysis of individual curves allowed a more thorough understanding of driver behaviour given that data was available for each 10 m section of the curve. Initial analysis of this data was useful because for the aggregated data, curves varied substantially in length. Because of this, curves were split into different segments (e.g. approach, start etc.). Understanding of individual curves allowed a more detailed understanding of behaviours, and this informed the eventual analysis.

Figure 4.22 shows driver behaviour through curve 23R, a high risk curve that was 130 m in length. This curve had the highest risk of all curves in terms of the required speed reduction, and this is likely due to a long downhill approach and a severe hair-pin bend as shown in Figure 4.23.

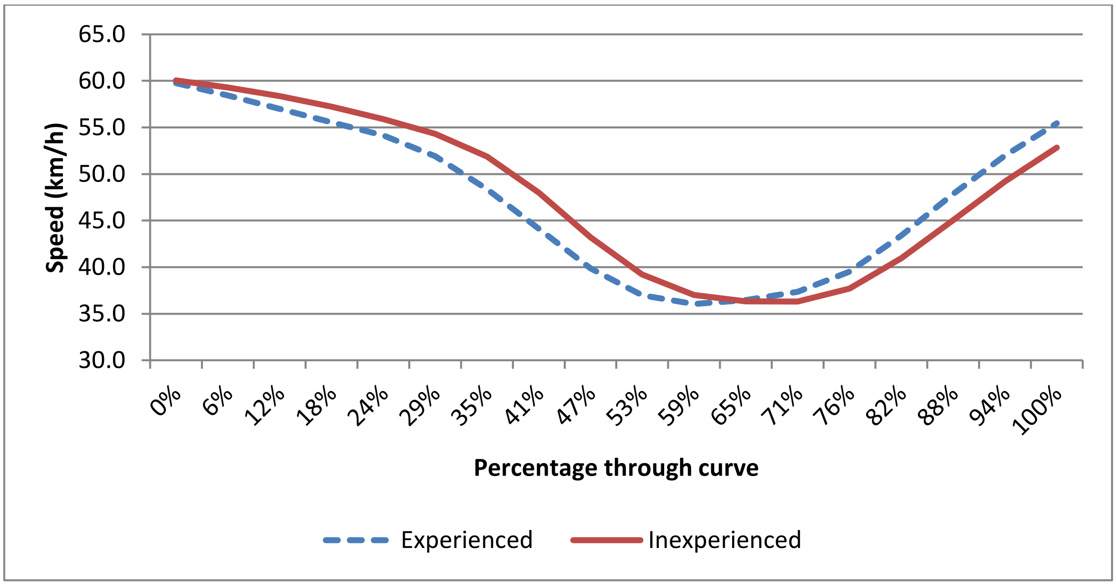

Figure 4.22: Curve 23R – Speed for experienced and inexperienced drivers

Figure 4.23: Curve 23R

The graph compares experienced and inexperienced drivers through this curve, with a mean for each group provided. It is clear for this curve that speeds are identical on approach to the curve, but that experienced drivers slow earlier, and reach their lowest speed before the inexperienced drivers. The experienced drivers then accelerate out of this curve more quickly and are at a higher speed by curve end. As indicated in the earlier results (for all curves combined) this driving pattern is not consistent for all curves, or even for all high risk curves. There was a large degree of variation for individual drivers (inexperienced and experienced).

4.5.2 Acceleration/deceleration

Table 4.9 provides information on acceleration and deceleration for each curve (in m/s/s). The data relates to the entire curve (i.e. from approach to end), and includes information on mean, maximum, minimum and standard deviation values. Maximum values correspond with the highest acceleration value in the sample, while minimum values correspond with the greatest degree of deceleration.

Table 4.9: Acceleration/deceleration for high and low risk curves (m/s/s)

High risk curves					Low risk curves				
Curve	Mean	Maximum	Minimum	Std.dev	Curve	Mean	Maximum	Minimum	Std.dev
10F	.15	5.07	-7.67	1.46	12F	.28	8.11	-7.32	1.14
11F	.12	5.00	-7.62	1.47	13F	-.40	5.36	-5.05	.90
1F	-.66	4.38	-7.35	1.99	14F	.58	5.40	-2.38	.91
22R	-.29	5.24	-9.95	2.00	15F	.39	2.38	-2.86	.76
23R	-.60	8.40	-14.17	4.02	16F	.12	2.11	-2.74	.85
24R	-.09	6.70	-9.34	2.02	17F	.10	1.64	-3.20	.85
25R	-.09	4.46	-6.17	1.29	18F	.72	6.56	-4.28	.97
26R	-.06	4.28	-6.42	1.47	19F	1.02	5.07	-3.25	1.07
27R	-.03	5.27	-4.53	.97	20F	-.12	5.25	-6.51	.94
28R	.06	4.03	-3.59	1.35	21F	.40	3.36	-5.23	1.01
29R	-.18	6.83	-5.24	1.21	31R	.60	8.06	-7.33	1.50
2F	-1.17	10.02	-11.99	3.76	32R	.10	2.68	-4.15	.78
30R	-1.08	9.24	-6.54	1.55	33R	.12	7.41	-8.82	1.17
3F	-.02	5.75	-4.77	1.29	34R	-.09	1.99	-2.96	.83
4F	-.14	4.06	-4.40	1.33	35R	-.07	4.67	-3.01	.75
5F	-.13	5.10	-5.41	1.60	36R	.07	4.90	-3.39	.87
6F	.02	5.86	-6.65	1.40	37R	.06	3.00	-2.04	.64
7F	.39	4.34	-8.55	1.54	38R	.10	1.53	-3.13	.49
8F	.13	4.93	-7.71	1.62	39R	-.02	4.86	-7.32	.88
9F	.20	5.40	-5.93	1.36	40R	.43	7.87	-5.22	1.38
Mean	-.17	5.72	-7.20	1.74	Mean	.22	4.61	-4.51	.93

As already indicated, both acceleration and deceleration were greater for high risk curves. There was also a much greater degree of variability for the high risk curves (a standard deviation of 1.74 compared to 0.93).

Appendix E.2 shows the raw data for each curve and driver. This result represents the acceleration or deceleration at the minimum point. The results from this, as well as those from Table 4.9 can be used to test the assumption from road design guidance relating to acceleration and deceleration. As an example, the maximum comfortable deceleration by drivers is assumed to be 2.5 m/s/s (Austroads, 2010). It is clear this value is exceeded in a number of cases. Although not shown in Appendix E.2, further analysis found that in all cases for high risk curves this value was exceeded by one or more drivers at some point in each curve, and the value was exceeded in most cases for low risk curves.

Recognising that deceleration is often at its peak at curve start, or on the approach to the minimum point, an analysis was undertaken to determine typical values at these locations. This identified that out of 1268 measures of deceleration, the 2.5 m/s/s threshold was exceeded in 513 cases (40% of journeys through curves). When comparing high risk and low risk curves it was calculated that the threshold was exceeded in 415 out of 639 cases for high risk curves (65% of curves), and 98 out of 629 cases for low risk curves (16%). When comparing experienced and inexperienced drivers on this measure, the inexperienced drivers exceeded the 2.5 m/s/s threshold on 276 out of 648 cases (43%) while experienced drivers exceeded the threshold on 237 out of 620 cases (38%).

Figure 4.24 shows the deceleration and acceleration for one curve (23R, described in detail in Section 4.5.1). It can be seen that deceleration for this curve started earlier for experienced drivers and was generally greater on approach. Peak deceleration was greater for inexperienced drivers, but both groups were notably well in excess of assumed comfort levels. Deceleration turned to acceleration earlier for experienced drivers and it is notable that inexperienced drivers continued to decelerate beyond the curve minimum point (which is located 65% through the curve). Experienced drivers had greater acceleration out of the curve. As discussed in Section 4.5.1, this difference between inexperienced and experienced drivers was not repeated for all curves, but merely presented to illustrate driver behaviour for a single curve.

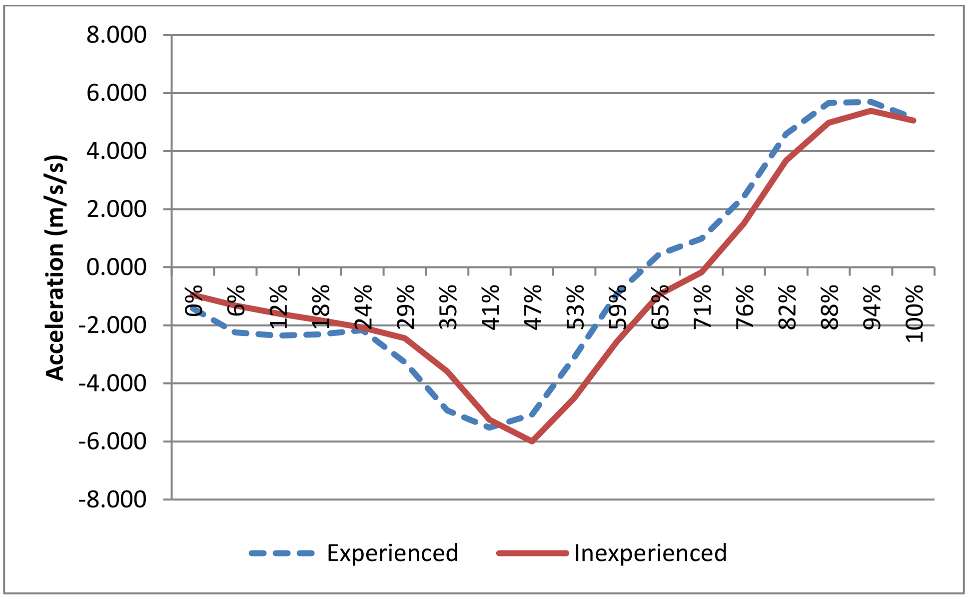

Figure 4.24: Curve 23R – Deceleration/acceleration for experienced and inexperienced drivers

4.5.3 Side force

Table 4.10 provides information on side force for each curve. The values are in 'g', and represent the mean, minimum, maximum and standard deviation through each curve.

Table 4.10: Lateral acceleration for high risk and low risk curves (g)

High risk curves					Low risk curves				
Curve	**Mean**	**Minimum**	**Maximum**	**Std.dev**	**Curve**	**Mean**	**Minimum**	**Maximum**	**Std.dev**
10F	.10	.00	.30	.07	12F	.05	.00	.18	.04
11F	.12	.00	.43	.09	13F	.03	.00	.10	.02
1F	.20	.00	.42	.10	14F	.04	.00	.13	.03
22R	.21	.00	.48	.12	15F	.09	.00	.24	.05
23R	.20	.00	.73	.17	16F	.02	.00	.07	.02
24R	.15	.00	.52	.11	17F	.03	.00	.08	.02
25R	.09	.00	.32	.07	18F	.03	.00	.15	.03
26R	.11	.00	.25	.06	19F	.10	.00	.24	.05
27R	.11	.00	.33	.07	20F	.03	.00	.11	.02
28R	.15	.00	.40	.11	21F	.06	.00	.18	.04
29R	.14	.00	.35	.07	31R	.05	.00	.35	.04
2F	.15	.00	.46	.12	32R	.03	.00	.13	.02
30R	.09	.00	.28	.06	33R	.06	.00	.18	.04
3F	.13	.00	.34	.09	34R	.04	.00	.14	.03
4F	.06	.00	.29	.06	35R	.03	.00	.08	.01
5F	.05	.00	.33	.07	36R	.01	.00	.04	.01
6F	.06	.00	.28	.06	37R	.04	.00	.13	.03
7F	.11	.00	.38	.09	38R	.04	.00	.09	.02
8F	.12	.00	.36	.09	39R	.02	.00	.08	.01
9F	.09	.00	.38	.06	40R	.05	.00	.20	.03
Mean	.12	.00	.38	.09	Mean	.04	.00	.14	.03

Appendix E.3 shows the figures for each driver for each of these curves as a maximum value. It is clear from both of these results that that side force was greater for higher risk curves. What is also clear is that the assumed 0.35g comfort level from road design guidance (see Section 2.3) was exceeded in a number of cases. In half of all high risk curves, at least one driver exceeded this threshold. The threshold was not exceeded for any low risk curves. Closer analysis of the results presented in Appendix E.3 shows that when considering individual drivers, the 0.35 g threshold was exceeded for 13% of journeys through curves. There was a slightly higher tendency towards inexperienced drivers exceeding this threshold than experienced drivers (13.4% for inexperienced and 11.6% for experienced).

The results for one curve (Curve 23R described in Section 4.5.1) are presented in Figure 4.25.

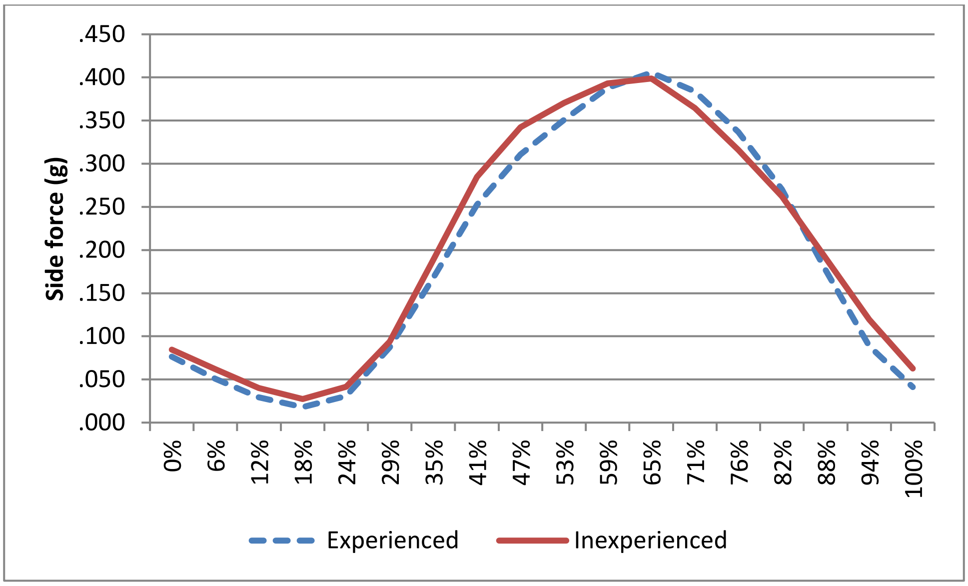

Figure 4.25: Curve 23R – Side force for experienced and inexperienced drivers

Inexperienced drivers show slightly higher side force on approach to the curve, and substantially greater side force on approach to the curve minimum point (65% through the curve). Side force was very similar for both groups and curve minimum, peaking at this point. The mean side force at this point for each group was around 0.4 g, above the maximum assumed in curve design. Side force was greater for experienced drivers immediately after curve minimum, but this reversed near the end of the curve where side force was again slightly greater for inexperienced drivers.

4.5.4 Lane position

Table 4.11 provides information for individual curves for the distance to the edgeline (in metres) for left curves, while Table 4.12 shows this information for right curves. Information is provided on the mean, minimum, maximum and standard deviation. These values are taken across the whole of the curve (approach to curve end; e.g. the mean is for the entire curve).

Table 4.11: Distance to edgeline for left curves (m)

High risk curves					Low risk curves				
Curve	Mean	Minimum	Maximum	Std.dev	Curve	Mean	Minimum	Maximum	Std.dev
10F	-.77	-1.85	.17	.46	12F	-.45	-1.35	.11	.22
22R	-.92	-1.65	1.33	.45	13F	-1.01	-1.99	.05	.42
24R	-.81	-1.83	.09	.32	16F	-.91	-1.83	-.13	.25
25R	-.83	-1.63	-.03	.30	17F	-.35	-.97	.21	.20
29R	-.74	-1.91	.03	.34	20F	-.56	-1.11	-.13	.19
2F	-.94	-1.81	-.21	.34	33R	-.83	-1.61	.07	.28
4F	-.62	-1.81	.11	.29	34R	-.80	-1.57	-.07	.27
5F	-.72	-1.41	-.11	.22	36R	-.40	-.85	-.01	.18
7F	-.72	-1.99	1.45	.36	37R	-.41	-1.03	.17	.24
9F	-.78	-2.37	.75	.36	39R	-.52	-1.49	.23	.23
					40R	-.58	-1.25	.11	.27
Mean	-.78	-1.83	.36	.34	Mean	-.62	-1.37	.06	.25

Table 4.12: Distance to edgeline for right curves (m)

High risk curves					Low risk curves				
Curve	Mean	Minimum	Maximum	Std.dev	Curve	Mean	Minimum	Maximum	Std.dev
11F	-1.02	-1.73	-.37	.24	14F	-1.08	-2.05	-.35	.27
1F	-.70	-2.01	.33	.48	15F	-1.16	-1.95	-.19	.30
23R	-.90	-2.61	.19	.57	18F	-.67	-1.41	-.11	.24
26R	-.97	-1.89	-.11	.33	19F	-.56	-1.35	.09	.22
27R	-.85	-1.51	-.13	.23	21F	-.93	-1.51	-.23	.26
28R	-.62	-2.39	.29	.36	31R	-1.06	-1.83	-.41	.24
30R	-.97	-2.61	-.07	.34	32R	-1.04	-1.63	-.39	.23
3F	-1.01	-2.37	.03	.49	35R	-.90	-1.39	-.51	.19
6F	-.59	-1.83	1.45	.23	38R	-.48	-1.01	.15	.18
8F	-1.02	-2.41	-.17	.36					
Mean	-0.86	-2.14	0.14	0.36	Mean	-0.88	-1.57	-0.22	0.24

Detailed information by subject is provided in Appendix E.4. In both cases it can be seen that variance in lane position was far greater for high risk curves than for low risk. There is also quite high variability within individual curves. It is also clear that assumptions made in road design guidelines (see Section 2.3) may not be met based on this dataset. Given the high variability of the data, it is possible that not all drivers are starting and finishing their journey through curves in the centre of the lane. This issue is explored in further detail in the following results sections.

4.5.5 Summary for individual differences

Two aspects of the results are of interest in relation to the core study objectives. Firstly, there was a large degree of variability for individual curves and drivers. It is noted that for high risk curves there is greater variability (when compared to low risk curves) in speeds, acceleration/deceleration and lane position. There was slightly greater variability for side force.

Secondly, when analysing individual differences it is apparent that several of the values assumed in road design guidelines were exceeded by this group of subjects, particularly for the high risk curves. Key findings were that:

- there were greater levels of deceleration than assumed in guidelines (the 2.5 m/s/s level was exceeded in 40% of all individual curves, and in 65% of cases for high risk curves)
- inexperienced drivers exceeded the 2.5 m/s/s level more often than experienced drivers (43% of all individual curves compared with 38% of curves)
- side force was greater than assumed (the 0.35 g comfort level was exceeded by at least one driver for half of the high risk curves, and 13% of all journeys through high risk curves exceeded this threshold)
- there was a higher tendency for inexperienced drivers to exceed the 0.35 g compared to experienced drivers.
- results regarding lane position and speed were also outside of design assumptions.

4.6 Summary of results in relation to hypotheses

Based on the results presented above, the hypotheses identified prior to the experimental phase are either supported or rejected.

4.6.1 Research question 1: Differences between high risk and low risk curves

Hypothesis 1a:

H_o: there will be no difference in driver speeds through high risk curves compared to low risk curves.

H_A: driver speeds will be different through high risk curves compared to low risk curves.

The null hypothesis is rejected, and therefore the alternative hypothesis is supported. Speeds were higher for low risk curves; lower for high risk curves.

Hypothesis 1b:

H_o: there will be no difference in longitudinal acceleration and deceleration through high risk curves compared to low risk curves.

H_A: longitudinal acceleration and deceleration will be different for high risk curves compared to low risk curves.

The null hypothesis is rejected, and therefore the alternative hypothesis is supported. There were substantial differences on this measure between high and low risk curves. There was little deceleration for low risk curves, while for high risk curves deceleration peaked at the start of the curve; remained high on approach to the curve minimum; continued beyond the curve minimum; and then switched to acceleration on the departure.

Hypothesis 1c:

H_o: there will be no difference in side force through high risk curves compared to low risk curves.

H_A: Side force will be different for high risk curves compared to low risk curves.

The null hypothesis is rejected, and therefore the alternative hypothesis is supported. Side force was significantly greater for high risk curves.

Hypothesis 1d:

H_o: there will be no difference in lane position through high risk curves compared to low risk curves.

H_A: lane position will be different for high risk curves compared to low risk curves.

The null hypothesis is rejected, and therefore the alternative hypothesis is supported. There are clear differences for left and right curves when comparing high and low risk curves.

4.6.2 Research question 2: Differences between inexperienced and experienced drivers

Hypothesis 2a:

H_o: there will be no difference in speed through curves for inexperienced drivers compared to experienced drivers.

H_A: speed will be different through curves for inexperienced drivers compared to experienced drivers.

The null hypothesis is rejected, and therefore the alternative hypothesis is supported. There were modest (but statistically significant) differences in speeds, with inexperienced drivers being more conservative in their choice of speed through curves.

Hypothesis 2b:

H_o: there will be no difference in longitudinal acceleration and deceleration for inexperienced drivers compared to experienced drivers.

H_A: longitudinal acceleration and deceleration will be different through curves for inexperienced drivers compared to experienced drivers.

The null hypothesis is supported. Acceleration and deceleration for inexperienced and experienced drivers was not statistically different.

Hypothesis 2c:

H_o: there will be no difference in side force through curves for inexperienced drivers compared to experienced drivers.

H_A: side force will be different through curves for inexperienced drivers compared to experienced drivers.

The null hypothesis is supported. Side force for inexperienced and experienced drivers was not statistically different.

Hypothesis 2d:

H_o: there will be no difference in lane position for high risk curves for inexperienced drivers compared to experienced drivers.

H_A: lane position will be different through curves for inexperienced drivers compared to experienced drivers.

The null hypothesis is rejected, and therefore the alternative hypothesis is supported. There were statistically significant differences in lane position for inexperienced and experienced drivers.

4.6.3 Research question 3: Differences between inexperienced and experienced drivers through high and low risk curves

Hypothesis 3a:

H_o: there will be no difference in speed through high risk curves for inexperienced drivers compared to experienced drivers.

H_A: speed will be different for drivers through high risk curves for inexperienced drivers compared to experienced drivers.

The null hypothesis is rejected, and therefore the alternative hypothesis is supported. There were modest (but statistically significant) differences in speeds, with inexperienced drivers being more conservative in their choice of speed through high risk curves.

Hypothesis 3b:

H_o: there will be no difference in longitudinal acceleration and deceleration through high risk curves for inexperienced drivers compared to experienced drivers.

H_A: longitudinal acceleration and deceleration will be different through high risk curves for inexperienced drivers compared to experienced drivers.

Overall, the null hypothesis is supported. Acceleration and deceleration for inexperienced and experienced drivers was not statistically different. However, for individual points within high risk curves, and for individual curve types there was evidence of statistically significant differences.

Hypothesis 3c:

H_o: there will be no difference in side force through high risk curves for inexperienced drivers compared to experienced drivers.

H_A: side force will be different through high risk curves for inexperienced drivers compared to experienced drivers.

Overall, the alternative hypothesis is supported. Side force for inexperienced and experienced drivers was not statistically different. However, when disaggregated by curve risk, there were modest differences in side force for low risk curves, with inexperienced drivers exhibiting less side force than experienced drivers.

Hypothesis 3d:

H_o: there will be no difference in lane position for high risk curves for inexperienced drivers compared to experienced drivers.

H_A: lane position will be different through high risk curves for inexperienced drivers compared to experienced drivers.

The null hypothesis is rejected, and therefore the alternative hypothesis is supported. There were statistically significant differences in lane position for inexperienced and experienced drivers.

4.6.4 Research question 4: Design assumptions

The final research question related to assumptions used when designing curves. The basic hypothesis for this research question was that assumptions would be supported based on the analysis.

Hypothesis 4:

H_o: the assumptions used in curve design reflecting deceleration, side force and lane position behaviours are valid.

H_A: the assumptions used in curve design reflecting deceleration, side force and lane position behaviours are not valid.

As discussed in Section 4.5.5, the null hypothesis was not supported. There were substantial differences between the assumptions used when designing curves and the results from the analysis.

The implications of these results are presented in the following chapter, including discussion relating to the key research questions and hypotheses. This also includes discussion on how an understanding of differences in behaviours might better help understand crash risk at curves.

5 DISCUSSION

5.1 Discussion of results

As outlined in Chapter 1, the purpose of this research was to better understand the behaviours of drivers that might contribute to the elevated crash risk at curves. The relationship between speed and lane position was of interest given that these are two elements that provide a direct link to risk through side force at curves, and that are within the control of drivers. This study included an assessment of differences in behaviours between high and low risk curves; and for experienced drivers and inexperienced drivers. A better understanding of these combined elements might help identify solutions to improve safety at curves whether these relate to changes in the road environment or improved driving strategies. This is particularly important given the high level of risk at curves.

To achieve this objective, driver speed, acceleration/deceleration, side force and lane position were assessed at different points through curves. Assessments were made based on key research questions, and statistical analysis undertaken on related hypotheses. These were selected to identify differences between high risk and low risk curves and differences between experienced and inexperienced drivers.

The following sections summarise the key findings for each of these issues while section 5.2 discusses the implications of these findings. Methodological strengths and limitations from this study are discussed in Section 5.3 while recommendations for further research are presented in Section 5.4. Concluding comments and a summary of research contributions from this study are provided in Chapter 6.

5.1.1 Research question 1: Differences between high risk and low risk curves

There were quite marked differences in behaviours between high risk and low risk curves. In accordance with previous research and with expectations based on design guidance:

- speeds were lower for high risk curves
- acceleration and deceleration levels were greater
- side force was greater
- variance between drivers was greater.

In addition to these validations of previous findings there were three new findings from the analysis that are of interest, and relate directly to the research questions. These relate to speed (and more specifically deceleration in speed beyond the curve minimum point), lane position and side force.

Deceleration beyond curve minimum

One particularly interesting finding from this study was that deceleration continued through and beyond the curve minimum point (or mid-point) for high risk curves. Given this is a high risk location (this is the point at which maximum side force is reached, and vehicles are closest to either oncoming vehicles or the roadside) it is highly desirable that drivers will have already fully decelerated by this point. Road design standards typically assume that speed reduction is complete at curve start, let alone at this point later in the curve (Austroads, 2010). Although there are some indications from previous research confirming continued reduction in speed within curves (e.g. Campbell et al. 2008), the finding regarding the extent of deceleration beyond the curve minimum is new. This information is only available because of the methodology adopted in this research whereby continuous data at a high resolution was collected over a large number of curves. Previous research utilising discrete data collection at points through curves was unable to provide reliable information on this issue.

This finding could have implications for design guidance and treatment options as discussed below.

Lane position through curves

There are substantial differences in lane position on approach and through curves when comparing high and low risk curves. Lane position also differed by curve direction as discussed in Section 4. Although ‘curve cutting’ has been identified in previous research (e.g. Chrysler et al., 2009; Jamieson, 2012), the magnitude of this difference for different curve types (e.g. high and low risk) has not been previously documented. This finding may have significant potential impacts, offering new insights into driver behaviour, as well as informing future development on road design and possibly construction requirements, as noted in Section 5.2.

Closer analysis of the results on lane position identified a number of occasions whereby drivers crossed either the edge or centreline. Given that this happened most often on approach (crossing the centreline for left curves, and crossing the edgeline for right) it appears that this might be a deliberate strategy by drivers to further reduce side force. This is an interesting hypothesis, as it is often assumed that crossing edge or centrelines is a dangerous manoeuvre by drivers preceding a loss-of-control. In some situations, especially when sight distance is limited, or there are vehicles in the opposite lane, this is undoubtedly a dangerous situation. However, with adequate sight distance and no oncoming vehicles, this may actually prove to be a risk mitigating strategy by drivers. Implications of this finding are discussed in Section 5.2.

Side force

As expected, side force is higher for more severe curves. However, it is clear that assumed values from current road design guidelines are exceeded based on the results from this study. Values are not expected to exceed 0.35 g (Austroads, 2010), but on many occasions drivers in this study produced side force greater than this assumed maximum, often by a substantial amount (values exceeding 0.7 g were recorded). This only occurred on high risk curves. This might indicate that drivers have a higher tolerance for side force than previously assumed, or that drivers unintentionally find themselves in situations where this assumed maximum is exceeded. Either way, the assumptions made in guidance seems inappropriate. This may be for a variety of reasons, including improved vehicle design or flaws with previous research. Whatever the cause, there are implications for this finding for road design (as discussed in Section 5.2).

5.1.2 Research question 2: Differences between inexperienced and experienced drivers

The results indicated that there were few substantive differences for drivers with different levels of experience. It was expected that inexperienced drivers would have exhibited higher speeds given the higher risk of this group. The opposite was observed in this sample. Inexperienced drivers showed lower speeds at all points through curves. It may have been that inexperienced drivers were more cautious in this sample because they were being monitored, or that they are more cautious in selection of speed through curves in general (at least from the short exposures to rural driving gained through this study). Given that some quite extreme behaviours were recorded in the sample (e.g. very high speeds and side force by individual drivers through individual curves) despite being observed, both situations may be true. It is therefore possible that issues instead of (or in addition to) speed selection are significant in the elevated crash risk of inexperienced drivers.

There were no differences for acceleration or side force. The one major difference between these groups of drivers was in the selection of lane position.

Lane position by driver group

Lane position was statistically and substantively different for inexperienced and experienced drivers for left but not right curves. For left curves, experienced drivers were further from the edgeline at all points except at the curve minimum and curve end, indicating that these drivers cut the corner, reducing side force to a greater degree than inexperienced drivers.

5.1.3 Research question 3: Difference between inexperienced and experienced drivers through high and low risk curves

Similar to results for research question 2, there were few substantive differences for drivers with different levels of experience through high and low risk curves. It was expected that inexperienced drivers would have exhibited higher speeds, especially through high risk curves, given the higher risk of this group. As for research question 2, the opposite was observed in this sample. Inexperienced drivers showed lower speeds at all points through both low and high risk curves, the only exception being at the point of minimum curve radius for high risk curves where there was no statistically significant difference. Again, it may have been that inexperienced drivers were more cautious in this sample because they were being monitored, or that they are more cautious in selection of speed through curves in general. Results for acceleration and side force were very similar.

The main difference between these groups of drivers was in the selection of lane position.

Lane position by driver group

The lane position results for inexperienced and experienced drivers become even more pronounced when results are separated for high and low risk curves. Lane position was statistically and substantively different at many points for inexperienced and experienced drivers for both left and right curves. The differences were particularly notable for high risk curves.

For high risk left curves, experienced drivers were further from the edgeline at all points except at the curve minimum and curve end, indicating that these drivers cut the corner, reducing side force to a greater degree than inexperienced drivers. The results for low risk curves showed a similar pattern, but the differences between inexperienced and experienced drivers were not statistically significant. The data from the results section have been reproduced in Figure 5.1 to better illustrate this point (note that the diagram is not to scale, but rather illustrative only).

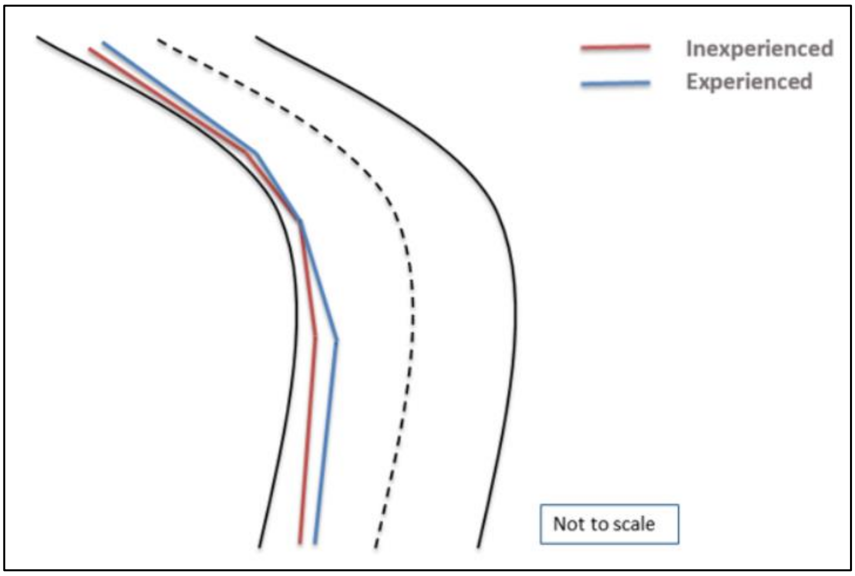

Figure 5.1: Lane position for left curves – inexperienced and experienced drivers

For right curves, the behaviour is also quite different between the driver groups. Experienced drivers again 'cut the curve' and recover their lane position more quickly on departure. They tend to approach the curve from a wider position (i.e. closer to the edgeline), but travel closer to the centreline at the point of minimum curve radius as indicated in. Figure 5.2 illustrates the difference in driving pattern. Again the difference was statistically significant for high risk curves. Although the pattern was similar for low risk curves, the differences between inexperienced and experienced drivers was not statistically significant.

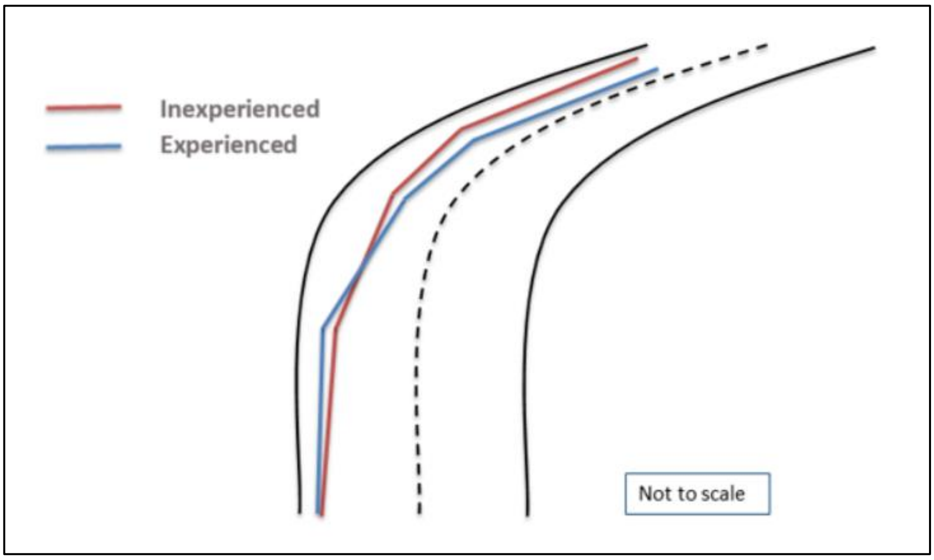

Figure 5.2: Lane position for right curves – inexperienced and experienced drivers

Although the finding regarding corner cutting has been documented in previous research, this appears to be the first time that information on group differences have been identified. It is notable that this difference in lane position was most evident for high risk curves, the location where crash risk is higher for the inexperienced driver group. The implications of these findings are discussed in Section 5.2.

5.1.4 Research question 4: Design assumptions

There were several clear differences between the data obtained in this study, and values assumed in road design guidelines. This is especially the case for high risk curves. Speed reductions were less through low risk curves than would have been expected, and for some low risk curves, speeds actually increased when compared to the curve approach.

Austroads (2010) suggests that the maximum comfortable deceleration level by drivers is 2.5 m/s/s. This value was exceeded in almost half (40%) of all journeys through curves. For high risk curves this was even greater, with this value exceeded in around two-thirds of cases (65%). Inexperienced drivers exceeded this level in more cases than experienced drivers (43% and 38% respectively). Given that deceleration is one of the components of the operating speed model this could have implications for the design of curves.

Side force was often greater than values assumed in design where 0.35g is suggested as the maximum in dry conditions (as experienced by drivers in this study; Austroads, 2010). The threshold was exceeded in half of the high risk curves by at least one driver. For one curve, the maximum side force exceeded 0.7g, which was suggested by Harwood et al. (2003) as the point at which a passenger vehicle was likely to lose control in wet conditions. Again there was a slight tendency for inexperienced drivers to exceed the 0.35g threshold.

Results for lane position also differed to what would be expected based on design assumptions. It is assumed that vehicles start and finish their transition through a curve in the centre of their lane. However, it is clear, especially for high risk curves, that drivers cut the curve, positioning themselves at different points within the lane to achieve this.

These results have implications for road design, as discussed in Section 5.2.

5.2 Implications and recommendations from findings

The findings in relation to the key research questions are synthesised in this section to better identify the implications relating to speed, lane position and a combination of these factors.

Findings relating to speed

One conclusion from this research is that speed selection through curves is not as effective as it could be. Drivers continued to decelerate beyond the point of minimum curve radius, a finding that is consistent with some previous research (at least to the point that driver deceleration was thought to continue beyond the curve entry), but not with assumptions made in road design guidelines. Commencement of deceleration at an earlier point, or a greater degree of deceleration (when done safely) would mean that drivers are travelling at more appropriate speeds at this critical point in curves.

Mechanisms to ensure speed reduction is completed before curve minimum would most likely reduce crash risk. Options need to be explored regarding how this might best be achieved. Such options might include improved advanced warning (e.g. signs located further in advance of curves), or other infrastructure measures to help slow vehicles on approach (see Section 2.7 and Appendix A). In-vehicle technologies might also assist (see the discussion on in-vehicle warning systems in Appendix A.2), by providing warnings to drivers where speed is excessive, or governing vehicle speeds where this is higher than a safe level.

Assumptions in design guidelines relating to speed behaviour through curves appear to be flawed, particularly for high risk curves. The implications for this finding need to be explored further, and appropriate advice provided.

Findings relating to lane position

Lane position was substantially different through high and low risk curves. Drivers tended to select a lane position that resulted in less side force through the high risk curves. Lane position was also substantially different for inexperienced and experienced driver groups. Experienced drivers displayed lane positioning that reduced side force to a greater extent for any given speed through the curve.

Poor lane position combined with speed selection that is too high for the conditions increases the likelihood that the side force exceeds critical values. This issue has not been explored or quantified in previous research. Previous efforts to improve safety at curves have focused primarily on reduction in speed. The results from this research indicate that provision of information on more appropriate lane positioning (in addition to cues relating to speed) may have a beneficial impact on safety. Better knowledge and understanding by drivers and road managers regarding this issue of lane position might be a useful approach (combined with other interventions) when trying to reduce risk at curves. Traffic management and design options should be explored that provide appropriate guidance to drivers on the safest trajectory through high risk curves. This may be achieved through measures such as enhanced painted line marking that more clearly indicates the appropriate lane position on approach and through curves, or even improvements in maintenance regimes regarding existing line marking. Other mitigating measures might include adjustments to driver training regarding appropriate behaviours when driving through high risk curves.

A related issue is the finding that lane crossing behaviour may be a deliberate strategy employed by drivers. This technique, when conducted safely (i.e. when there is good advance sight distance and no oncoming vehicles) may actually improve safety by reducing side force. This issue requires further exploration. However, what is clear, assuming the hypothesis that this lane crossing is a deliberate tactic, is that lane crossing should not be used as a proxy for a high risk situation. A number of studies have used this measure as an indication of a pending lane departure crash. Further research is required on this topic, including analysis of situations where lane crossing may actually be dangerous (e.g. by analysing occurrences where sight distance is limited, or where there are oncoming vehicles).

Assumptions relating to lane position in geometric design guides should also be assessed with the knowledge that for severe curves, the position of vehicles is likely to differ more substantially than for less severe curves. The assumption that drivers start and finish their journey through curves in the centre of their lane appears to be flawed.

There are likely to be implications from the findings on lane position and lane crossing that relate to current road construction guidelines. There is information from the results presented here that might better inform pavement construction for high risk curves. One issue to consider is whether the road shoulder on the approach to right hand curves should be strengthened given vehicles are likely to be using this when approaching severe curves. Similarly, the point before and after curve minimum on left hand curves should be assessed.

Combining speed and lane position results

If the driving behaviour of inexperienced drivers from this study reflects the behaviours of all inexperienced drivers, it is possible that speed forms only one element of driver risk through curves. In this study, there was no great difference in speed between inexperienced and experienced drivers. Therefore the elevated risk of the inexperienced driver group may be the result of some other variable, or the interaction between speed and this variable. Therefore, one key learning from this research is that speed needs to be assessed in combination with other behaviours (particularly lane position) when trying to understand driver behaviour and risk at rural curves.

Although speed on its own is likely to be a contributor to safety through curves, there are other important variables that are also likely to influence safety. As previously highlighted, Spacek (2005) suggested that analysis of curves based on speed alone has led to failed attempts at understanding the risks at these locations. As indicated by Spacek, and supported in this research, lane position is one such variable that also appears to be important to safety outcomes.

Combining results relating to lane position and speed (particularly the need to improve deceleration at or before the curve minimum) may provide additional opportunities to reduce side force through curves, and therefore lead to improved safety. A combination of different approaches, including driver training and design through visual cues may help achieve better selection of speed and lane position.

Assumptions used in road design guidance relating to side force

It has already been highlighted above that results relating to speed and lane position may have implications for current design guidelines. The findings from this research indicate that other assumptions may also need to be assessed. There is evidence that design assumptions relating to acceptable side force through curves underestimate actual levels found in this study.

It is possible that design may need to change to better cater for desired driver behaviour. As one example, superelevation requirements may need to change in order to cater for higher speeds and side force than anticipated through curves. Similarly, current design assumes reduction in speeds from earlier curves in the design of subsequent curves. If drivers are not slowing for more moderate curves (e.g. the low risk curves from this experiment) then design will need to account for this for subsequent curves that are more severe.

Implications relating to the study methodology

It appears that continuous data that includes speed, acceleration/deceleration, side force and lane position has not been collected together in previous research. The approach adopted proved to be cost effective and provided outputs that allowed detailed analysis of relevant variables. The implications are that the method may be used for other studies assessing driving behaviour. Some of the options for research are listed in Section 5.4.

5.3 Methodological strengths and limitations

Emerging technologies have meant that collection of data was possible at a higher resolution (i.e. more data points) and for a larger number of variables. Data was collected at 10m intervals meaning that up to 30 data points were collected for some curves. This is in contrast to much of the previous research where typically only a small number of data points were collected (also see the discussion in Section 2.3.3 and Section 5.1.1). This is a particular strength of this current research, and has led to a better understanding of behaviours through curves. In addition, a device was available that allowed the accurate collection of lane position data. This appears to be the first time that this data has been collected in a comprehensive way across a large number of curves and for a large number of drivers.

As with any research of this type, there are a number of limitations to this study. The subjects selected included only a limited cross-section of the driving public, were all male, and all were volunteers. The reliance on male subjects removes study variance, but also excludes half of the driving public. It therefore prevents lessons to be learned from male versus female behaviour in curves. In addition, the male subjects included may differ in some way to the general male driving population. It is also assumed that the drivers were all in a reasonable state to drive. None appeared to be fatigued, or under the influence of alcohol or other drugs. Given that a high percentage of road crashes involve drivers who are fatigued or impaired, it is likely that at least a small proportion of all drivers on the road are similarly afflicted. Therefore, the sample in this study does not fully reflect the general driving population. Although a good number of subjects were included in this study providing some diversity, replication of this research is required with different groups of drivers to allow broader generalisation of the results.

One further issue was that drivers were being observed (indirectly through the recording devices) throughout the study. It is possible that drivers altered their driving behaviour as a consequence. In order to minimise this, drivers had a 20 minute period to adjust to being monitored, and feedback indicated that many drivers felt that they were relaxed and driving naturally by the start of the test route. In addition, it is possible that some of the behaviours exhibited by drivers were less subject to conscious or direct control, meaning that the fact they were being observed may have had less relevance. Drivers who do not possess the relevant skills or experience (e.g. in lane position selection) may not be able to alter their behaviour, regardless of whether they are being observed or not. Although the methodology used in this study was an improvement over methods from many previous studies, this issue is common to studies utilising an instrumented vehicle. In order to address this issue, further study involving much longer data collection periods (as seen in naturalistic driving studies) should be undertaken to help minimise any observer effect.

Although a number of potential limitations were identified that may influence the findings from this study, the method adopted provided a greater degree of control, collection of a greater number of variables, and a higher level of resolution in the data obtained when compared to most previous studies on this topic. Although care was taken to control limitations, it is possible that some of these limitations will have impacted the results. Care should be taken when extrapolating the results from this study, and further research is required to provide a greater level of confidence in the results and their applicability to a broader range of road environments, driving conditions, and for a broader range of drivers.

5.4 Recommendations for further research

The focus of this research has been on identifying key factors that might influence crash risk while driving through rural curves, and particularly those relating to speed and lane position. Although this research has added to knowledge on the topic, there are many issues that still need to be addressed to gain a full understanding of this problem, and help identify solutions.

The results of this research have provided a strong indication that lane position on approach and through curves is within the control of vehicle drivers. The decisions made by drivers regarding this are likely to have an impact on safety outcomes. Similarly, speed selection by drivers through curves (particularly high risk curves) is not ideal, with deceleration continuing beyond the highest risk location within curves. Research is now required to identify methods to provide better guidance to drivers about appropriate lane position, and to assess the impact of these methods on driver risk and eventual safety outcomes. Similarly, further efforts are required to identify ways to slow vehicles sooner on approach to curves. Both issues may be addressed through changes to the road environment or through driver education and training. Vehicle technologies may also offer solutions in future. All of these approaches need to be explored through further research, and effective solutions identified.

An additional finding was that drivers appear to display deliberate lane crossing behaviour, possibly as a strategy to reduce side force through curves. Further research is required on this issue to determine driver understanding on this behaviour, and the likely safety implications. More specifically, it would be useful to determine whether drivers do deliberately use this lane crossing approach, and in what circumstances.

The methodology that has been adopted in this study (including a wider range of variables collected at a higher level of resolution) offers a new opportunity to investigate a broader range of issues relating to crash risk at curves, as well as in other road environments. As an example, the methodology developed here could be used to test driver behaviour on approach to intersections, including roundabouts. There is currently no operating speed model for intersections, and this information is required to better inform design and operation at these locations.

The results from this study identified that some of the assumptions used in road design may not hold up in real world situations. As discussed in Section 2.3.3, many of these assumptions were developed decades ago when vehicles were different, and data collection was more difficult. More detailed testing of the assumptions used in road design could be undertaken using the approach adopted in this research. From the results of this study, more accurate guidance could be provided on deceleration and acceleration rates, side force assumptions, and lane position assumptions. Other assumptions in road design could also be tested in future research, and better guidance provided. This has implications for improving road safety, but also potentially for the costs of constructing new roads and reconstructing existing roads.

Lastly, the data collected through this study could be used to assess a number of other issues relating to driving on rural roads. In some cases further data extraction would be required to support this. Examples include an analysis of the influence of sight distance on speed and lane position; a comparison of behaviour at curves in situations where there are oncoming vehicles and situations where there are not; an assessment of additional design elements (e.g. curve length, superelevation) and combinations of road design elements (e.g. the combination of horizontal and vertical curves) and safety outcomes; and corrections made by drivers when certain speeds or side force thresholds are exceeded.

6 CONCLUDING COMMENTS AND SUMMARY OF RESEARCH CONTRIBUTIONS

Crashes at rural curves represent a significant road safety and societal problem. A large number of people are killed and seriously injured each year in crashes at these locations. This study was intended to help determine differences in inexperienced and experienced driver behaviour through high and low risk curves in order to better understand some of the mechanisms that contribute to this problem.

A study was undertaken to collect and analyse data on driver behaviours, and particularly those relating to speed and lane position through curves. As identified in the literature review, these two factors strongly influence safety outcomes through curves through their impact on side force. A number of predictions were made regarding expected differences between driver behaviour for high risk and low risk curves, and for inexperienced and experienced drivers. Contrasting these high and low risk groups was expected to provide an insight into these key driver behaviours. Most of these predictions regarding high and low risk curves were supported by the findings as described in the previous chapter. Predictions regarding differences in inexperienced and experienced driving were not always supported, but the findings relating to lane position were of particular interest.

A key objective of this research was to make significant contributions to the understanding of driver behaviour through rural curves and provide new knowledge on this topic. Based on an extensive review of literature, and the results from the analysis of data generated through the experimental study, there are several new contributions to knowledge relating to driver behaviour through rural curves.

The first such contribution is the finding that drivers continue to decelerate beyond the point of minimum curve radius (curve mid-point) for high risk curves. The methodology adopted in this study (continuous data collection on speed, and a definition of curve risk) allowed a detailed assessment of this issue. Previous research has indicated that deceleration appears to continue beyond the start point of the curve in some instances. However, it is clear from this work that deceleration continues to a greater extent (at least for high risk curves) than previously thought.

The second unique contribution from this research is the finding that lane position was substantially different for high and low risk curves. Previous research has indicated that there are likely to be different lane keeping behaviours for different curves, but this assessment has not been conducted based on curve risk.

Thirdly, it was found that lane position was substantially different for inexperienced and experienced driver groups for the high risk curves. This is also a unique finding, and as discussed in Section 5.2 has potential for significant contributions to improving safety.

Fourthly, drivers appear to display deliberate lane crossing behaviour, presumably to reduce side force through curves. Although lane crossing behaviour has been identified in previous research, it is usually assumed that this is a precursor to a run-off-road event. It is possible that this is not the case, but rather this is a deliberate strategy adopted by drivers.

Fifthly, the methodology of collecting continuous data that includes measures of speed, side force and lane position in combination is a new one. The approach has been shown to have merit, and offers a mechanism for addressing a number of issues relating to driver behaviour and road design (as indicated in Section 5.4). This methodology might be utilised by other researchers in future to further understanding on these issues.

Other findings from this study are not unique, but rather provide support or extend understanding for issues identified in previous research.

It is clear that factors other than speed are likely to play a significant role in safety of drivers through curves. Although speed plays a significant role, there is evidence from this study that supports previous research indicating that attention should also be given to other elements of driver behaviour, including lane position.

There was support for previous research that speeds do not tend to reduce for curves that are more moderate (represented by the low risk curves in this study). In aggregate, these curves are likely to contribute to a great deal of risk on rural roads because there are a large number of these on the rural road network (e.g. Levett, 2005). Methods to reduce speeds through curves of this type should be investigated.

Lastly, the assumptions made in road design guidelines need to be revisited based on findings from this study. Although this finding has been documented previously (see Section 2.3), this study provides quantification for several possible revisions under real driving conditions. Key revisions to assumptions include that drivers continue to decelerate beyond the start of the curve; that drivers have a higher tolerance for side force, or at least exhibit higher side force than currently assumed in design guidance; that speeds do not reduce substantially for moderate curves; and that there is considerable variability in lane position on entry and departure to curves.

The findings from this research thesis as well as current and future research papers based on this work will provide useful information for those seeking to improve safety at rural curves. Published papers to date include Turner, Woolley & Cairney (2015a) and Turner, Woolley & Cairney (2015b, provided in Appendix F).

In summary, the primary objective of this research has been met with an improved understanding of the factors that contribute to risk at rural curves. The hypothesis that a better understanding of driver risk at rural curves will be reached if speed is assessed alongside lane position has been supported by the analysis. The findings from this research contribute significantly to the existing pool of knowledge on safety at rural curves. This new knowledge has the potential to facilitate better design and management practices that will lead to fewer deaths and serious injuries at these locations.

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APPENDIX A REVIEW ON EFFECTIVE TREATMENTS FOR RURAL CURVES

A.1 Treatment of Rural Curve Speed through Road Engineering Measures

There are a lot of measures that are used in an attempt to address crash problems on high speed roads, a number of which attempt to do this through better management of speed, either at critical points on the road network (such as curves), or in general.

A large number of road safety engineering measures are available that serve to reduce speeds on rural roads. These vary by cost and effectiveness (in terms of crash reduction). Different measures are applied in specific situations (e.g. curves, intersections, at transition zones or for entire routes). The following section concentrates on the treatments that have been used at curves, and provides a summary of the general principles that apply for these treatments that act to reduce speeds.

A.1.1 Advanced Warning Signs

Warning signs are commonly used to reduce speeds in advance of bends. It is expected that such signs will raise the attention level of motorists, and slow them to a safer speed for the environment. Aside from the standard warning signs, a number of different sign configurations have been employed to raise awareness at particularly problematic locations. Measures include the use of larger than standard sized signs, brightly coloured backing boards, and flashing lights. Warning signs can also be accompanied by an advisory speed limit.

Donald (1997), in a review of curve warning signs found evidence of a reduction in crashes of 30% following the installation of such signs. Creasey and Agent (1985) developed a set of recommended crash reduction factors for Kentucky based on an extensive review of the literature (including before and after studies), as well as engineering judgement. They also reported the same reduction for the installation of warning signs at curves.

Agent et al. (1996) estimated accident reduction factors associated with various types of highway safety improvements, including curve warning signs, and suggested a 30% reduction in crashes from the use of such treatments.

Elvik et al. (2009) also reported a reduction of 30% in injury accidents from the use of curve warning signs.

A.1.2 Chevron Alignment Markers

Chevron alignment markers (CAMs) are commonly used to help indicate the presence and severity of curves. Austroads has conducted research on the application of various road safety countermeasures for use in the Australasian context based on published literature (Turner, 2007). This research suggested a reduction of 30% in casualty crashes could be expected from the introduction of CAMs.

A.1.3 Speed Advisory Signs

Advisory speed warning signs are sometimes used to help indicate the severity of a curve. Donald (1997) conducted a review of curve advisory speeds and found some limited evidence to show that such signs have a positive influence on crashes. Donald reported on one study that found a 62% reduction in casualty crashes, and a 56% reduction in all crashes following the installation of advisory speed signs. The Austroads (2016) guide to the treatment of crash locations included figures on a number of countermeasures, and suggested a 30% reduction could be expected in head-on crashes with the introduction of advisory speed signs on curves although it is unclear what this figure is based on. Elvik et al. (2009) reported a reduction of 13% in injury accidents from the introduction of recommended speeds in curves.

However, advisory speeds are often set based on standards which were designed for older style vehicles, and there is a general scepticism by the public as to the speeds that are advised (Donald, 1997). An audit in New Zealand of existing advisory speed warning signs found that there was a lack of consistency in their use. Only half (53%) of the speeds indicated were set at the recommended advisory limit (as determined by side thrust gauge testing), and almost 1 in 5 were more than 10 km/h out. Some indicated advisory speeds that were 20-25 km/h above that recommended by the warrant (LTSA, 1998).

The Australian Standard (AS1742.2) and Austroads Guide to Traffic Management (Austroads 2009b) both contain information on the appropriate location for warning signs. The location is based on the speed environment (measured by the 85th percentile speed), and whether there may be a need to stop, slow significantly, or slow moderately. The figures are provided in Table A 1 (Austroads 2009b).

Table A 1: Longitudinal location of warning signs

Road environment	A (m)			B (m)
	Must or may need to stop	Significant speed reduction required	No, low or moderate speed reduction required	
V_{85}: < 75 km/h	80 – 120	60 – 80	40 – 60	50
V_{85}: 75 – 90 km/h	120 – 180	80 – 120	60 – 80	60
V_{85}: > 90 km/h	180 – 250	120 – 180	80 – 120	70

Notes:
V_{85} = 85th percentile approach speed measured 1.5 to 2 times 'A' in advance of hazard.
A = distance from sign to hazard (or nearest sign to hazard where there are two or more signs)
B = minimum distance between successive signs where there are two or more.
Source: AS1742.2.

It is not clear where the information on advance warning location originates, although text in the Austroads guide suggested the following:

"A road sign must be located at a position along the road where it can be related to the road feature to which it refers, and if necessary, far enough in advance of that feature to ensure that all drivers will see the sign, read it, and make a decision before reaching a point where they must act" (p47).

It is also suggested that no sign should be located more than 15 seconds of travel time in advance of the hazard, indicating that there is a limited memory for such signs, or that there is a need for the sign to be clearly linked to the hazard it warns of. However, for situations that are relatively complex (the examples of services or tourist facility signs are provided) it is suggested that a maximum travel time of 12 seconds should be used.

What is clear is that current guidance provides little detail on critical sign locations based on specific curve characteristics. That is, beyond the distinction of curves where a significant speed reduction, or a moderate speed reduction, there is little else regarding appropriate locations of signs based on curve design.

A.1.4 Vehicle Activated Signs

Vehicle activated signs have been used at a number of sites in the UK and elsewhere to warn motorists of an upcoming bend (Figure A 1). The purpose of these signs is to raise awareness of the hazardous locations, resulting in greater attention by drivers, and a reduction in speed. These signs are usually activated for a short time (around 4 seconds) when an approaching vehicle exceeds a threshold speed limit (normally set at the 50th percentile speed as measured prior to the introduction of the signs). Once triggered, the sign displays the hazard, and may include a message to slow down. A further explanation of these signs can be found in Winnett and Wheeler (2002).

Figure A 1: Vehicle activated sign (from Warwickshire County Council)

The installation of vehicle activated signs at bends in the UK resulted in speed reductions of between 2.1 and 6.9 mph (3.4 to 11 km/h). At two sites where crashes were recorded, there was a reduction in crashes of 54% and 100% (although numbers were initially low at the latter site). A statistical analysis was conducted for all types of vehicle activated signs in one UK county (bends as well as junction treatments and other hazardous locations). Across all of these sign types, a 31% reduction in crashes was detected (Winnett and Wheeler, 2002).

Vehicle activated chevron alignment markers (Figure A 2) have been used in Denmark (Herrstedt, 2006) although details about their use and effectiveness was not provided.

Figure A 2: **Vehicle activated curve chevron (from Herrstedt, 2006)**

A.1.5 Other Delineation Devices

Various other delineation devices can be used at curves to improve safety (e.g. guideposts, line marking, pavement markers etc). Most of these provide additional guidance on the direction of the roadway to improve safe negotiation, but may also have some effect on speed. In some cases it is likely that the introduction of these treatments will lead to an increase in speed. For example, Elvik et al. (2009) provided the results of meta-analyses estimating the impact of various kinds of road markings. They identified only minor improvements in accidents, or in some cases increases and concluded that this might be associated with increased speeds. It could be expected that there might be some increase in speeds, particularly in dark conditions, if the road ahead is made clearer for motorists. Elvik et al. concluded that combinations of road markings were more effective than one type alone.

A.1.6 Transverse Rumble Strips

Audio-tactile treatments have been applied transversely, or across the driving lane, to warn motorists of approaching curves with the intention of increasing awareness and slowing drivers.

Although transverse rumble strips have been used in a number of locations there is little objective information available on their effectiveness in terms of speed or crash reduction at curves. McGee and Hanscom (2006) reported that there is no conclusive evidence of roadway rumble strip effectiveness in reducing crashes at curves, but that they did tend to reduce speed, in most cases, but not to a practical level.

The UK Department for Transport (2005) described a trial of a variant of rumble strips called ‘rumblewaves’. These are a quieter alternative to conventional rumble strips, creating noise and vibration within the vehicle driving on it, but not significantly increasing noise levels for those outside the vehicles. Rumblewaves have been tested on the approach to rural bends, but were found to have minimal impact on speed reduction (less than 1 km/h at the trial location).

A.1.7 Perceptual Countermeasures

Perceptual countermeasures are intended to improve safety through a change in a motorist's perception of the environment. As a speed countermeasure they can help give the impression that motorists are travelling faster than they actually are. Recent work in Australia has evaluated the effectiveness of perceptual countermeasures, including measures at curves. A study by Macaulay et al. (2004) found that the use of enhanced edge post spacing, with ascending post heights for curves (to give the impression of a more severe curve) produced mixed results.

The curve treatment (shown in Figure A 3) consisted of laterally diverging guide posts with ascending heights, applied on the outside of a curve, to create the perceptual illusion of the curve being tighter than it is in reality. A significant decrease in speeds was seen at three sites, with no change at two, and an increase at one.

Figure A 3: Perceptual Curve treatment (from Macaulay et al., 2004

A.1.8 Route Based Curve Treatments

In various locations across the rural road network, treatments have been installed at curves to address crash risk. However, if treatments are installed in an ad hoc manner, it is likely that inconsistencies will emerge. Signs and markings will be used in one location, but not at another with a similar design. Because there are numerous combinations of treatments available to warn motorists of adverse road alignment conditions, differing combinations of treatments may be used at similar locations. This can lead to confusion for motorists, and difficulties in judging the severity of curves. Even single treatments (in this case advisory speeds) can be applied in an inconsistent manner, thereby reducing the benefits of these treatments.

In order to address this problem, a number of systems have been developed that provide advice on the consistent application of treatments to address safety at horizontal curves across the whole road network.

As discussed in Section 2.4.2, Herrstedt & Greibe (2001) developed a model to identify risk for different types of bends. Their model was based on the approach speed to curves, and the curve design speed. Based on these factors, the model contained five risk categories as shown in Figure A 4. Curves within category A had very slight risk, while those in E had a very high risk. The risk was determined by the reduction in the kinetic energy of a vehicle required in order to navigate a bend safely. Other risk factors (such as sight distance, and curves with irregular radius) may also have been considered before assigning a curve to one of these categories.

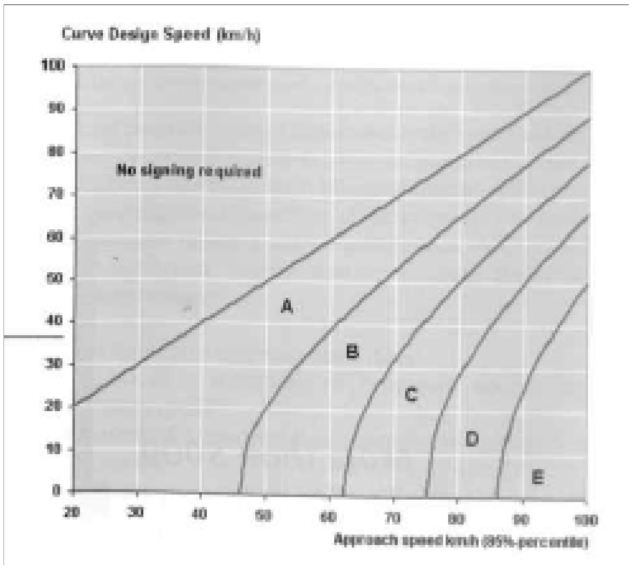


Figure A 4: Curve risk categories (from Herrstedt & Greibe, 2001)

Once the risk of the curve was identified, signs and markings for that curve were installed according to this risk category. An example of such a system is shown in Figure A 5 (note that the speed advisory for class D and E would be adjusted according to the requirements at individual curves).

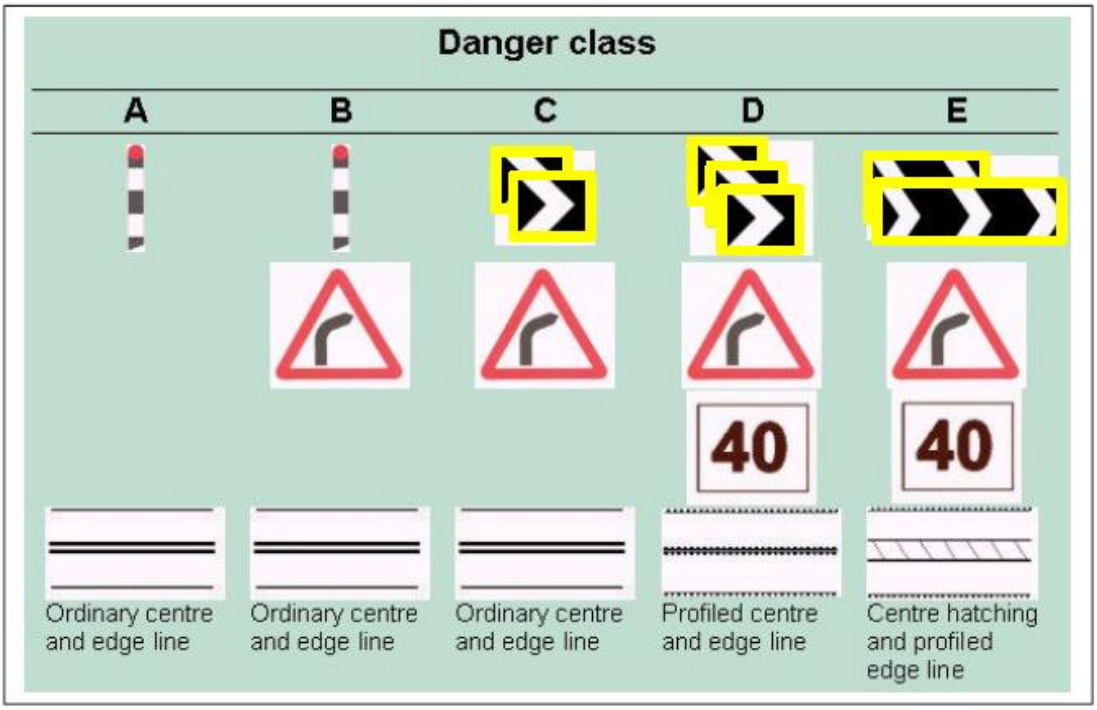


Figure A 5: **Signing for different risk categories (TRL and DfID, 2001)**

Cardoso (2005) developed a similar regime for use in Portugal. This system sought to determine the 'consistency class' of a curve, and apply a consistent treatment to each curve in this class. The consistency class was essentially a risk calculation based on a number of variables including information on the conformance of curves with driver expectations (based on calculated speed profiles), speed reduction on the approach to curves, the expected deceleration, and whether shoulders were paved.

A.2 Vehicle and driver-based interventions to address speed

As well as road-based and road user contributors to risk, vehicle factors also are likely to play a role in crash occurrence at curves. Issues such as tyre tread depth, provision of electronic stability control (ESC), standard braking performance, road departure warning systems, vehicle handling and stability may all play a part in the likelihood of vehicles losing control at curves. Vehicle features also play a key role in the severity of crashes when they do occur, with airbags, seatbelts and other safety features all likely to reduce the severity of injuries sustained.

As an example, ESC is thought to produce significant reductions in run-off-road crashes. This technology works by monitoring various aspects of vehicle performance (e.g. lateral acceleration), and applying braking to individual wheels to maintain vehicle control. A number of studies have evaluated the effectiveness of this technology. Green and Woodrooffe (2006) suggested that for single-vehicle crashes, ESC reduced the risk of a fatal crash involvement by 31% for passenger cars and 50% for utility vehicles. These figures are similar to those found in National Highway Traffic Safety Administration (2004). In that study it was found that fatal single-vehicle crashes were reduced by 30% in passenger cars, and 63% in SUVs.

Other vehicle-based feature are likely to provide safety benefits, although in many cases these benefits have yet to be quantified. In addition, although vehicle-based solutions are likely to produce significant safety improvements, with the obvious exception of ESC, these are typically not through reductions in vehicle speed. Many vehicle-based features provide passive safety improvements, resulting in a decrease in the severity outcome of a crash through vehicle occupant protection.

Significant improvements have been made in the safety features of vehicles over the last few decades, and this has led to a reduction in the probability of a severe injury when a crash does occur. Newstead et al. (2010) reported on improvements in vehicle safety based on the New Zealand vehicle fleet for vehicles manufactured between 1964 and 2008. They reported a significant improvement in safety for vehicles manufactured over this time, with a reduction of the chances of death or serious injury of 84%. The risk of a driver being killed or transported to hospital following a collision fell from above 10% for vehicles manufactured during the period between 1964 and 1982, to around 2% for vehicles manufactured in 2008.

Perhaps of higher interest to this review are in-vehicle safety systems, including technologies to alert motorists to their current speed (and in some cases directly influencing this speed), or to provide warnings that current speeds are too high.

A.2.1 Intelligent Speed Assist

Intelligent Speed Assist (also known as Intelligent Speed Adaptation or ISA) helps drivers maintain the correct speed by providing warnings or intervening in the control of the vehicle. Crackel (2007) classified three versions of ISA:

- Advisory ISA – systems that remind drivers of the prevailing speed limit and exert no control over the vehicle
- Supportive ISA – systems that provide some degree of vehicle-initiated limiting of speed, but which allow the driver to override the system
- Limiting ISA – systems that include vehicle-initiated speed limiting that cannot be overridden (usually accompanied by an emergency failure function)

The first large-scale field trial of ISA was conducted from 1999 to 2002 by the Swedish National Road Administration (SRA) (Biding and Lind 2002), and investigated Advisory and Supportive ISA. In the Advisory system the driver received a warning signal (audio and visual) when the legal speed limit was exceeded. In the Supportive system an 'active accelerator' applied a counter pressure when the driver reached the legal speed limit. The report concluded that:

- it was reasonable to believe that there was a general road safety improvement derived from ISA
- there would be 20% fewer road injuries in urban areas if all vehicles were equipped with ISA
- the average speed on stretches of road fell during the trial
- there was little difference between the two types of systems
- the ISA vehicles drove more homogeneously and with less spread of speed
- driver awareness of the presence of pedestrians increased
- entry speeds into intersections (at the beginning of the braking process) fell
- travelling times in urban areas remained unchanged despite lower driving speeds in specific areas.

Crackel (2007) suggested that international ISA trials indicated that genuine vehicle speed reductions were possible, and user acceptability was good, especially for advisory ISA systems. She cautioned that technical difficulties may, however, result in the driving public's loss of confidence in the system. It is noted that some trials have reported increased driver frustration, irritation and annoyance, mainly due to technical difficulties in the units. Other negative effects included risk compensation behaviour (where drivers compensated by driving faster on roads without ISA coverage), diminished attention when the system was not active, and overconfidence (in relying completely on the speed limit indicated by the system without observing real-time traffic circumstances) (Morsink et al. 2007).

There is little specific mention of the use of ISA in rural areas in the literature, and none relating to reduction of speeds at curves. The only trial identified which has occurred specifically on rural roads is a simulator study in the United Kingdom outlined by Carsten et al. (2008). The study was designed to quantify how the presence of mandatory or voluntary ISA systems might affect drivers' overtaking decisions on rural roads. Drivers became less inclined to initiate an overtaking manoeuvre or carry on with ill-timed overtaking when the mandatory ISA was enabled. However, the quality of the manoeuvres undertaken was compromised. In the case of the voluntary ISA system, there was no difference in the number of attempted and successful overtakes when the ISA was active or inactive. Drivers seemed to routinely disable the voluntary ISA when making an overtaking manoeuvre.

Doecke & Woolley (2011) examined the cost-effectiveness of using ISA in Australia. Based on a review of literature, the expected safety benefits for different types of ISA were determined. The study suggested that crash reductions of 7.7% could be expected from the use of advisory ISA; 15% from supportive ISA; and 26.4% for limiting ISA. A variety of different scenarios were assessed to determine the likely benefit-cost ratio (BCR) for ISA. Figures ranged from 0.29 to 4.03 over a 20 year horizon. Limiting ISA produced the greatest BCRs. The most cost-effective ISA solutions were suggested to be implementation of ISA in 'all vehicles' and 'new vehicles'. It was also suggested that implementing ISA for young drivers (who have an elevated level of risk) as well as new vehicles would provide the most cost beneficial solution.

The potential effectiveness of ISA specifically in rural areas is not clear, and may differ to that of urban areas. This is because a single rural default speed limit applies to the vast majority of rural roads, and there are fewer changes in speed limit. ISA would alert motorists when they are exceeding the speed limit, but in its present format does not alert motorists to other risks that may require a reduction in speed (for example, a severe bend in the road). It would be of benefit to examine a variant of ISA that included other risk-based information, including advisory speeds.

A.2.2 In-vehicle curve warning systems

Perhaps of greater interest to the reduction of speeds at curves is the evolving technology of curve warning systems. Two types of systems have been tested. The first of these involves the transmission of curve-related information to passing vehicles. Only basic trials of this technology have so far been undertaken. For instance Pérez et al. 2010 presented a paper on an infrastructure-to-vehicle Radio Frequency Identification (RFID) based sensor system capable of adjusting the speed of a vehicle to meet existing road conditions.

The second type of curve warning system has been the subject of more extensive trials. This system involves on-board maps with information about curve geometry on the surrounding network. This information is coupled with GPS, which provides information about a vehicle's current location on the network, its direction of travel, and the current vehicle speed. Algorithms determine whether the current speed on approach to a curve is above a safe threshold, and if so, a warning is given.

Leblanc et al. (2006) discussed the evaluation of a Road Departure Crash Warning System (RDCWS) in the United States. The RDCWS comprises a Curve Warning System (CWS) and a lane departure warning system. This review will focus on the CWS component of the RDCWS.

The CWS relies on GPS and a digital map in order to identify vehicle location and curve radius. The technology is aimed at alerting motorists on freeway standard roads that they are taking exit ramps at too great a speed. It utilises a set of visual, audio and haptic alerts with the intention of slowing drivers before entering a curve.

Several other studies present emerging results from this type of technology in differing road environments (e.g. Glaser, Mammer & Chouki, 2009; Hatakenaka et al., 2008; Misener et al., 2010; Sayer et al., 2010). Although in relative infancy, it appears that in-vehicle warning systems may provide a valuable tool for the management of speed at rural curves in the future.

A.3 Enforcement

There are various types of enforcement employed to reduce speeds in rural areas. These include mobile enforcement (using visible or covert police vehicles) and camera-based technology (both fixed and mobile).

It is important to note that to be most effective, speed enforcement needs to be combined with an adequate education and publicity campaign (see Section A.4).

The use of fixed speed cameras is now widespread in Australia and New Zealand. Austroads (2008) reported that this technology was either being used or trialled in most states. The effectiveness of fixed speed cameras has been evaluated both in Australasia and internationally. For example, Diamantopoulou and Corben (2002) evaluated fixed speed camera use in the Domain Tunnel in Melbourne. Average vehicle speeds fell from 75 km/h to 72.5 km/h and the proportion of drivers exceeding the 80 km/h speed limit fell by 66%. The proportion of drivers exceeding speeds of 90 and 110 km/h were also significantly reduced (by around 80% in both cases).

ARRB Group (2005) assessed the effectiveness of fixed speed cameras in NSW. This study found that mean speeds reduced by around 6 km/h up to 2 years after camera installation, while the proportion of vehicles exceeding the speed limit fell by around 70%. At the treated sites, casualty crashes reduced by 20%, while fatal crashes reduced by 90%.

A UK study of fixed cameras by PA Consulting (2005) identified similar high casualty reductions. For rural operations, killed and seriously injury casualties reduced by over 60%, while all injury severities reduced by a third.

Mobile speed cameras (typically vehicle-based or roadside) have also been used extensively, and there have been various evaluations regarding the effectiveness of this technology. Tay (2000) evaluated the installation of 24 mobile speed camera zones in New Zealand. Serious crashes reduced by a third, while all crash severities reduced by almost 10%.

Speed cameras can be used either overtly or covertly. A study in New Zealand by Keall et al. (2002) assessed the differences in effectiveness in the two types of cameras. Between mid-1997 and mid-2000, a trial of covert speed camera operation took place in 100 km/h speed limit areas in one of New Zealand's police regions. Cameras remained overt elsewhere, and after the trial, camera operation in the trial area reverted to overt operation. An evaluation of the program showed that in speed camera areas, mean speeds reduced by 2.3 km/h, while casualties reduced by around a third. For open roads throughout the police region in general, mean speeds reduced by 1.3 km/h, while casualty crashes reduced by almost 20% (compared to control locations). This indicates that covert camera use in rural areas can have a substantial benefit over overt camera use.

A relatively new enforcement technology is the use of a system of two or more cameras to measure the average speed between points. The average speed is determined by linked cameras that measure the time it takes to travel between two points a known distance apart. Time clocks on each camera are synchronised to ensure accurate measurement. Automatic Number Plate Recognition (ANPR) is used to identify and match individual vehicles. The system can be used over short or long lengths of road (in some cases many kilometres apart).

The system has been used for a number of years in the UK, and more recently is being trailled in Australia (e.g. Pacific Highway in NSW; Hume Highway in Victoria). Evidence from the UK shows that the system is highly effective at reducing speeds over sections of the road network. Cameron (2008) provided a review of point-to-point camera technology, including results of two UK-based evaluations. A study by Keenan (2002) is cited that found a 36% reduction in casualty crashes at a site in Nottingham, England, while a study by Gains et al. (2002, cited in Cameron 2008) reported a 31% reduction (not statistically significant) in serious injuries at the same location. A similar evaluation in Strathclyde, Scotland was also reported by Cameron (2008). This indicated a 20% reduction in reported injury crashes; a one-third drop in fatal and serious crashes; and a more than halving of road deaths at the trial location (although not statistically significant).

Cameron (2008) reported similar results from Austria, where a point-to-point system was installed in a 2.3 km urban tunnel. Speeds initially fell by 10-15 km/h, and then settled at about 5 km/h below the speed limit. Injury crashes reduced by one-third, while fatal and serious crashes almost halved (Stefan 2006, cited in Cameron 2008).

A.4 Education, training and publicity

Delaney et al (2004) provided a useful source of information on conducting successful road safety campaigns.

Numerous attempts have been made to slow vehicle speeds through the use of education and publicity campaigns, and driver education. Typically education and publicity approaches are used in association with enforcement-based measures, and to some extent, changes to the road environment. Indeed, research generally indicates that campaigns conducted in isolation have a limited effect (e.g. Huguenin 2008; McKenna 2010). However, it is also clear that such measures are important to the success of enforcement. The OECD report on speed management (OECD 2006) suggested that targeted education and information for the public and policy makers is an important part of an effective speed management strategy.

McKenna (2010) reviewed the effectiveness of training and education campaigns in improving road safety. A number of studies cited in this review indicated that training was perceived to be of benefit, and that education was thought to be a plausible way to improve safety. However, the evidence confirming the benefit is far less clear. A number of reviews cited by McKenna suggested that there was little evidence to support the benefit of driver education, and that in some cases, there appeared to be a decrease in safety. A systematic review of post-licence training (Kerr et al. 2003, cited in McKenna 2010) concluded that there was no evidence that driver education programs were effective in reducing crash risk. McKenna cited several studies (including two reviews of skid training, one by Helman et al. 2010, and the other by Williams 2006; and a systematic review of education programs by Roberts and Kwan 2001) that indicated there could actually be increases in risk. McKenna suggested a number of reasons why such programs are ineffective, including:

- They may be designed with little regard for theory and formal evidence.
- They may increase exposure to risk.
- They may increase the perceived frequency of risky behaviours.

However, McKenna suggested the introduction of certain measures (and specifically those that are intrusive such as seatbelt and drink drive laws) may have been more difficult in the absence of education campaigns. He concluded that the success of education campaigns should perhaps be judged on whether they change the ‘perceived legitimacy of action’.

Road safety training is also sometimes used in attempts to reduce driver speeds, including for recidivist drivers. Courses can include group-based discussions, delivery of educational material, individual sessions, and more recently, computer-based assessments. Austroads (2008c) reviewed a number of courses aimed at recidivist speeders. That study included a review of the UK Speed Awareness Scheme which has been widely evaluated. The results from that course showed that the majority of attendees intended to drive more slowly in future (although as the review highlighted, an intention does not always translate into behaviour). Re-offending rates also tended to be lower for those attending courses, although the review noted that there may be a self-selecting bias in evaluations of this type (e.g. those most motivated to attend such courses are most likely to change their behaviour). Further controlled trials are required before firm conclusions can be drawn about the effectiveness of such training. Austroads (2008) suggested that a mixture of group-based discussions and in-vehicle technology (similar to that identified in Section A.2 as well as in-vehicle data recorders) might be a useful mechanism for changing recidivist driver speeds.

A.5 Summary

Given the significance of the speed problem at rural curves, a great deal of research has been conducted on approaches that might be taken to improve this situation. Responses include those relating to road design (see Section 2.3), road engineering improvements, vehicle safety improvements, and efforts to improve driver behaviour (e.g. enforcement, education, training and publicity).

However, despite considerable research, and widespread use of these different approaches, the safety problem at rural curves persists as a serious issue.

APPENDIX B PARTICIPANT INFORMATION SHEET AND CONSENT FORM

Methods to improve safety on rural roads

Participant Information Sheet

The Centre for Automotive Safety Research and ARRB Group Ltd (formerly called the Australian Road Research Board) are conducting a study into the safety of drivers on rural roads. This study should help identify some of the factors that could make driving safer for all road users on rural roads.

If you choose to participate in this study, you will be asked to complete a survey relating to your attitudes about driving. This should take no more than 10 to 15 minutes to complete. You will then be asked to drive a set route in a car equipped with various recording devices including a video camera. This route will take around one and a half hours to complete. You will be given full instructions regarding the route you will drive. If required you will be given time to familiarise yourself with the vehicle. The time to complete the route will not be recorded and is not of interest to the study. Therefore, you should drive at your own pace, and as you normally would. This includes adhering to all road rules, including driving within the speed limit (in the unlikely event that you receive an infringement notice while driving, this will be forwarded to you).

When driving on any single lane roads, please ensure that you keep adequate distance to the vehicle in front. If you are following a slow moving vehicle, please pull over where it is safe to do so, and allow the vehicle in front to move well ahead.

Participation in this study is entirely voluntary and, even if you agree to participate, you are free to withdraw at any time. For your valued involvement you will be reimbursed for your time with a $50 gift voucher. While driving you will be fully insured under existing ARRB insurance arrangements. All information gathered in the study will be kept completely confidential. Only group results will be reported in any publications that result from this study. If you are interested, you will be provided with feedback about the final results of the study.

Your written consent to participate in the study will be sought before you start. This study has been approved by the Human Research Ethics Committee, University of Adelaide. If you have any concerns or wish to discuss the study you may contact Dr Jeremy Woolley from the University of Adelaide on (08) 8303 3633 or Mr Blair Turner from ARRB Group on 9881 1661. For any concerns regarding the ethical aspects of this research, please contact the Human Research Ethics Committee's Secretariat on phone (08) 8313 6028 or by email to hrec@adelaide.edu.au. More information on ethical issues or complaints regarding this research project can be found on the reverse of this information sheet.

The University of Adelaide

Human Research Ethics Committee (HREC)

This document is for people who are participants in a research project.

CONTACTS FOR INFORMATION ON PROJECT AND INDEPENDENT COMPLAINTS PROCEDURE

The following study has been reviewed and approved by the University of Adelaide Human Research Ethics Committee:

Project Title:	**Methods to improve safety on rural roads.**
Approval Number:	**H-2012-136**

The Human Research Ethics Committee monitors all the research projects which it has approved. The committee considers it important that people participating in approved projects have an independent and confidential reporting mechanism which they can use if they have any worries or complaints about that research.

This research project will be conducted according to the NHMRC National Statement on Ethical Conduct in Human Research (see http://www.nhmrc.gov.au/publications/synopses/e72syn.htm)

1. If you have questions or problems associated with the practical aspects of your participation in the project, or wish to raise a concern or complaint about the project, then you should consult the project co-ordinator:

Name:	**Dr Jeremy Woolley**
Phone:	**(08) 8303-3633**
Name:	**Mr Blair Turner**
Phone:	**03 9881 1661**

2. If you wish to discuss with an independent person matters related to:
   - making a complaint, or
   - raising concerns on the conduct of the project, or
   - the University policy on research involving human participants, or
   - your rights as a participant,

   contact the Human Research Ethics Committee's Secretariat on phone (08) 8313 6028 or by email to hrec@adelaide.edu.au

CONSENT FORM

1. I have read the attached Information Sheet and agree to take part in the following research project:

Title:	**Methods to improve safety on rural roads.**
Ethics Approval Number:	**H-2012-136**

2. I have had the project, so far as it affects me, fully explained to my satisfaction by the research worker. My consent is given freely.

3. I have been given the opportunity to have a member of my family or a friend present while the project was explained to me.

4. Although I understand the purpose of the research project it has also been explained that involvement may not be of any benefit to me.

5. I have been informed that, while information gained during the study may be published, I will not be identified and my personal results will not be divulged.

6. I understand that I am free to withdraw from the project at any time.

7. I am aware that I should keep a copy of this Consent Form, when completed, and the attached Information Sheet.

Participant to complete:

Name: ______________________ Signature: ________________________

Date:________________________

Researcher/Witness to complete:

I have described the nature of the research to

____

(print name of participant)

and in my opinion she/he understood the explanation.

Signature: ____________________ Position: __________________________

Date: ________________________

APPENDIX C DRIVER DETAILS FORM

Driver details

Driver ID # ____________

Licence No. ____________

Name: _________________________________

Address: ____ Postcode: ____________

Date of birth: _____________________________

Contact phone number: __________________________

How long has it been since you received your car licence (either probationary or full)?

Years: _____________ Months: ___________________

What type of car do you own or most often drive?

Make ________________________ Model _______________________

Year_________________

Does this vehicle have automatic or manual transmission?

Auto / manual (please circle one)

How much driving would you undertake in a normal week?

Less than 1 hour / 1-5 hours / 5-10 hours / 10 hours+ (please circle one)

How much of your driving has been on country roads (e.g. not freeway, winding roads) in the last year?

None / a few times / once a month / weekly / daily (please circle one)

How much of your driving has been on country roads in the last month?

None / once / 2-3 times / 4 or more times (please circle one)

APPENDIX D DRIVING INSTRUCTIONS

Exit from ARRB and turn left onto Burwood Hwy, entering the right turn lane at the first set of lights.

Make a U-turn at the lights and drive east to Ferntree Gully. This will take around 20 minutes and will allow you to get used to driving the car.

A short distance after Upper Ferntree Gully Train Station you will pass under a rail bridge.

Veer left into the slip lane to join the C415, towards Olinda and Mt Dandenong

Continue along this road (the C415), not making any turns or deviations, until Montrose. This route will take around half an hour, passing through several small towns including

Sassafras and Olinda.

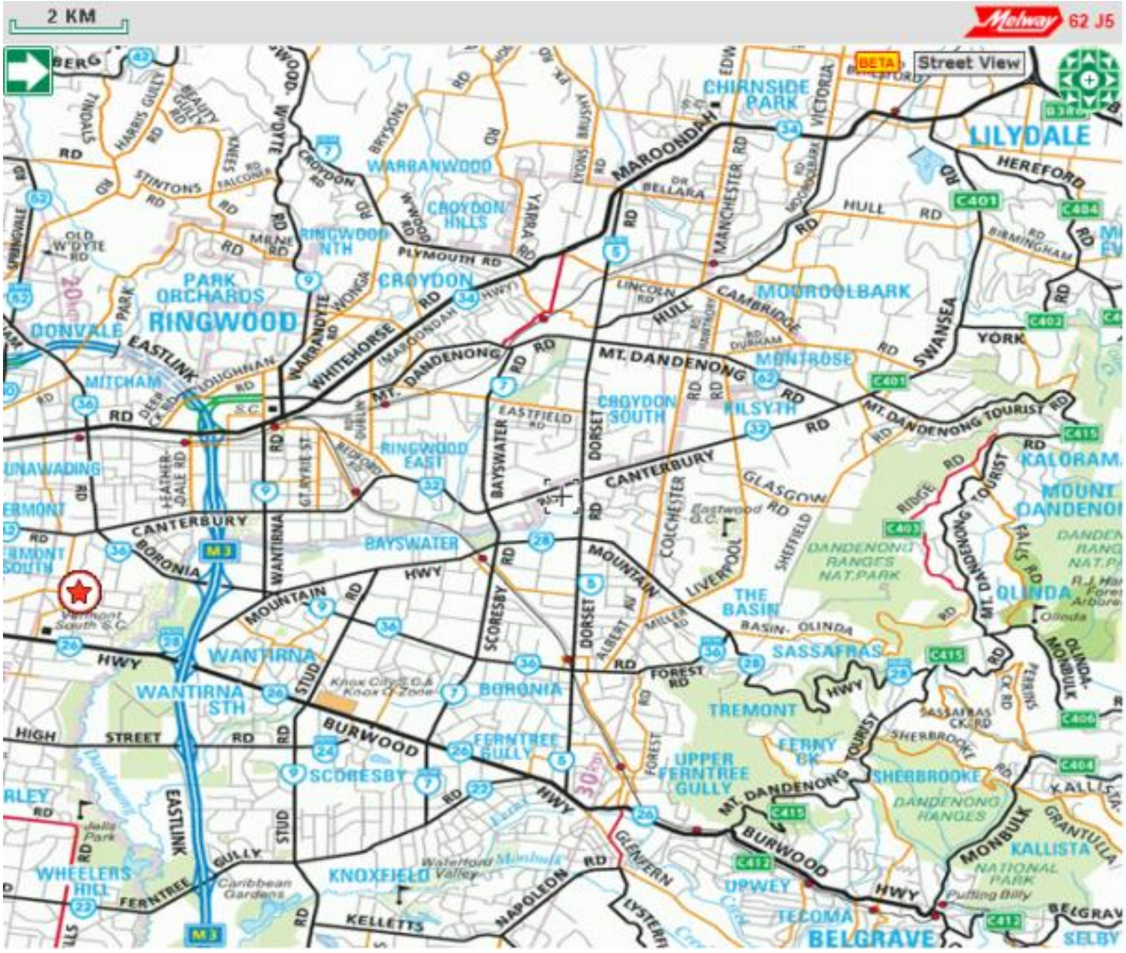
When you near Montrose you will approach a roundabout. Enter this roundabout in the right lane. Do a U-turn at the roundabout and travel back along the same route you came towards Olinda and Mt Dandenong.

Follow this road, again not making any turns or deviations, until you reach the end of the road.

At the end of the road, pick either lane and make a right turn to proceed along Burwood Hwy towards Ferntree Gully and ARRB.

ARRB is just prior to the shops at Vermont South, just after the Bunnings store. When you reach ARRB, enter the first slip lane turn into the driveway you used to exit.

Return the car to where you got in, and leave the engine running with the keys in the ignition. You will be met when you return.


2 KM
Melway
62 J5
BETA
Street View
CHIRNSIDE PARK
LILYDALE
WARRANWOOD
CROYDON HILLS
RINGWOOD NTH
PARK ORCHARDS
RINGWOOD
CROYDON
MOOROOLBARK
DONVALE
MITCHAM
MONTROSE
KILSYTH
CROYDON SOUTH
RINGWOOD EAST
KALORAMA
MOUNT DANDENONG
BAYSWATER
DANDENONG RANGES NAT.PARK
OLINDA
THE BASIN
SASSAFRAS
WANTIRNA
WANTIRNA STH
BORONIA
TREMONT
FERNTREE GULLY
UPPER FERNTREE GULLY
FERNY CK
SHERBROOKE
SCORESBY
DANDENONG RANGES
KALLISTA
WHEELERS HILL
KNOXFIELD
UPWEY
TECOMA
BELGRAVE
MAROONDAH
MT. DANDENONG
CANTERBURY
BURWOOD
EASTLINK

APPENDIX E RESULTS FOR CURVES AND SUBJECTS

E.1 Speed at curve minimum point

E.1.1 High risk curves (km/h)

		10F	11F	1F	22R	23R	24R	25R	26R	27R	28R	29R	2F	30R	3F	4F	5F	6F	7F	8F	9F
Subject	E01	50.6	53.6	43.8	49.8	36.6	59.2	50.7	44.9	54.2	50.7	55.3	27.5	55.6	53.2		42.9	47.8	47.0	39.9	49.4
	E02	52.1	50.8		52.4	40.6	60.2	52.9	47.7	56.5			29.2		53.3	51.4	47.1				
	E03	58.4			52.6	38.8	53.4	50.8	44.7	57.6	55.5	55.8		57.2	51.7	50.9	46.1	50.3	53.5	44.3	45.3
	E04	55.2	56.0	45.1			53.2	50.0	44.1	55.9	49.3	45.7	34.3	52.7	54.4	46.2	40.0	50.8	53.0	41.5	44.0
	E05			49.6						60.8	43.0	46.8	36.4	50.3	57.1	46.9	42.0				
	E06	52.5	53.1	47.5	45.8	39.3	54.0	51.5	42.5	50.8	45.8	54.9	33.1	55.1	53.2	51.3	46.1	46.8	48.1		47.9
	E07	63.1	60.5							64.8	57.7	56.4		63.9	57.6			55.8	59.0	48.7	61.2
	E08		58.2		48.0	40.9	62.6	56.0	49.1	61.4	47.1		29.0		54.1	54.0	50.1	51.2	52.9	44.2	52.1
	E09			44.1	43.0	34.8	50.7	45.1	40.3	50.9	47.1	46.9	28.6	50.7	47.8	44.8	47.2	47.0	45.0		
	E10	51.1	52.8	47.1	45.9					58.7	47.4	51.6	32.7	53.3	55.5	47.3	42.6	50.6	49.1	44.1	51.1
	E11	51.6	53.3			38.3	52.8	46.8		54.4	47.7	49.8	30.4	57.7	50.5	41.5	34.0	45.4	44.1		49.0
	E12	54.2		42.1	51.5	40.4	58.2	56.6	48.2	58.3		53.6	29.5	61.4	55.5	52.3	43.8			45.6	48.4
	E13	45.8	50.5	44.7	46.9	35.7	58.3	51.4										41.1	42.3	43.7	46.1
	E14	45.5	49.3	40.0	41.2	31.9	48.7	47.4	44.0	51.0	46.7	48.7	28.5	55.3	47.8	45.4	37.7	46.5	45.0		43.8
	E15			48.7				57.7					24.7					56.8	58.3		
	E16	52.0	47.7	46.1	41.5	32.9	49.6	51.5	44.3	50.5	47.6	48.5	28.0	47.7	52.7	41.3	37.5	50.4	48.0	38.2	46.7
	E17				39.9	36.2	48.8	47.3			46.1	48.2	28.0	52.6	52.1	44.7	42.8	46.9	48.7	43.5	48.2
	E18	50.3	53.7	43.5	49.5		59.0	52.5	48.9	57.0		54.2	39.8	54.0	47.1	43.6	38.2	50.8	44.8	41.6	46.5
	E19	45.3	46.7	38.5	40.0	31.5	44.4	44.3	37.9	49.3	43.5	43.9	23.9	44.2	43.3	38.2		42.3	38.2	35.3	41.0
	E20	47.6	47.6	41.1	38.7	32.6	50.7	44.8	44.8	52.2	46.0	48.1	24.6	56.3	51.4	55.6	42.6		48.5	32.1	45.1
	Y01	56.6	57.0	46.6	53.3	42.3	58.1	53.4	48.6	57.3	58.0	59.3	31.3		58.5	48.5	47.9	56.5	60.6	48.5	63.9
	Y02	51.0	50.5	38.3				49.1	41.1	49.8	49.4	48.5	29.3	46.1	44.5	48.4	41.9	54.4	51.6		
	Y03	53.0	51.8	45.7	44.9	41.5	62.0	49.1	36.5	50.4	48.5	46.2	34.8	48.9	49.5	45.1	46.0	48.3	49.3	39.6	40.7
	Y04	45.9		37.8	35.9	25.5	41.4	46.5	40.2	42.2	43.8	45.4	20.9	41.6	40.6	40.0	29.8	43.3	42.4	30.9	40.3
	Y05	55.7	53.6	43.8	49.9	35.6	57.4	52.3	42.3	47.1	47.5	50.7	26.4	53.3	43.6	41.7	37.2	47.2	46.5	38.0	42.8
	Y06	53.7	57.4			36.5	52.8	48.3	45.2	54.3	50.8	53.6	33.1	60.1	43.9	47.5	46.2	58.3	52.7	42.2	44.7
	Y07	52.5	42.6		39.1	27.8	56.2	52.6	42.8	49.3	44.4	50.8	30.2	55.2	49.1	51.1	43.4	48.4	47.5	42.9	48.1
	Y08	55.3	51.2	42.9	48.8	35.9	59.2			54.0	51.8	53.8		54.3		51.9			51.2	44.7	49.2
	Y09	56.3	50.0	45.3					42.1	57.0			33.8		57.7	52.7	49.1	50.9	54.7	50.9	55.4
	Y10	54.0	49.9	42.8	46.5	34.0	56.8	48.4	47.8	56.9	49.5	53.6	30.2	57.1	51.9	51.7	47.7	46.0	50.7	41.4	49.1
	Y11	51.7	53.3	44.4	44.2	37.0	55.1	48.1	45.1	51.8	52.6	51.4	32.6	55.8				50.1	45.8	43.2	40.1
	Y12	50.7	48.3	38.3		38.1	66.7	51.8		55.7		46.0	31.7	49.9	50.9	38.0	45.3	48.1	48.1	46.5	46.3
	Y13	55.4	56.9		50.0	37.7	55.6	50.7	49.2	55.9	54.6	57.9		62.1	54.2	49.0	50.3	51.6	52.6	47.8	54.8
	Y14	47.7	45.6	42.5	45.1	35.0	52.4	47.6	45.4	54.2	47.0		30.2		48.8	42.3	40.3	48.1	47.1		
	Y15	54.6	51.3		48.1	38.5	56.1	53.6	49.1			53.1	32.3	54.9	46.6			55.1	49.2	45.3	46.0
	Y16				48.1						51.8	51.6	31.5	56.4						40.6	47.2
	Y17		37.0	32.2	38.2	28.3	47.9	46.6	34.1	45.4	38.3	39.8	20.7	43.3	44.3	30.7	34.3	44.9	44.0	38.5	44.1
	Y18	49.5	48.2	35.3	40.7	35.3	51.7	47.6		50.7	46.0		28.9		49.3	39.6	41.8	48.5	46.5	35.4	42.8
	Y19			42.3		36.6	63.9						33.8		55.0	56.6			50.5		
	Y20	50.6		43.8	48.0	52.1	56.9			53.5	50.3	52.5	34.4	59.6	48.3	42.8	36.4	54.6	54.7	42.7	45.4

E.1.2 Low risk curves (km/h)

	12F	13F	14F	15F	16F	17F	18F	19F	20F	21F	31R	32R	33R	34R	35R	36R	37R	38R	39R	40R
E01	59.3	53.3	57.7	52.8	56.0	57.4	59.0	62.7	59.3	58.9	75.5	60.6	61.4	47.9	56.3	59.2		55.9	56.9	61.3
E02							60.0	64.1	61.8	61.7	69.1	58.1	59.5	55.9	50.8					
E03	57.6	55.9	57.0	57.6	57.0	58.5	57.6	59.2	64.8		68.2	54.0	54.8	54.4		55.9	56.1	56.6	56.9	55.5
E04	55.6	56.7	59.2	52.7	56.0	58.8	56.1	61.6	60.6	61.4	65.6	55.9	51.7	59.6	56.5	57.5	52.7	57.4	57.6	57.9
E05	64.2					62.9								68.5	65.5					57.6
E06	56.6	56.9	53.4	47.6	51.0	54.9	49.1	56.8	58.2	57.2	69.4	57.7	57.8	59.6		61.0	59.2	58.3	57.6	57.5
E07	71.4	68.8	71.3	66.3	61.6	68.8	69.2	76.4	72.4	71.8				69.0	65.7	66.2	65.2	74.2	69.0	70.2
E08			57.6	59.0	61.8	63.9	57.4	62.0		61.1	75.2	61.0	70.4	59.5	56.6	61.0	64.4	59.9	64.1	63.6
E09	57.0	54.1	54.1			55.7	54.3	53.7	55.1		63.2	54.9	54.3	54.8		49.3	53.2	57.0	56.8	
E10	64.4	56.1	59.0			61.3	54.6	59.7	63.5	58.3				57.3		59.6	58.9	61.7	66.2	64.7
E11	61.7	60.9		51.9	57.9	57.6	61.6	63.5	58.0	64.5	71.3	57.7	57.9	59.2	57.2		56.3	58.4	57.1	55.8
E12	58.3	60.7	58.5			60.3	54.4	59.7	61.4	62.7	82.9	68.1	69.2	60.9	57.3	61.0			61.7	
E13	55.4	62.5		58.4	53.4	52.9	60.2	65.4	69.2	66.7	80.8	68.2	58.2							
E14	55.8	57.1	51.0	47.2		54.4	56.3	57.7	61.8		65.2	57.6	55.7	54.8		54.6	56.5	59.8	57.8	58.2
E15	68.1	70.1																		
E16	57.1	56.2	53.7	56.0	57.1	51.0	56.4	58.2	57.4	61.4	77.6	56.8	58.2	56.8	46.8	63.3	64.5	56.5	64.3	58.8
E17	55.6	54.3	55.3	54.4	58.1	55.0					68.8	54.6	55.0	55.7	54.4	59.0	54.6	57.6	60.3	60.7
E18	55.2	56.7	53.0			53.3	52.4	60.3	44.3	58.4	63.3	61.1	58.5	54.5	56.3	56.8	55.8	53.0		53.6
E19	50.6	51.6	51.3	47.9	49.0	51.7		57.4	55.9	58.6	70.5	58.7	54.5	53.9	51.0	57.9	52.0	57.3	53.4	55.1
E20	56.8	54.6	50.8	50.4	54.5	52.3	51.5	55.8	57.1	57.9	66.8	57.6	54.1	59.2	54.3	48.1	51.3	59.0	57.6	55.4
Y01	64.8	51.6	64.4	55.0	60.5	61.9	58.9	63.5	59.4	63.9	76.0	58.8	52.7	53.1	63.0	58.4	57.7	64.1	61.4	69.6
Y02	57.9					54.8	60.6	61.5	57.3	58.9				59.6	54.7	55.9	56.8	58.9	53.6	56.1
Y03	56.3	53.3	54.1		53.1	56.2	56.3	62.0	57.3	65.5	71.6	53.5	57.6	55.9	54.3	56.5	55.2	55.4	56.6	55.8
Y04	51.6	47.8	53.9	47.7	51.1	47.3	53.4	53.4	54.5	51.6	64.2	51.9	50.9	51.5	50.5	49.5	50.4	54.2	54.9	56.5
Y05	54.0	54.8	54.1	53.6	52.5	52.1	52.8	75.9	60.9	65.9	74.2	57.2	63.2		50.4	54.0	59.7	62.8	56.4	81.0
Y06	60.2	54.5	52.1	51.3	53.6	47.5	50.8	58.7	58.8	59.4	69.8	54.7	56.3	53.5	53.8	54.3	54.1	54.5	57.6	56.8
Y07	50.6	50.2	51.4	47.8	53.5	53.6	54.5	53.4	56.6	55.7	65.5	58.6	53.3	54.4	55.0	52.9	51.3	57.1	55.7	53.4
Y08			55.7	55.5	59.3	56.7	57.8	58.7	56.4	55.9	67.3	57.5	54.7		55.9	54.1	51.7	56.1	57.5	56.9
Y09	66.0	64.2		59.0	65.8			76.7	73.4	81.5				67.3	59.9			64.3		
Y10	61.6		55.5	54.4		60.2	61.2	58.8	59.0	58.3	71.2	57.3	62.3	59.3	58.3	58.9	57.9	55.8	56.4	59.9
Y11			55.9			51.1	53.6	58.8	56.6	59.0	62.1	57.2	55.3	54.8	47.5	50.4	53.5	59.6	55.4	56.3
Y12	54.0	50.8	52.1	48.4	51.6		58.3	55.8	55.8		80.7	63.9	63.0	65.0	58.6	46.6	54.9			62.4
Y13	60.0	55.2	57.6	58.1	62.6	63.7	55.3	62.3	60.2	64.1	71.9	57.7		54.6	60.2	54.6	56.5	63.1	57.9	63.1
Y14	55.5			53.8		53.0	54.7		57.9	60.0	71.0	60.0	57.9	55.0	50.9	55.9	58.5	58.6	56.3	54.5
Y15	57.7	52.8	56.4	56.5	56.6	59.2	60.2	58.8		63.3	64.6									57.2
Y16			58.1	55.6	57.5	60.4	61.2	61.7	58.4	63.3										
Y17	50.9	50.1	51.9	51.7	51.9	53.3	49.1	56.0			63.8	49.5	52.7	49.0	47.4	51.7	54.2	54.4	50.3	52.7
Y18	55.1	50.9	56.9	50.1	55.1	55.4	58.7	58.1	57.4	59.9	68.7	59.0	57.1	56.5	55.5	52.9	56.1	53.8	54.1	53.4
Y19							61.4		65.4			61.9								
Y20	56.7	58.9	59.1				56.8	56.5	61.0	58.4	69.7	67.3	61.6	62.4	56.3	61.6	55.3	62.1	63.5	60.5

E.2 Acceleration at minimum point

E.2.1 High risk curves (m/s/s)

	10F	11F	1F	22R	23R	24R	25R	26R	27R	28R	29R	2F	30R	3F	4F	5F	6F	7F	8F	9F
E01	.281	.149	.242	-.139	-.918	.820	-1.281	-1.890	-.605	-.565	-1.240	-.075	-1.089	.295		-1.572	0.000	.909	.332	.546
E02	.433	.421		.579	2.576	.831	-.739	-.265	1.093			-.327		-.596	-.286	-.394				
E03	.324			.437	.850	0.000	-.855	-2.900	-.321	.308	-.467		-1.120	-.722	-.426	-.515	1.248	1.478	0.000	.501
E04	0.000	-.942	-.126			-1.045	-3.693	-.369	-.937	-.551	-.510	-2.946	-1.780	-.608	-1.165	-.334	.841	0.000	-1.161	-.122
E05			-.552						-.338	-1.081	-.130	-3.007	-1.268	.475	-.785	-1.797				
E06	-.146	-.296	.525	-.127	.540	-3.428	1.136	.351	-.283	-1.027	0.000	-.939	0.000	-.446	-.286	-2.489	.900	-.675		.133
E07	-.175	3.125							-.725	1.271	.156		-.892	1.431			.926	1.307	1.989	-2.239
E08		.161		.133	-.459	1.552	-1.724	-.274	-.171	-.262		.462		-.150	-2.426	-1.694	.985	-1.799	1.790	.578
E09			-.743	.828	1.053	.141	-1.396	.554	-.569	0.000	-.524	.547	-6.543	-.801	.124	-.660	-.792	.619		
E10	.983	.147	0.000	1.013					-1.992	-.660	-2.182	-1.117	-2.715	-1.247	.131	-2.538	.561	-1.667	.804	.426
E11	.571	.590			2.168	2.317	-.524		-.761	-.133	-1.542	0.000	-2.288	-.991	.458	-.472	1.001	1.208		-.546
E12	-.302		.464	.711	.891	1.761	-.952	-.268	-.325		-.902	-3.229	-1.034	-.154	0.000	-1.488			0.000	0.000
E13	.630	.560	-.124	.517	.589	2.235	.284										.227	.350	1.548	-1.972
E14	-.380	.546	-.448	-.230	.959	-.406	-.661	-.367	.142	.259	.404	-.480	-1.085	-.400	.501	-.529	1.026	1.480		-.122
E15			-1.094				-2.267					-2.151					.629	.645		
E16	.288	.922	-1.302	1.468	1.251	1.766	-2.935	-.741	.140	-.265	.135	-.702	-2.447	.146	.794	-.210	.420	2.102	1.353	-1.311
E17				1.958	.791	.938	-1.726			-.514	-.268	-.712	-5.155	-.877	.864	-.841	1.657	1.332	.121	.134
E18	-.140	-.450	-.365	-.553		.979	-.734	-.960	.316		0.000	-3.778	-2.450	.131	.121	.526	.843	.618	-2.251	-.129
E19	-.126	.517	-.215	.663	-4.074	-.247	-1.249	-1.597	.137	-.852	-.988	-3.395	-2.399	-.120	-.427		.235	0.000	2.162	-.918
E20	-.133	.264	-2.237	-.108	0.000	-1.432	-2.032	-2.324	-1.622	-1.427	-1.081	-5.593	-1.586	0.000	-.465	-1.200		.536	-.812	-.504
Y01	-.632	.158	0.000	1.470	-.473	2.377	.886	-1.648	-.319	-.647	1.796	-4.294		.163	.670	-3.714	.157	.503	.538	-3.055
Y02	.843	0.000	.212				-.273	.565	-.277	.274	.538	-1.531	-1.290	.369	.134	0.000	.151	1.274		
Y03	1.606	-.289	.629	1.350	1.679	.516	-.273	-.920	0.000	-.270	-.647	1.226	-3.233	.275	.250	-1.302	0.000	.817	.439	-.455
Y04	.381		-.317	0.000	.976	-.803	-4.158	-1.242	0.000	.121	0.000	-.171	-2.381	-.225	.988	.246	.720	1.856	.929	.111
Y05	.924	-.149	.958	-.138	-1.597	1.425	.290	-2.639	-.131	-1.474	-.995	-1.321	-1.047	.841	.460	-.626	-.395	1.277	2.228	1.625
Y06	.149	.319			-.509	.584	-.541	.125	-.151	.701	.149	-.278	-.167	.484	.132	.384	-.325	1.439	.928	.618
Y07	.146	-1.329		.108	1.038	-.786	0.000	-2.980	-1.104	-.746	-1.278	1.206	-1.703	.272	1.268	1.788	.268	1.169	.712	.532
Y08	.915	.706	0.000	.945	.492	2.576			0.000	-.287	-.300		-2.445		1.145			.984	-.628	1.763
Y09	.156	-.556	-.379					-2.878	-.797			-4.467		-.965	-3.927	-.137	.985	.906	.565	-2.817
Y10	.893	.552	0.000	1.532	.751	1.558	-.405	-.670	-.158	-1.822	-1.653	.167	-2.412	-.724	-1.446	-4.831	1.012	1.385	.799	-.273
Y11	.144	.296	.246	.245	-.308	.305	-1.486	-1.263	-.144	0.000	-.574	-.363	-2.530				.139	1.133	-1.217	-.787
Y12	.701	0.000	.317		.732	1.476	-1.165		-.310		0.000	1.123	-3.147	.141	1.037	1.238	.931	1.585	-1.310	1.018
Y13	-.154	.158		1.643	.104	-2.605	.141	-.411	-.782	-.456	-.161		0.000	-.302	.136	-3.026	.143	1.734	.923	0.000
Y14	1.301	.628	.586	1.858	.574	-.584	-.928	-3.022	3.871	-1.184		.648		-.546	.468	.777	1.187	1.538		
Y15	.605	0.000		1.452	.637	0.000	-1.204	-.546			0.000	.446	-2.486	.900			.306	.950	1.367	-1.683
Y16				1.451						-1.313	-.288	-.794	-2.235						1.334	.392
Y17		-1.903	.266	-.320	-4.037	-1.478	-.391	-.865	.126	-2.093	-.111	.886	-2.357	.971	1.710	1.116	.374	1.329	-1.198	.365
Y18	.274	-1.896	0.000	-.342	-.296	-1.158	-.936		.281	-.904		-1.321		-.689	.654	-.706	-.810	-.648	.292	-.836
Y19			-1.433		-3.958	-5.720						-5.408		-.615	-3.692			-.564		
Y20	-.423		-1.623	.266	-11.912	-1.915			-.298	-2.437	0.000	-3.504	-1.678	.800	-1.321	.599	-.152	-.458	-1.077	-.252

E.2.2 Low risk curves (m/s/s)

	12F	13F	14F	15F	16F	17F	18F	19F	20F	21F	31R	32R	33R	34R	35R	36R	37R	38R	39R	40R
E01	-.165	-.746	1.273	1.018	0.000	.634	.492	1.211	.165	.327	.629	-.169	0.000	1.821	.624	.164		-.312	-.158	0.000
E02							.499	1.415	.172	-.172	.574	-.812	-.332	-.468	-.567					
E03	-.321	0.000	.158	.160	-.477	-.490	.160	.164	.180		-1.908	.150	0.000	.151		.311	-.783	-.157	.158	0.000
E04	.462	-.316	-.495	1.018	.621	-.328	.929	1.022	-.506	.340	-.366	.618	-.144	.331	.157	.477	-.888	.159	-.482	-.810
E05	1.064					.349								-.191	.182					-.482
E06	-.632	.158	1.032	.263	.704	1.210	.543	.472	.484	-.319	.385	-.970	.958	-.166		-.511	.164	.162	0.000	.160
E07	.790	-1.157	1.181	1.461	.681	.573	1.908	2.311	.602	.795				.192	.182	.551	.723	.206	.383	-1.176
E08			.797	.491	.514	.531	1.731	1.370		.676	-2.326	-.170	0.000	-.166	0.000	0.000	.535	.166	-.357	.177
E09	.158	-.453	.600			.615	.451	.890	.153		0.000	0.000	-.303	0.000		-.413	-.297	-.955	-.158	
E10	.713	.156	-.164			1.349	1.052	.166	-.177	.805				-1.770		.987	-.823	1.025	.367	.893
E11	.342	-.339		.144	1.275	.637	.171	1.572	-.161	.715	.198	-.161	-.323	0.000	.633		.156	.646	.475	-1.723
E12	.323	.336	.808			.669	1.050	1.475	-.514	.348	.918	.189	.766	.338	.159	.508			-.172	
E13	0.000	.520		.647	2.053	.147	1.654	2.700	.192	.555	1.341	.190	.483							
E14	-.155	0.000	.844	.131		1.047	.624	.320	.513		.904	-.643	-1.252	-.614		-.152	-.157	-.166	0.000	.162
E15	1.689	.195																		
E16	.943	-.313	.595	.773	.317	-.859	.781	.162	-.480	.511	.216	-.317	-.651	.315	.646	-.176	.716	.314	-2.168	.327
E17	.615	.451	.460	.302	.483	.759					.951	.303	.305	0.000	-.303	.164	.604	.638	.167	-.169
E18	.761	-.316	.878			.589	.580	.998	-2.548	0.000	-4.664	.339	.968	.752	.468	.472	-.311	-.593		-.149
E19	1.386	.286	.710	.266	1.210	.286		.318	.155	.325	-.393	.487	-1.073	.447	.424	-.970	-.290	.318	-2.105	.914
E20	-.955	0.000	.843	.833	.753	.579	.710	.771	-.159	.641	-3.223	0.000	.748	.655	.601	-.539	-.575	.164	.320	.460
Y01	.180	-2.039	.536	.457	.168	.343	0.000	.176	-.497	.177	.632	.488	-8.819	.588	.350	.966	-1.297	.178	0.000	.579
Y02	-.646					.910	1.004	1.191	.159	.327				-.166	.908	.155	.627	.654	.297	.311
Y03	-.314	0.000	0.000		-.743	0.000	1.856	2.700	-.319	1.630	.199	.149	0.000	-.626	.896	-3.038	.153	.307	.939	-1.565
Y04	0.000	-.805	-.150	.789	.283	1.038	1.180	.884	.602	.714	-1.070	0.000	-1.578	.569	.420	.275	-.845	.301	0.000	0.000
Y05	1.913	.303	-.454	.445	.725	-.291	.585	3.527	-1.024	.183	.823	-.962	.524		-.140	1.340	0.000	.174	0.000	.226
Y06	1.490	0.000	-.583	1.547	.740	-.667	.978	.650	.163	.657	-1.371	-.305	-.314	.445	-.150	.898	-.910	.151	1.115	-.317
Y07	.697	.139	-.286	.791	.445	-.449	.752	.148	.157	.462	.363	.325	-.596	1.493	.153	.874	.426	-.637	.155	.296
Y08			.771	.921	.657	.157	-.323	-.820	.780	.924	1.667	.478	0.000		.155	.150	.429	.311	-.160	.629
Y09	-.551	.534		.653	.909			3.358	1.619	2.257				-.187	-.334			-.179		
Y10	.342		.462	.302		.831	1.679	2.572	0.000	0.000	-.396	.159	-1.750	0.000	.807	.327	0.000	-.155	.313	.498
Y11			1.537			-.142	.741	1.294	.157	1.305	-1.213	.475	-.154	.304	-.398	.559	-.149	0.000	-.463	.313
Y12	1.622	-.569	.720	.667	.570		.485	-.624	.770		1.119	-.534	0.000	0.000	0.000	.897	1.810			.347
Y13	.332	-.308	-.481	.643	.521	.530	.612	.346	-1.524	0.000	.399	.480		.603	.334	.303	.626	-.176	-.323	.175
Y14	-.309			1.627		-.445	1.205		.801	0.000	-1.393	.333	-.322	.608	.423	.465	.810	.487	.777	.453
Y15	-1.296	-.147	-.947	2.160	.937	.984	.334	.326		.176	-2.170									-1.439
Y16			-.486	1.073	.160	-1.864	.339	1.695	-.325	.351										
Y17	.842	.416	.431	.429	-.145	1.312	-.137	1.534			.177	.183	.292	.675	.784	0.000	-.605	0.000	.140	.292
Y18	0.000	-.713	.631	.554	-.616	-.464	1.621	0.000	.635	-.167	-.574	0.000	.631	-.791	.308	-.887	-.313	.149	.300	.444
Y19							2.179		.725			0.000								
Y20	-.158	-.164	1.465				2.031	1.396	.338	.648	-1.365	.373	.681	.518	-.314	.513	-.154	.344	1.054	1.504

E.3 Side force: maximum in curve

E.3.1 High risk curves (g)

Curve	10F	11F	1F	22R	23R	24R	25R	26R	27R	28R	29R	2F	30R	3F	4F	5F	6F	7F	8F	9F
E01	.160	.308	.306	.413	.437	.309	.233	.198	.210	.314	.271	.316	.200	.262		.214	.159	.180	.192	.182
E02	.176	.283		.452	.461	.367	.263	.212	.243			.294		.234	.230	.280				
E03	.256			.469	.475	.204	.242	.201	.255	.367	.265		.211	.215	.236	.263	.189	.264	.252	.149
E04	.207	.347	.348			.234	.230	.165	.228	.281	.157	.350	.167	.251	.177	.179	.191	.266	.234	.137
E05			.425						.281	.210	.175	.419	.156	.337	.196	.196				
E06	.181	.300	.377	.351	.506	.240	.258	.180	.192	.234	.253	.403	.191	.232	.238	.248	.160	.203		.174
E07	.301	.434							.330	.401	.282		.277	.328			.244	.337	.348	.316
E08		.365		.401	.579	.365	.312	.214	.283	.262		.322		.273	.275	.306	.201	.240	.279	.204
E09			.306	.292	.377	.224	.172	.143	.189	.247	.163	.311	.156	.188	.168	.285	.155	.171		
E10	.167	.286	.356	.350					.265	.308	.217	.350	.166	.258	.189	.224	.185	.199	.262	.198
E11	.171	.306			.424	.304	.209		.214	.262	.222	.326	.220	.254	.128	.173	.139	.154		.189
E12	.196		.340	.430	.495	.418	.303	.250	.264		.257	.356	.236	.275	.253	.221			.277	.167
E13	.181	.258	.321	.350	.393	.298	.257										.109	.156	.245	.149
E14	.124	.250	.240	.269	.311	.250	.211	.189	.184	.247	.203	.289	.205	.188	.167	.153	.147	.184		.136
E15			.393				.321					.291					.251	.343		
E16	.185	.227	.356	.297	.346	.251	.255	.186	.179	.251	.183	.268	.127	.220	.120	.144	.179	.214	.206	.153
E17				.267	.415	.216	.195			.256	.174	.311	.167	.256	.157	.207	.155	.194	.237	.167
E18	.153	.317	.288	.438		.367	.253	.232	.242		.242	.418	.164	.183	.165	.192	.215	.177	.215	.156
E19	.108	.232	.216	.243	.267	.184	.142	.150	.165	.200	.128	.175	.101	.148	.102		.116	.098	.148	.106
E20	.138	.237	.261	.260	.347	.221	.157	.145	.178	.217	.171	.157	.162	.216	.289	.198		.185	.096	.140
Y01	.243	.364	.366	.480	.616	.395	.292	.240	.255	.403	.349	.400		.335	.213	.291	.272	.378	.326	.375
Y02	.194	.278	.225				.228	.204	.175	.289	.184	.294	.122	.193	.208	.206	.241	.246		
Y03	.202	.285	.350	.343	.668	.414	.234	.181	.185	.290	.148	.456	.138	.191	.180	.259	.178	.220	.197	.113
Y04	.119		.210	.192	.160	.152	.190	.155	.122	.217	.150	.147	.113	.194	.118	.075	.125	.153	.083	.093
Y05	.217	.306	.344	.434	.493	.300	.254	.167	.154	.269	.215	.262	.168	.189	.126	.154	.159	.185	.199	.128
Y06	.205	.354			.471	.289	.220	.210	.214	.277	.251	.392	.231	.198	.194	.266	.279	.274	.235	.140
Y07	.186	.168		.237	.213	.260	.267	.153	.170	.220	.217	.302	.183	.236	.223	.232	.167	.205	.248	.171
Y08	.217	.284	.306	.403	.424	.342			.209	.318	.254		.193		.233			.258	.298	.214
Y09	.244	.277	.378					.230	.245			.339		.322	.247	.310	.212	.315	.364	.273
Y10	.197	.282	.291	.348	.369	.313	.216	.214	.240	.287	.249	.331	.222	.254	.252	.322	.145	.290	.235	.179
Y11	.171	.306	.310	.317	.454	.282	.221	.190	.186	.325	.215	.361	.215				.192	.178	.250	.104
Y12	.165	.250	.234		.719	.423	.275		.234		.171	.315	.147	.224	.089	.252	.175	.222	.310	.149
Y13	.222	.356		.436	.456	.325	.259	.254	.235	.351	.323		.277	.243	.214	.330	.218	.278	.321	.248
Y14	.153	.224	.302	.354	.381	.285	.212	.209	.211	.256		.289		.198	.136	.179	.171	.186		
Y15	.215	.286		.396	.465	.359	.308	.242			.245	.331	.196	.235			.238	.261	.257	.164
Y16				.410						.318	.229	.324	.191						.207	.161
Y17		.152	.157	.253	.219	.291	.177	.110	.134	.163	.097	.133	.092	.176	.055	.121	.130	.154	.179	.124
Y18	.150	.240	.206	.280	.367	.226	.184		.188	.243		.258		.209	.108	.167	.180	.199	.166	.130
Y19			.273		.437	.524						.360		.273	.275			.255		
Y20	.160	.251	.292	.382	.730	.271			.208	.251	.237	.352	.202	.203	.145	.120	.241	.274	.226	.150

E.3.2 Low risk curves (g)

Curve	12F	13F	14F	15F	16F	17F	18F	19F	20F	21F	31R	32R	33R	34R	35R	36R	37R	38R	39R	40R
E01	.106	.041	.091	.151	.041	.047	.081	.154	.042	.099	.192	.037	.113	.064	.045	.029		.045	.049	.098
E02							.136	.167	.064	.105	.220	.063	.107	.082	.033					
E03	.094	.051	.094	.186	.035	.046	.134	.203	.057		.117	.070	.117	.078		.038	.101	.042	.028	.084
E04	.083	.064	.093	.146	.050	.040	.130	.196	.055	.115	.169	.039	.084	.099	.058	.028	.092	.057	.036	.089
E05	.135					.069								.140	.072					.064
E06	.090	.055	.084	.145	.029	.030	.093	.197	.052	.088	.138	.061	.117	.092		.024	.100	.066	.057	.083
E07	.175	.097	.131	.217	.055	.084	.123	.223	.084	.149				.127	.077	.020	.115	.090	.081	.136
E08			.087	.224	.066	.063	.060	.235		.108	.235	.061	.178	.114	.047	.037	.102	.064	.061	.105
E09	.093	.048	.077			.047	.099	.149	.040		.163	.067	.129	.081		.031	.081	.067	.040	
E10	.130	.052	.105			.049	.085	.232	.065	.093				.077		.025	.097	.062	.063	.115
E11	.126	.079		.133	.052	.040	.110	.173	.056	.123	.125	.047	.121	.105	.047		.081	.058	.037	.075
E12	.098	.073	.091			.047	.109	.165	.051	.102	.263	.072	.167	.091	.044	.033			.070	
E13	.090	.089		.166	.044	.049	.113	.160	.082	.118	.234	.065	.130							
E14	.085	.063	.068	.122		.042	.088	.161	.057		.145	.066	.119	.075		.034	.083	.056	.044	.090
E15	.155	.094																		
E16	.089	.060	.082	.170	.040	.050	.110	.114	.045	.113	.155	.072	.116	.071	.024	.022	.110	.046	.056	.086
E17	.078	.036	.071	.130	.044	.036					.174	.036	.097	.074	.043	.027	.074	.056	.042	.100
E18	.097	.049	.081			.054	.122	.235	.049	.105	.353	.129	.145	.095	.050	.035	.102	.065		.110
E19	.095	.043	.069	.103	.022	.044		.143	.033	.090	.176	.089	.119	.073	.038	.021	.084	.049	.034	.123
E20	.141	.046	.065	.137	.045	.041	.102	.143	.044	.097	.216	.060	.127	.103	.038	.032	.103	.076	.032	.107
Y01	.138	.082	.127	.240	.043	.078	.106	.237	.046	.121	.171	.046	.159	.080	.072	.031	.106	.082	.052	.141
Y02	.101					.052	.091	.170	.046	.095				.105	.044	.025	.070	.061	.052	.068
Y03	.101	.052	.084		.026	.050	.086	.166	.039	.134	.159	.036	.117	.080	.042	.028	.064	.055	.057	.101
Y04	.066	.025	.078	.111	.028	.060	.094	.122	.050	.068	.090	.036	.071	.050	.038	.037	.061	.053	.057	.079
Y05	.077	.047	.075	.142	.034	.046	.079	.235	.053	.144	.110	.088	.178		.031	.028	.110	.067	.040	.198
Y06	.130	.061	.076	.124	.035	.062	.077	.148	.052	.100	.149	.052	.105	.067	.048	.024	.062	.045	.031	.076
Y07	.070	.034	.065	.147	.042	.023	.084	.120	.028	.091	.133	.052	.106	.081	.053	.018	.060	.059	.034	.066
Y08			.083	.210	.053	.046	.124	.218	.045	.080	.227	.047	.097		.044	.034	.088	.048	.066	.095
Y09	.145	.097		.209	.073			.219	.107	.184				.141	.057			.079		
Y10	.123		.080	.208		.056	.124	.128	.054	.089	.205	.048	.137	.097	.053	.028	.079	.048	.049	.084
Y11			.083			.044	.071	.134	.043	.099	.122	.067	.110	.071	.029	.028	.080	.061	.044	.087
Y12	.081	.051	.077	.127	.032		.069	.153	.040		.147	.061	.159	.121	.063	.025	.088			.121
Y13	.119	.057	.097	.213	.067	.066	.080	.207	.051	.119	.233	.046		.076	.068	.031	.074	.071	.040	.102
Y14	.095			.146		.057	.081		.057	.102	.198	.070	.101	.072	.030	.032	.090	.055	.032	.080
Y15	.111	.047	.103	.153	.038	.052	.073	.155		.109	.078									.086
Y16			.099	.169	.048	.050	.103	.179	.054	.123										
Y17	.065	.035	.056	.123	.026	.046	.054	.120			.228	.087	.146	.052	.032	.029	.079	.049	.046	.063
Y18	.096	.033	.077	.177	.036	.039	.129	.211	.038	.119	.183	.096	.141	.075	.036	.029	.125	.047	.034	.102
Y19							.154		.079			.093								
Y20	.107	.073	.096				.146	.156	.062	.102	.231	.119	.158	.132	.050	.023	.121	.072	.056	.108

E.4 Distance to edgeline: maximum in curve

E.4.1 High risk curves (m)

	Curve direction	Left	Right	Right	Left	Right	Left	Left	Right	Right	Right	Left	Left	Left	Right	Left	Left	Right	Left	Right	Left
	Curve	10F	11F	1F	22R	23R	24R	25R	26R	27R	28R	29R	2F	30R	3F	4F	5F	6F	7F	8F	9F
Subject	E01	-.15	-.67	-.21	1.33	-.47	-.25	-.23	-.73	-.81	.01	-.35	-.31	-.75	-.21		-.11	-.33	-.09	-.71	-.25
	E02	.01	-.77		-.83	-.65	-.09	-.19	-.51	-.53			-.63		-.29	-.19	-.59				
	E03	-.13			1.13	-.65	-.63	-.37	-.63	-.81	-.15	-.27		-.49	-.15	-.07	-.33	-.25	.01	-.63	-.25
	E04	-.17	-.71	-.05			-.53	-.53	-.57	-.65	-.19	-.55	-.93	-.63	-.21	-.21	-.55	-.45	-.99	-.81	-.35
	E05			-.03						-.37	.05	-.43		-1.03	.01	-.23	-.65				
	E06	-.25	-.53	-.25	-.67	-.73	-.51	-.17	-.73	-.61	-.03	.03	-.29	-.49	.03	-.31	-.41	-.27	-.63		-.43
	E07	.01	-.61							-.51	-.15	-.35		-.55	-.11			-.61	-.81	-.45	-.21
	E08		-.71		-1.13	-.21	-.05	-.27	-.11	-.43	.01		-.53		-.07	-.03	-.19	-.17	-1.03	-.39	-.07
	E09			-.33	-1.13	-1.01	-.27	-.23	-.69	-.55	-.09	-.49	-.49	-.49	-.35	-.37	-.43	-.27	-.41		
	E10	-.37	-.79	-.41	-.65					-.23	.29	-.25	-1.05	-.47	-.23	-.27	-.33	-.61	-.63	-.79	-.39
	E11	-.35	-.55			-.85	-.59	-.65		-.53	-.25	-.41	-.85	-.79	-.35	-.35	-.31	-.55	-.79		-.59
	E12	-.09		-.31	-.11	-.21	.03	-.21	-.75	-.51		-.13	-.81	-.31	-.29	-.13	-.25			-.47	-.13
	E13	-.39	-.83	-.35	-.65	-.47	-.55	-.25										-.51	-.73	-.99	-.29
	E14	-.31	-.43	-.55	-1.03	-1.23	-.67	-.61	-.71	-.39	-.17	-.63	-.81	-.61	-.59	-.41	-.53	-.27	-.57		-.51
	E15			-.07				-.13					-.59					-.39	-.39		
	E16	-.11	-.39	-.25	-.99	-.55	-.23	-.51	-.63	-.61	-.27	-.33	-.39	-.55	-.39	-.35	-.37	-.55	-.03	-.55	-.39
	E17				.15	-.11	-.35	-.13			-.17	-.25	-1.03	-.45	-.43	-.35	-.15	-.47	-.21	-.35	-.21
	E18	-.27	-.65	-.37	-.23		.09	-.19	-.91	-.65		-.49	-1.03	-.79	-.31	-.21	-.27	-.25	-.53	-.39	-.23
	E19																				
	E20																				
	Y01																				
	Y02	-.25	-.57	-.01				-.19	-.49	-.51	-.07	-.19	-.95	-.61	-.41	-.01	-.43	-.51	-.07		
	Y03	-.37	-.79	.31	.47	.19	-.11	-.35	-.63	-.41	.13	-.37	-.21	-.43	-.23	-.13	-.35	-.33	-.73	-.55	-.47
	Y04	-.05		.15	-.39	-.23	-.33	-.03	-.33	-.13	.09	-.21	-.45	-.07	-.19	-.19	-.25	-.01	-.21	-.17	-.25
	Y05	-.57	-.37	.33	-.77	-.19	-.59	-.15	-.45	-.33	.05	-.43	-1.01	-.69	-.27	-.13	-.25	-.43		-.65	-.27
	Y06	-.51	-.67			-.65	-.65	-.81	-.89	-.75	-.39	-.63	-1.51	-.77	-.27	-.29	-.55	1.45	1.45	-.85	-.43
	Y07	-.31	-.85		-1.15	-.99	.09	-.35	-.69	-.61	-.23	-.33		-.63	-.43	-.21	-.37	-.81	-.59	-.85	-.27
	Y08	-.13	-.53	-.25	-.13	-.19	-.41			-.21	-.13	-.43		-.43		-.29			-.21	-.39	-.35
	Y09	-.11	-.41	-.01					-.63	-.35			-.41		-.23	.11	-.17	-.39	-.53	-.67	.75
	Y10	-.09	-.57	-.09	.05	-.75	-.37	-.27	-.71	-.69	-.13	-1.05	-1.03	-.61	-.39	-.23	-.25	-.31	-.69	-.55	-.11
	Y11	-.17	-.81	-.07	-1.05	-.29	-.21	-.13	-.87	-.67	-.23	-.35	-.73	-.67				-.33	-.27	-.61	-.43
	Y12	.17	-.55	-.17		-.55	-.57	-.63		-.19		-.19	-.27	-.59	.01	.07	-.35	-.29	.03	-.63	-.17
	Y13	-.17	-.61		-.99	-.31	-.31	-.45	-.47	-.33	-.19	-.43		-.65	-.53	-.37	-.41	-.31	.11	-.45	-.47
	Y14	-.21	-.81	-.05	-.97	-.27	-.35	-.23	-.57	-.69	-.07				-.03	-.21	-.21	-.49	-.39		
	Y15	-.21	-.81		-.73	-.25	-.31	-.39	-.49			-.09	-.71	-.65	-.19			-.21	-.19	-.67	-.21
	Y16				.47						-.39	-.53	-.99	-.67						-.71	-.21
	Y17		-.37	-.13	-.73	-.57	-.15	-.61	-1.03	-.49	-.35	-.37	-.75	-.57	-.37	-.29	-.37	-.59	-.17	-1.09	-.43
	Y18	.11	-.59	-.29	.73	-.35	-.57	-.27		-.47	-.21		-.63		-.25	-.15	-.35	-.49	-.45	-.51	-.11
	Y19			-.45		-.47	-.53						-.89		-.11	-.27			-.37		
	Y20	-.59	-.91	-.41	-.91	-.39	-.61			-.43	-.23	-.79	-.95	-.95	-.55	-.33	-.55	-.55	-.43	-.69	-.61

E.4.2 Low risk curves (m)

	Low risk																			
Curve direction	Left	Left	Right	Right	Left	Left	Right	Right	Left	Right	Right	Right	Left	Left	Right	Left	Left	Right	Left	Left
Curve	12F	13F	14F	15F	16F	17F	18F	19F	20F	21F	31R	32R	33R	34R	35R	36R	37R	38R	39R	40R
E01	-.19	-.41	-.59	-.53	-.47	-.03	-.51	-.49	-.33	-.61	-.87	-.69	-.27	-.55	-.51	-.25		-.49	-.31	-.47
E02							-.43	-.55	-.57	-.81	-.87	-.87	-.51	-.83	-.55					
E03	-.13	-.67	-.81	-.91	-.59	.05	-.17	-.13	-.15		-.93	-.79	-.41	-.65		-.17	.01	-.45	-.27	-.51
E04	-.33	-.69	-.83	-.89	-.39	-.17	-.33	-.35	-.35	-.93	-.85	-.97	-.75	-.51	-.77	-.29	-.11	-.23	-.37	-.23
E05	-.35					-.31								-.63	-.83					.11
E06	-.19	-.47	-.77	-.79	-.57	-.35	-.15	-.31	-.43	-.25	-.89	-.73	-.79	-.49		-.21	-.27	-.17	-.13	-.23
E07	-.25	-.35	-.57	-1.57	-.61	-.29	-.35	-.17	-.29	-.49				-.17	-.97	-.29	-.25	-.19	-.17	.01
E08			-.73	-.55	-.71	-.17	-.35	-.27		-.33	-.85	-.39	-.17	-.55	-.67	-.39	-.13	-.19	-.25	-.35
E09	-.19	-.55	-.73			-.07	-.19	-.27	-.15		-.53	-.69	-.63	-.69		-.09	-.43	-.05	-.39	
E10	-.25	-.51	-1.05			-.27	-.59	-.21	-.41	-.65				-.15		-.09	.11	-.37	-.13	-.09
E11	-.27	-.67		-.37	-.83	-.11	-.37	-.07	-.21	-.63	-.95	-.85	-.53	-.53	-.85		.11	-.35	-.41	-.41
E12	-.21	-.19	-.65			-.13	-.33	-.29	-.37	-.27	-.49	-.83	.07	-.27	-.71	-.19			-.07	
E13	-.33	-.89		-.89	-.81	-.07	-.45	-.25	-.63	-.65	-.99	-.81	-.49							
E14	-.19	-.59	-.71	-.59		-.07	-.23	-.19	-.31		-.79	-.79	-.79	-.59		-.21	-.35	-.35	-.49	-.59
E15	-.39	-.41																		
E16	-.37	-.71	-.93	-1.03	-.93	-.21	-.41	-.37	-.53	-.73	-.57	-.55	-.61	-.49	-.61	-.33	-.11	-.39	-.31	-.37
E17	-.13	-.51	-.49	-.87	-.47	-.07					-.77	-.87	-.31	-.31	-.83	-.27	-.35	-.27	-.29	-.17
E18	.11	-.31	-.59			-.15	-.51	-.25	-.13	-.95	-.73	-.83	-.35	-.61	-.87	-.29	-.05	.05		-.37
E19																				
E20																				
Y01																				
Y02	.07					.21	-.11	-.49	-.35	-.39				-.47	-.71	-.07	-.01	-.33	-.37	-.03
Y03	-.13	-.61	-.77		-.63	-.25	-.45	.03	-.19	-.63	-.77	-.87	-.31	-.33	-1.01	-.53	-.15	-.27	.03	-.33
Y04	.07	.05	-.35	-.31	-.13	.19	-.25	.09	-.15	-.49	-.41	-.41	-.21	-.07	-.67	-.01	-.25	-.07	-.21	-.11
Y05	-.03	-.59	-.65	-1.41	-.65	-.03	-.49	-.25	-.39	-.23	-.83	-1.09	-.27		-.51	-.17	-.21	-.55	.23	-.17
Y06	-.43	-.87	-.95	-.57	-.67	-.05	-.43	-.55	-.87	-1.03	-.99	-1.05	-.51	-.41	-.97	-.41	-.13	-.55	-.51	-.47
Y07	-.35	-.53	-1.25	-1.23	-.91	-.29	-.47	-.65	-.39	-.63	-1.17	-.91	-.39	-.51	-.55	-.37	-.23	-.47	-.41	-.51
Y08			-.91	-.77	-.37	-.11	-.51	-.61	-.53	-.55	-.57	-.69	-.29		-.85	-.03	.09	-.27	-.19	-.01
Y09	-.09	-.67		-.19	-.71			-.47	-.29	-.75				-.65	-.65			-.25		
Y10	-.23		-.77	-.75		-.23	-.49	-.29	-.27	-.67	-.83	-.75	-.53	-.63	-.55	-.17	.05	-.31	-.31	-.29
Y11			-.85			-.05	-.37	-.17	-.43	-.47	-.65	-.89	-.55	-.37	-.73	-.27	-.17	-.35	-.49	-.35
Y12	-.15	-.37	-.83	-.91	-.89		-.27	-.35	-.43		-.75	-.97	-.19	-.63	-.79	-.19	-.03			-.25
Y13	-.11	-.73	-.61	-.81	-.45	-.15	-.27	-.43	-.31	-.53	-.71	-.67		-.35	-.69	-.15	-.09	-.11	-.37	-.27
Y14	-.11			-.87		.07	-.41		-.43	-.57	-.61	-.47	-.19	-.23	-.87	-.03	.03	-.27	-.11	-.05
Y15	-.03	-.69	-.89	-.73	-.63	.17	-.41	-.35		-.67	-.49									-.41
Y16			-1.11	-.99	-.95	-.11	-.41	-.45	-.55	-.83										
Y17	-.19	-.57	-.71	-.97	-.79	-.19	-.49	-.51			-.67	-.97	-.71	-.59	-.95	-.43	-.37	-.35	-.41	-.63
Y18	-.25	-.55	-.61	-.77	-.61	-.17	-.23	-.33	-.31	-.43	-.89	-.71	-.45	-.55	-.53	-.07	.17	.15	-.35	-.15
Y19							-.55		-.31			-1.01								
Y20	-.39	-.85	-1.07				-.33	-.47	-.49	-.87	-.87	-1.05	-.77	-.81	-.85	-.43	-.29	-.43	-.21	-.73

APPENDIX F EXAMPLE PEER REVIEWED PUBLICATION

Turner, B, Woolley, J, and Cairney, P, 2015, An analysis of driver behaviour through rural curves: Exploratory results on driver speed, Journal of the Australasian College of Road Safety, 26, 4, 31-37.

An analysis of driver behaviour through rural curves: Exploratory results on driver speed

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Abstract

Speed, whether above the speed limit or too fast for the conditions, is a significant contributor to fatal and serious injuries at curves on rural roads. The driving behaviour of 40 motorists was assessed using an instrumented vehicle. This vehicle tracked driver behaviour through around 200 curves on a set driving route. Factors including speed, acceleration, side force and lane position were recorded for each driver. Details regarding the design elements of the route were also collected, including curve severity, direction (left or right), horizontal alignment, grade and cross slope. This paper provides initial results for driver speed behaviour through different types of curves, and discusses the implications of the findings.

Introduction

Road crashes result in a significant number of deaths and serious injuries every year. The high incidence of crashes on rural roads has been identified in various countries. IRTAD (2010) report figures for fatal crashes, including those outside urban areas in many countries. These range from a low of 46% in Japan, to a high of 79% in Spain, with the average of all countries providing data being 62%. In the UK 58% of all deaths, and 41% of deaths and serious injuries occurred on rural roads (King & Chapman 2010). In the US, rural crashes accounted for 57% of fatalities, despite less than a quarter (23%) of the population living in rural areas (NHTSA 2007). The rate of crashes (per km travelled) was 2.5 greater than for urban roads.

The situation is also similar in Australia. In a review of road safety on rural roads, Tziotis et al. (2006) calculated that 60% of fatal crashes in Australia occur on the rural high speed road network resulting in over 1,000 fatalities per year in Australia, and more than 22,000 injuries. A number of road environment factors were identified as contributing to these crashes, including the road condition, road design, the roadside environment and speed. The predominant crash types identified were vehicles travelling 'off path' (i.e. run off road) followed by vehicles travelling in the same direction (e.g. side swipes, lane changes and rear end crashes), and opposite direction (i.e. head-on) crashes.

Curves appear to have an elevated level of risk, producing a significant amount of all rural crashes. For example, Steyer et al. (2000) report that around half of all rural road crashes in Germany occur at curves. Retting and Farmer (1998) report that around 40% of fatal roadside crashes in the US are at curves. A report by the OECD (1999) suggests that relatively high numbers of crashes on rural roads occur at curves when compared to tangents and that run-off-road and head-on crashes at these locations are a particular problem. It was suggested that isolated curves or the first curve in a series are of greatest danger particularly as the result of inappropriate speed and lane position. Cenek et al. (2011) identified that in New Zealand, loss of control on curve crashes represented around half (49%) of all injury crashes in 2009 on rural state highways. That study identified that around 26% of the rural state network is curved (defined as having a curve radius of 500 m or less), meaning that crashes at these locations are vastly over-represented.

Charlton & de Pont (2007) discuss three causative factors that may have an influence on crashes at curves. It is suggested that attentional demand may be higher at curves than on straight roads, and that this is exacerbated by higher speeds. Misperception of speed and curvature, especially on approach and at curve entry, was suggested as another factor in crashes at curves. Charlton & de Pont provide evidence to suggest that misperception of curvature is 'relatively common'. Wooldridge et al. (2003) also suggest that crashes may occur at curves when there is a disparity between the perceived safe speed of the curve, and the actual speed at which the curve can be safely negotiated. They suggest that driver expectation based on prior experience plays a large part in safe curve negotiation, and that fewer crashes occur at curves that conform to driver expectations. The third cause suggested by Charlton & de Pont is that motorists have difficulty maintaining lateral position through a curve, leading to a loss of control.

Turner (2009) identified that speed was thought to be a major contributor to crashes at curves. This study reviewed the types of crashes on rural roads that were thought by police to be caused by speed (typically defined as 'too fast for the conditions' or above the speed limit). This is a relatively coarse measure of causality as often police do not attend the scene of a crash, or when they do, they may have a limited amount of information available to form an accurate judgement of crash causation. However, the most common crash types in order of occurrence were:

- Off path on curve (i.e. running off the road while negotiating a curve)
- Off path on straight
- Vehicles travelling in opposing directions colliding
- Overtaking.

Off path on curve was by far the most common crash type, with around 80% of all rural speed related crashes. Compared with 'non speed related' crashes (i.e. where speed was not indicated as a contributing factor) this crash type is also over-represented. In non speed crashes, off path on curve crashes accounted for only 20% of crashes.

Despite many years of research on this topic, crashes at curves still occur in significant numbers, and as identified above, many are related to speed. In order to explore this issue, a study was undertaken to determine behaviour of drivers through curves. A number of such studies have been undertaken over the last few decades (e.g. Johnston, 1982; Fildes, 1986; Campbell et al., 2008), but advances in data collection technologies now allow more detailed and comprehensive information to be collected. This study utilised an instrumented vehicle to collect continuous data on speed and other behaviour through multiple curves. A number of different variables were collected, creating a rich data source which will enable a range of hypotheses relating to driver curve negotiation to be tested.

The study upon which this paper is based assesses broader issues based on the variables collected, including road design elements, traffic management, driver lane position etc.

However, this current paper focuses on initial results obtained on driver speed through high risk and low risk curves.

Method

Data on driver behaviour was collected using an instrumented vehicle. Each driver travelled a set route on their own in this vehicle. A total of 40 male subjects were included, 20 with limited driving experience (less than three years) and 20 with more experience (15 years or more). Males were selected to reduce study variance, but also because this is a higher risk group of drivers. All recruited drivers were unfamiliar with the test route.

The vehicle was fitted with devices to measure speed, acceleration/deceleration, side force, GPS location (all collected using ARRB's GipsiTrac and associated devices; see ARRB, 2015), lane position, and distance to vehicle in front (collected using a Mobileye device; see Mobileye, 2015). Video images of the view in front of the vehicle were also collected.

Subjects were recruited using a variety of means, including social media, and other sources of advertising. Information was collected for each driver, including details on driving experience (including on rural roads), and type of vehicle normally driven. Information was also collected on attitudes to driving through the Driver Behaviour Questionnaire (DBQ; Parker et al., 1995).

The study commenced with subjects travelling 13 km along an urban arterial route to the start of the test route. This allowed a period of familiarisation with the vehicle. Journey time to the start of the route was approximately 16 to 18 minutes. This route had various types of delineation, including centre and edgeline marking throughout the route, and a mixture of advance warning signs and curve advisory speeds at more severe curves. The semi-rural test route itself was 21.9 km, taking approximately 30 minutes. At the end of the route, drivers negotiated a roundabout and returned along the same route. The journey to the start of the test route, route negotiation, and return to the starting point took around 1 hour and 35 minutes.

The route was a hilly area on the edge of Metropolitan Melbourne, and involved a mixture of speed environments. In some locations it passed through small townships, while in others it was quite rural. With the mixed nature of development along the route, the speed limit varied between 80km/h and 60 km/h. A higher speed environment would have been preferred, but this was not possible given study constraints (particularly travel time to the starting point).

There were many curves along the route, some of which were quite severe with high speed approaches. There were 101 curves for each direction of travel, giving a total of 202 curves over the whole route. The start of a curve was defined as the point on the road where the curve radius fell below 1000m, or where the curve changed direction when the radius was already below 1000m. The end of a curve was defined as the point at which the curve increased above 1000m, or where it changed direction.

Data was categorised by the point within the curve. Data for the 40m prior to curve commencement was classed as the ‘approach’; the point at which the radius fell below 1000m was the ‘start’; the segment between the start and point of curve minimum was the ‘to minimum’; the point of minimum radius was ‘minimum’; the segment between the minimum and curve end was the ‘departure’; and the point at which the curve finished was the curve ‘end’.

Calculations were made for each curve (based on data collected) of curve start point, point of minimum radius (i.e. the most severe point of the curve in terms of curvature), curve length, and curve direction. An estimate of curve risk was also calculated. This risk assessment was based on previous literature on this topic. The measure used for this study was based on a calculation of the difference between approach speed and speed at minimum curve radius. This was identified by several prominent studies (Turner & Tate, 2009; Krammes et al.,1995) as the most sensitive measure of crash risk for curves. The 20 highest risk curves, and 20 low risk curves were identified, and included in this study for analysis.

Data was excluded where drivers were following another vehicle, during periods of rain (defined as when the wipers were in use) or when roadside activity was likely to influence behaviour (e.g. pedestrians, road works).

Results

The results presented here relate to driver speed through the different curves, and at different points on approach and through the curve. This includes an assessment of speed against some design elements of the curve; and speed through high risk and low risk curves. An assessment was also made of difference in driving speed between young and experienced drivers. Other factors of interest are being evaluated and will be published separately.

All results relating to group differences are statistically significant at least to 0.05 level unless indicated otherwise (based on t-tests, applying a Bonferoni correction for use of multiple tests).

The first analysis shows the relationship between curve radius and speed (Figure 1). This presents the average speed for each curve (across all drivers). It is clear that as the curve radius decreases, the mean speed reduces. This finding is as expected based on road design guidance, where the relationship between vehicle speed, curve radius, pavement superelevation, friction between tyre and road surface and gravity is well documented (see Austroads, 2010). It is only really below a 100m radius that speeds fall consistently below 55 km/h. From this point there is a sharp reduction in speeds, to a low of 30 km/h with a radius of 20m (quite a severe bend).

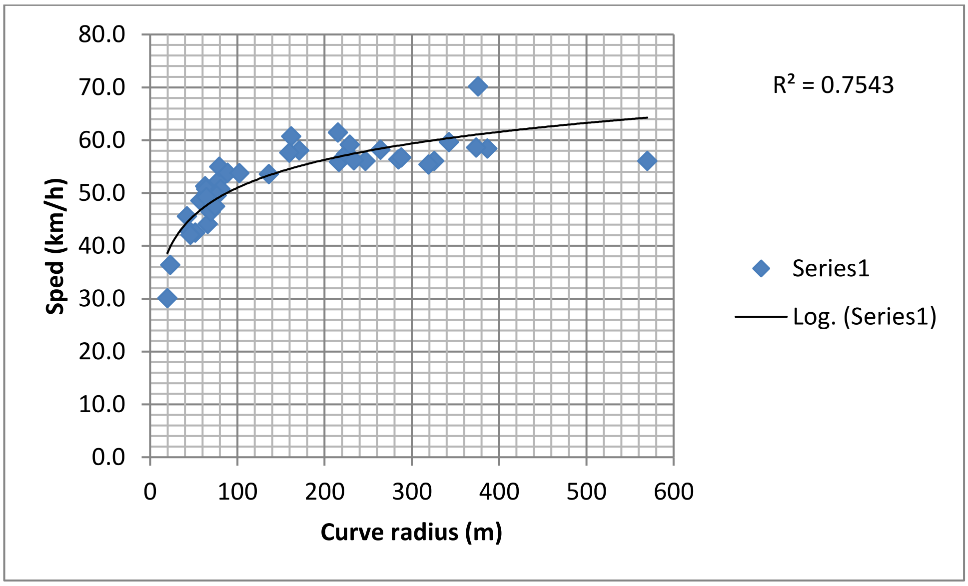

Figure 1. Mean speed by curve radius

Figure 2 shows the speed reduction that occurs from the start of the curve to the point of minimum curve radius. Again, there is a clear relationship between radius and the speed behaviour, with the greatest reduction in speed occurring for the most severe curves.

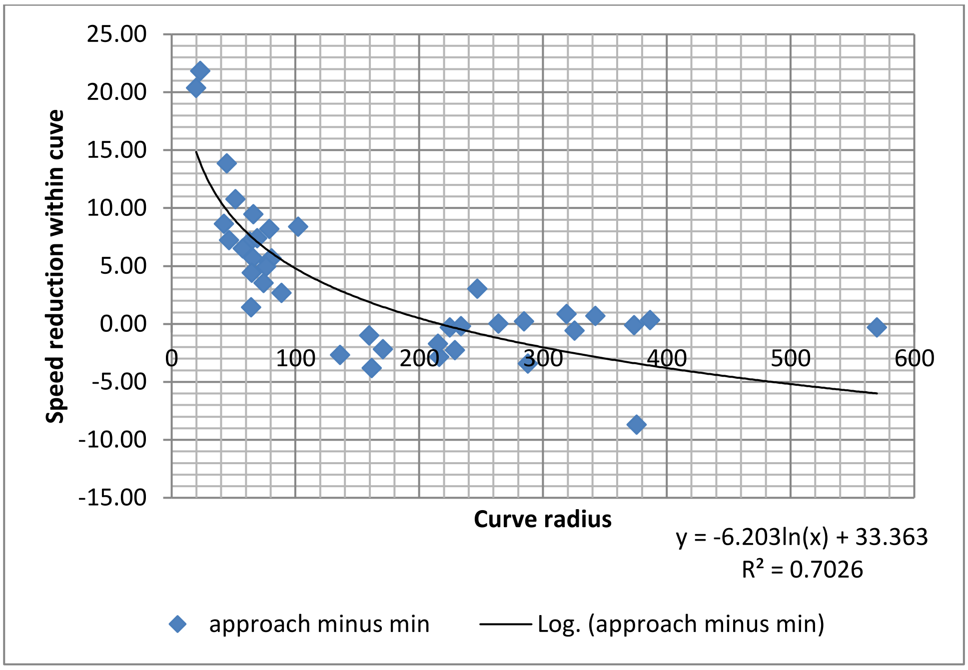

Figure 2. Mean speed reduction by curve radius

Figure 3 shows the reduction in speed based on the calculated crash risk of the curve (defined as the difference in approach speed, and the speed at the point of minimum curve radius).

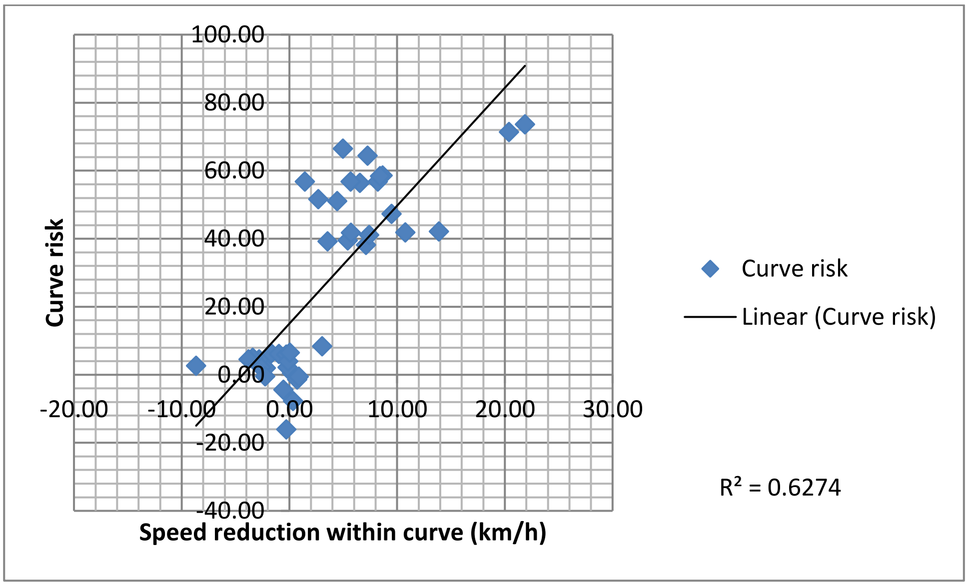

Figure 3. Mean speed reduction by curve risk

Although there is a broad trend for greater speed reduction with higher risk, the relationship is less clear than for curve radius. The two categories of curves (low and high risk) can be clearly observed. Within each of these two groups there is a degree of variance, indicating that although there is a relationship between speed reduction and risk, this is not clear-cut within the two types of curve.

The next set of analyses show speeds at different points throughout curves, comparing high and low risk curves. Mean speeds were lowest through the high risk curves (52.3 km/h compared with 58.5 km/h). Speeds are lower at all points through the curve, with the minimum speed coinciding with the point of minimum curve radius, as shown in Figure 4:

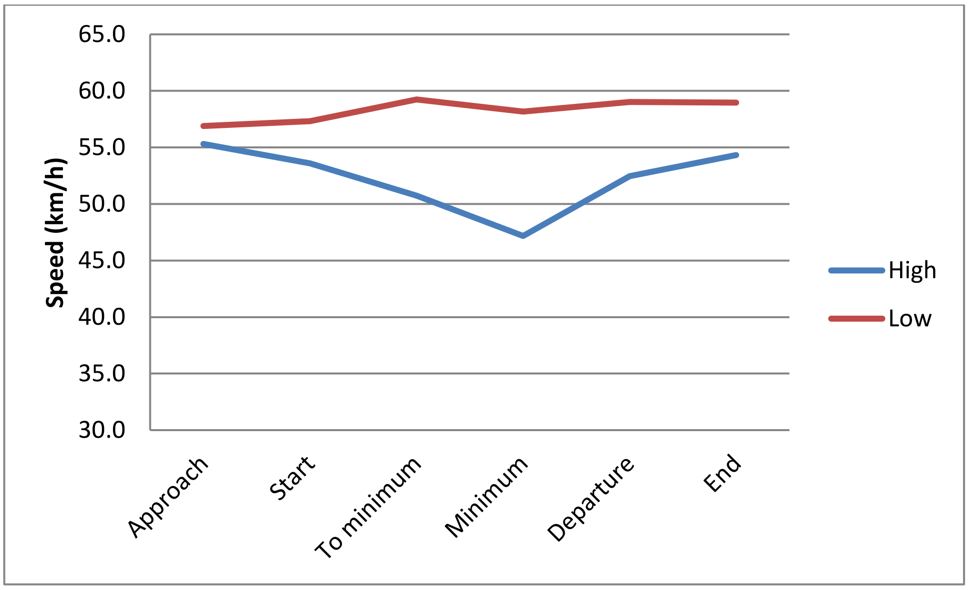

Figure 4. Mean speed by curve risk type

On closer analysis, several things are apparent. For the high risk curves, it appears that speed reduction may have commenced in advance of the 40m buffer used in this analysis, given the mean speed at approach is lower than for low risk curves. It is also apparent that speeds had not returned to the pre-curve level at the end of the curve (10m beyond where the curve radius exceeded 1000m).

A separate analysis was conducted for left versus right curves. This can be seen graphically in Figures 5.

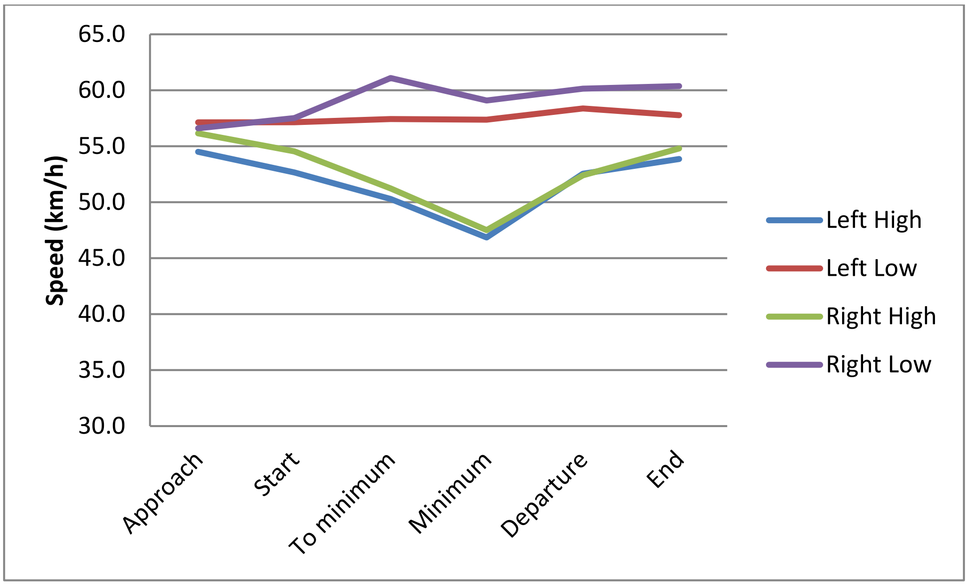

Figure 5. Mean speed by curve risk type and direction

The driving behaviour for both left and right curves was similar, although it is clear that speeds are higher for right curves than for left for both high and low risk curves. For high risk curves, the higher speeds occur when approaching the curve minimum (differences were not statistically significant at minimum, departure or curve end).

Given that speed data is continuous (i.e. gathered every few metres along the roadway) and information was also available on elapsed time for each driver, it was possible to make an accurate calculation of vehicle acceleration and deceleration. Figure 6 shows the result for (a value above 0 m/s/s) and deceleration (values below 0 m/s/s) through different types of curves.

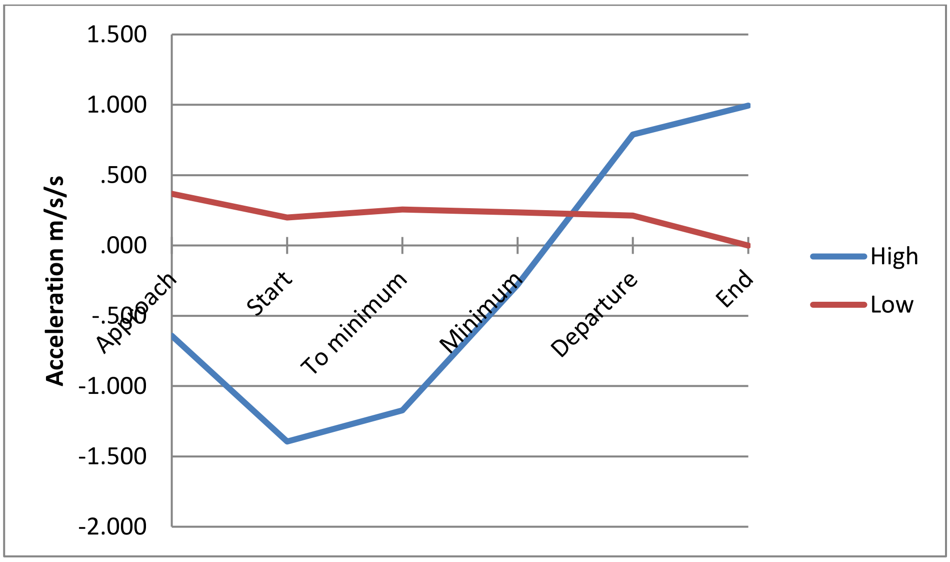

Figure 6. Mean acceleration/deceleration through curves of different risk

It is clear that deceleration has commenced in advance of the curve approach point for high risk curves, and is at its maximum level at curve start. Deceleration continues on approach, and beyond the point of curve minimum. Vehicles are accelerating at curve departure, and continue to do so through curve end.

Lastly, a comparison was made between driving speeds of young drivers and experienced drivers. Figure 7 shows that there is no clear difference in speeds based on driver experience. Although the results were statistically different (except at the point of curve minimum), the results were not at all substantive, particularly for the high risk curves.

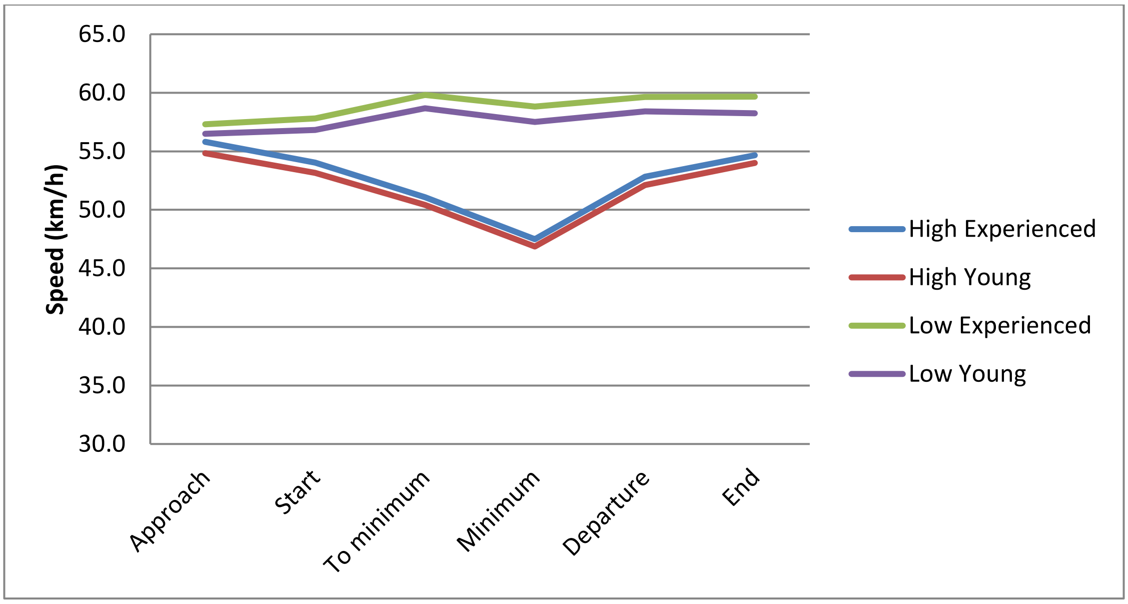

Figure 7. Mean speed by driver experience

Further analysis has been undertaken on difference by driver experience for other driving behaviours, and will be reported in future.

Discussion

It appears that driver selection of speed through curves is highly correlated to curve radius. Drivers seem highly attuned to this element of curve design when making decisions about an appropriate speed. However, it was also noted that these reductions only really commence below a curve radius of 100m. This is interesting, as although risk is greatest for curves below this radius (Veith et al., 2010 suggest the risk is six times greater than for straight roads), there is still a greatly elevated risk for curves with a greater radius (i.e. a less severe curve). The risk for curves with a radius of less than 400m is double that of straight roads, and as highlighted by Levett (2005), curves in this band are far more common, and may (in aggregate) form the greater risk for drivers. Measures to highlight the risk for curves of less than 400m, and the requirement for speed reduction, would be desirable. Jurewicz et al (2014) suggest that categories of curve should be defined based on risk, and differential forms of delineation used for individual curves depending on this category. The findings from this study tend to support this approach, with different curves likely to require different methods for highlighting severity and the appropriate speed.

Speed reduction based on curve risk was less clear-cut within the two broad risk bands (high risk and low risk curves). Within the high risk curves, the amount of speed reduction from curve start to curve minimum was relatively independent of curve risk. This may be because speed reduction had already commenced well in advance of the curve. It would be possible to assess this issue with further analysis.

Speed patterns within curves were as would be expected. Speeds were lower at all points for high risk curves, and the lowest speeds (at least when broadly banding curve segments) occurred at the curve minimum. The result indicating higher speeds through right curves is interesting. Right curves are known to have higher risk (Kloeden et al., 1997; Levett, 2005), a finding that was confirmed from an analysis of crashes on the test route. In an analysis of crashes from the VicRoads crash database (VicRoads, 2014) it was identified that 55% of crashes at curves occurred at a right hand bend. The higher speeds at right hand curves therefore deserves further attention to determine additional risk factors, and to help to identify the means to address these.

One particularly interesting finding from this study was that deceleration continued through and beyond the curve minimum point for high risk curves. Given this is a high risk location it is highly desirable that drivers will have already fully decelerated by this point. Although there are some indications from previous research confirming this finding, road design standards assume that speed reduction is complete at curve start, let alone at this point later in the curve (Austroads, 2010). This finding could have implications for design guidance. Further analysis is required to determine the situations (e.g. the types of curves) where this issue is most prevalent. Given the data set created through this study, this is very feasible. Mechanisms to ensure speed reduction is completed before curve minimum would most likely reduce crash risk. Options need to be explored regarding how this might best be achieved. Such options might include signs located further in advance of curves.

The result indicating no substantive difference for different drivers with different levels of experience is interesting. It could have been expected that young drivers would have exhibited higher speeds, especially through high risk curves, given the higher risk of this group. The opposite was observed in this sample, as young drivers showed lower speeds at all points through both low and high risk curves (the only exception being at the point of minimum curve radius for high risk curves where there was no statistically significant difference). It may have been that young drivers were more cautious in this sample because they were being monitored, or that they are more cautious in selection of speed through curves in general (at least from short exposures to rural driving). Given that some quite extreme behaviours were observed in the sample (e.g. very high speeds and side force by individual drivers through individual curves) despite being observed, it is possible that both situations may be true. It is possible that issues in addition to speed selection are significant in the elevated crash risk of young drivers.

There are a number of limitations to this study. These include that drivers were driving in an unfamiliar vehicle, and were being ‘observed’. Despite a period of familiarisation prior to reaching the test route (and some settling of behaviour towards ‘normal’), it is possible that drivers were not performing as they normally would. Secondly, the driving route in this study was a constrained hills environment with a maximum speed limit of 80km/h. Although some quite severe curves (in terms of the required speed reduction) were able to be included in the study, analysis of a higher speed environment would be desirable. Thirdly, there are a number of elements that differ between curves, including traffic management and delineation (such as presence of advance warning signs and chevron alignment markers). Although the large number of curves included in this study will compensate for such differences to some extent, it could be expected that these elements will also have an impact on driver selection of speed. Further analysis including these elements is required to help determine their actual impact.

Due to these limitations, generalising of the findings from this study to other contexts should be done with caution.

The data set created through this study will continue to be explored, including the analysis of other behaviours. Assessment of side force and lane position will be important to more fully understand driver behaviour through curves, as will the relationship between these variables and speed. This additional analysis will be presented in future.

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