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Acronyms and abbreviations

AADT	Average annual daily traffic
CAS	Crash Analysis System (Ministry of Transport)
GVM	Gross vehicle mass
MOTSAM	*Manual of traffic signs and markings* (Transit New Zealand)
PCM	Perceptual countermeasure (treatment)
RAMM	Road assessment and maintenance management database
RGDAS	Road Geometry Data Acquisition System
RRPM	Raised reflective pavement markers
SRT	Static Rollover Threshold
SUV	Sport utility vehicle
VMAE	Visual motion after effect

Contents

Executive summary

Horizontal curves have been recognised as a significant safety issue for many years, a more important factor than road width, vertical clearance or sight distance. There is good agreement in the road safety research community that increasing degrees of curvature cause more accidents.

An analysis of crashes associated with speed through curves, using the New Zealand Ministry of Transport's Crash Analysis System (CAS) database, generally supported this relationship between increasing curvature and increasing crash risk. However, it was found that when the curvature became very severe (advisory speed of 25 km/h) the crash rate was substantially reduced. Although this appeared to contradict the findings of a number of other researchers, their studies generally grouped the curves in bands that were not sufficiently fine to isolate this result.

Twenty-one curves were surveyed in detail by an experienced traffic engineer. Sixteen of these had been the site of at least one crash (most had more than one) while five sites had no recorded crashes but were in the same roading environment as one or more of the crash site curves. Although for most of the crash sites safety improvements could be identified, there were no obvious underlying differences between the crash site curves and the curves without crashes. It was not possible to deduce a standardised approach for identifying and treating at-risk curves with no crash history.

An important aspect of curve speed management is determining the appropriate safe speed. Currently advisory speed values are determined using the methodology specified in the *Manual of traffic signs and markings* (Transit New Zealand 1998) and are based on passenger car comfort. We have developed an alternative approach based on vehicle performance limits and the engineering concept of a factor of safety. Using this approach we can determine the appropriate speeds for different vehicle types on a given curve. The key to safe vehicle operations is to provide the cues so that the drivers of these different vehicle types can accurately determine what the appropriate speed is and react accordingly.

A review of the research literature suggests that driver errors associated with horizontal curves appear to be the result of three inter-related problems: failure of driver attention, misperception of speed and curvature and poor lane positioning. The first problem area arises when a driver's attention is diverted or they fail to notice a curve ahead, either due to familiarity with the route, fatigue, or some other factor. This account focuses on the conscious processing of the curve and the driver's decision to make appropriate adjustments in their speed and trajectory. To address this issue, advance warning signs designed to attract a driver's attention early and give them time to prepare for the curve have become the treatment of choice. Unfortunately, both research findings and crash statistics indicate that advance warning signs do not provide an adequate safety measure. Part of the reason for this appears to be the tendency of drivers to rely on proceduralised

or habitual motor programmes to maintain their speed and lane position (ie driving on 'automatic pilot') and they thus fail to attend to and process most advance warning signs.

Drivers' perceptions of speed and curvature appear to work at both a conscious (explicit) and unconscious (implicit) level. For this reason, curve warnings and delineation treatments that highlight the sharpness of the curve ahead or increase drivers' momentary sense of their apparent speed appear to offer promise in getting drivers to enter curves at a lower speed. Delineation treatments may also assist drivers with the third problem area: selecting and maintaining appropriate lane position while travelling through the curve.

Based on input from road safety practitioners and researchers, two groups of curve speed management treatments were identified for laboratory testing. The first group of treatments to be compared consisted of four combinations of warning signs designed to alert drivers to the presence of curves and reduce speeds at the approach to, and through the curves:

1. standard advance warning signs with an advisory speed plate
2. advance warning signs followed by chevron sight boards
3. advance warning signs followed by a series of repeater arrow signs
4. advance warnings followed by chevron sight boards and a series of repeater arrows.

The second group of treatments compared was comprised of several types of road markings designed to affect drivers' lateral displacement (lane position) as they drove through curves:

1. advance warnings accompanied by double yellow lines through the curves
2. advance warnings followed by centreline and edgeline rumble strips
3. advance warnings followed by a herringbone pavement marking treatment designed to 'flatten' drivers' path through the curve and provide increased separation between opposing traffic.

The two types of treatments, warning signs and road markings, were applied to a simulated 3.4 km section of State Highway 27 centred on the Kaihere Hill summit in the Hauraki District. Another 3.5 km section of level road containing four horizontal curves with consistent radii (two 85 km/h and two 45 km/h curves) was added to the front of the simulated road to compare with the more challenging vertical and horizontal curves along the summit road. Sixty participants were recruited to test the treatments in the University of Waikato driving simulator. The results indicated that advance warning signs on their own were not as effective at reducing speeds as when they were used in conjunction with chevron sight boards and/or repeater arrows. Of the road marking treatments only the rumble strips produced any appreciable reductions in speed. It should also be noted that there were no adverse reactions to the presence of rumble strips on the left edgelines of left-hand curves, an issue of some interest to road safety practitioners. The herringbone treatment had the effect of flattening the drivers' path through the curve, with a somewhat more substantial effect for curves to the right than curves to the left. The finding that the herringbones did not produce reductions in speeds may have been due to the markings' indication of an optimal path through the curve (which could be traversed at higher speeds) thus offsetting any potential speed reductions. A follow-on test with 24 additional participants found that when the herringbone treatment was combined with chevron and repeater arrow signs, the treatment did achieve both a reliable reduction in speed as well as improved lane positions.

Consultation with road safety practitioners indicated that the results were of considerable practical importance, particularly regarding the effectiveness of chevron sight boards, rumble strips and the potential for some form of herringbone pavement markings. Future work should include field trials to determine the longevity of the pavement markings under conditions of heavy use. Further laboratory testing to determine how sharp a curve needs to be to benefit from these signs would be instructive.

Abstract

Horizontal curves have been recognised as a significant safety issue for many years, a more important factor than road width, vertical clearance or sight distance. This study investigates the issue of speed selection through curves from several different perspectives.

The relationship between safety and curve speed in New Zealand was analysed using data from the Ministry of Transport's Crash Analysis System (CAS) database. A sample of curves was selected and surveyed. Following this, a method for determining the appropriate safe curve speed for different vehicles was developed based on the vehicle performance characteristics. In parallel, a driving simulator was used to investigate the effect of different warning sign and road marking treatments on drivers' curve speed selection and lateral positioning.

1. Introduction and background

Horizontal curves, particularly on two-lane rural roads, have been recognised as a significant safety issue for many years (Bhatnagar 1994; Johnston 1982). In an analysis of 34,000 road crashes in the United States, Gupta and Jain (1975) found that horizontal curvature was highly correlated with crash rates on rural highways; a more important factor than road width, vertical clearance or sight distance. Head-on collisions, collisions with fixed objects and rollover crashes were all found to occur disproportionately on curved sections of road. It has been estimated that crash rates on curves are 2 to 4.5 times higher than on straight road sections, with truck crashes at the highest end of this range (Johnston 1982; Leonard et al. 1994). In Germany nearly one-half of rural road crashes occur on curves while in Denmark 20% of traffic-related injuries and 13% of all fatal accidents occur on rural curves (Herrstedt and Greibe 2001; Steyer et al. 2000). The crash figures associated with horizontal curves are similar for other European countries (Herrstedt and Greibe 2001; Nielsen and Greibe 1998; Taylor and Barker 1992) and in the United States it has been estimated that about 40% of fatal roadside crashes occur on curves (Retting and Farmer 1998). In Australia 48% of all fatal crashes on rural roads are associated with curves, with 70% of those crashes occurring on curves where the radius of the curve was less than 300 m (Moses 1990). In New Zealand there were 24 fatal, 98 serious injury and 235 minor injury crashes on curves signposted with advisory speed signs in 100 km/h speed zones in the year 2002 equating to a social cost of $165 million (LTSA 2003).

There is good agreement in the road safety research community that increasing degrees of curvature cause more accidents (Haywood 1980; Johnston 1982; McDonald 2004). Single sharp curves in highways with long tangents and flat curves create some of the more hazardous situations (Haywood 1980). Curves with a radius of less than 600 m are over-represented in crash statistics (Choueiri and Lamm 1987; Johnston 1982) and there is ample evidence that horizontal curves with radii less than 400 m or over 3 degrees of curvature[1] directly contribute to driver crashes (Cirillo and Council 1986; McLean 1981; Moses 1990). For single vehicle accidents, there is a 34% increase in accident frequency per 'sharp' curve[2] per kilometre (McDonald 2004). The positive correlation between horizontal curvature and crash rates appears to be strongest for two-lane rural roads. In a study of two-lane rural roads in the United States, it was found that crash rates increased with increasing degrees of curvature despite the presence of traffic warning devices at curve sites (Choueiri and Lamm 1987). Based on these findings, the researchers recommended that sites with more than 10 degrees of curvature and speed changes of more than 19 km/h should be redesigned. An extensive literature review (Good 1978) on

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[1] The degree of curvature (also called degree of curve) is a measure of curvature used primarily in the United States and is the angle subtended by 100 ft of arc.

[2] Sharp curves are defined as those marked with a chevron and/or curve warning sign.

road geometry noted that most horizontal alignment design standards were inadequate for assuring safe driver behaviour because:

- drivers' speeds were not constant throughout a curve
- drivers might use different speed selection criteria for high- and low-speed curves
- values of side-friction calculated from measured vehicle speeds and the centreline radius of the curve would be inaccurate because on small radius curves many drivers cut the corner and on larger radius curves vehicle path curvatures generally exceeded the roadway curvature.

Although the geometry of horizontal curves (specifically the degree of curvature) has a well-established positive correlation with the frequency of crashes, there has been little consensus on the identification of the proximal causes of crashes on curves. Several causative factors have been proposed, including: inability to meet increased attentional demands (McDonald and Ellis 1975); misperceptions of speed and curvature (Johnston 1982; Messer, Mounce and Brackett 1981); and failure to maintain proper lateral position on the curve (Eckhardt and Flanagan 1956; Glennon and Weaver 1971; Good 1978). Each of these three proposed causative factors (attentional factors, misperceptions of speed and curvature, and maintaining lateral position) will be explored in this report in some detail.

1.1. Attentional factors

The importance of drivers' conscious attention to the driving task has been demonstrated across a wide range of situations. When attention is diverted, either through the presence of distractions inside or outside the vehicle, or when attentional resources are diminished through fatigue or some other driver condition, the probability of a crash is significantly increased (Knowles and Tay 2002; Wang et al. 1996). For example, competing attentional demands from secondary tasks such as radio tuning or cellphone conversations appear to increase driver workload and decrease driver situation awareness, resulting in increased reaction times to road and traffic hazards such as stop lights and braking vehicles (Alm and Nilsson 1995; Hancock et al. 2003; Mathews et al. 2003; McKnight and McKnight 1993; Strayer et al. 2003). Similarly, psychological fatigue associated with too little sleep and rest has been demonstrated to increase reaction times and can pose a crash risk equivalent to driving with a 0.1% blood alcohol concentration (Charlton and Baas 2001; Lamond and Dawson 1999; Maruff et al. 2005; Williamson and Feyer 2000).

Although many of the crash risks associated with decreased driver attention result from an inability to respond to traffic hazards in a timely fashion, lowered attention may also have a role in crashes on horizontal curves. Negotiating curves requires that drivers anticipate the curve by adjusting their speed and lane position to accommodate the severity of the curve (Reymond et al. 2001). Negotiating curves thus requires more attentional resources than driving on a straight section of road. When a secondary task (digit shadowing) was used to determine what proportion of drivers' attention was required to drive curves of various radii, it was found that straight sections of road demand approximately 23% of a driver's attentional resources at speeds ranging from

64 km/h to 129 km/h (McDonald and Ellis 1975). In contrast, drivers’ attentional demands on curves were significantly higher (26% at 32 km/h on a 17-degree curve) and increased as vehicle speeds increased (42% at 64 km/h on a 17-degree curve). Simply stated, decreases in driver attention result in a decreased ability to negotiate curves and this is exacerbated by higher speeds.

Another contributing factor associated with decreased attention is that drivers may fail to notice warning signs and other cues needed to anticipate curves. In a study of drivers’ ratings of the relative importance of various curve characteristics four factors were found to be most important: sight distance through the curve (curvature); road cross section (lane width and number of lanes); curve warning signs; and separation of opposing traffic (eg median barriers) (Kanellaidis 1995). Interestingly, when drivers were classified as either non-violators (those who always or mostly obeyed speed limits) or violators (ie those who seldom or never obeyed speed limits), it was found that advisory speed signs at curves were the most important variable in determining curve speeds for non-violators whereas for violators, the road-layout factor was the most important factor. In a more recent study of attentional factors associated with curve warnings it was found that distractions produced by secondary tasks (verbal and memory tasks) resulted in higher speeds through both unmarked curves and curves marked with advance warning signs (Charlton 2004).

1.2. Misperceptions of speed and curvature

Another significant factor contributing to crashes at curves is drivers’ speeds (Retting and Farmer 1998), particularly their speeds during the curve approach and curve entry. Johnston (1982) reported that curves requiring drivers to substantially reduce speed are over-represented in accident statistics. Similarly, field test data have confirmed that a driver’s initial speed prior to entering a curve has a significant effect on their ability to successfully negotiate the curve (Preston and Schoenecker 1999). Unfortunately drivers appear to often underestimate their speed through curves, particularly when travelling at higher speeds (Milošević and Milić 1990). Milošević and Milić suggest that this might be due to motion perception cues specific to the deceleration associated with curves, in addition to a more general tendency to underestimate curve speeds. This suggestion is bolstered by findings that drivers’ speed selections appear to be based on both implicit perceptual cues and conscious cues such as checking their speedometer (Salvatore 1968; Recarte and Nunes,1996). This perceptual information appears to involve implicit, or unconscious, processing of edge rate cues in the peripheral visual field and is the reason that driving down a narrow road or through a tunnel is often accompanied by an exaggerated sense of speed (Lee 1974; Lewis-Evans and Charlton 2006; Salvatore 1968). Continuous visual exposure to edge rate often leads to some perceptual habituation and can result in a visual motion after effect (VMAE) so that decreases in speed (and edge rate), are often accompanied by perceptions that one’s speed is much lower than the actual speed (Charlton et al. 2002). In the case of curve approaches, wide lanes or roadways can produce underestimates of speed, and as a driver decelerates during the curve approach that underestimation is exacerbated further by VMAE, resulting in a tendency to enter the curve at too high a speed. The greater the speed differential between the baseline (straight road) and the curve, the larger the degree of speed misperception likely to result, as is borne out by both experimental findings and crash statistics (Johnston 1982; Milošević and Milić 1990).

Similarly, misperceptions of curvature, eg curves appearing less severe and closer than they actually are, is a characteristic of many high accident curves (Shinar 1977). Drivers do slow down more for curves they perceive as being sharper (just as they do for roads that appear narrower), but the perceptual characteristics giving rise to the perceived sharpness of a curve are not always clear (Shinar 1977; Shinar et al. 1980). In a laboratory test of curve perception, drivers reported that high-accident curves appeared sharper (than low-accident curves) from 200 yards, but not from closer distances and they were generally perceived as closer than equally distant low-accident curves (Shinar 1977). Further, although the angle turned through by the curve is a highly predictive measure of its accident risk, drivers appeared to be relatively insensitive to this characteristic and the researchers concluded that misperceptions of curvature may be based on other, geometrically irrelevant, information (Shinar 1977). It has been reported that, under some conditions, reductions in curve radius are actually associated with perceived decreases in the degree of curvature (Fildes and Triggs 1985).

Other researchers have reported that misperceptions of curvature are greatest in situations where vertical curvature is combined with horizontal curvature (Hassan and Easa 2003; Hassan et al. 2005). Specifically, when a crest or oververtical curve is superimposed on a horizontal curve, the horizontal curvature is perceived as more severe, and when a dip (sag or undervertical curve) is combined on a horizontal curve the curvature appears less severe and is underestimated. The degree of driver misperception is asymmetric in that underestimations of curvature associated with sag vertical curves are more prevalent than the overestimates associated with crest vertical curves (Hassan et al. 2005). Further, the degree of drivers' misperceptions of curvature increases as the radius of a horizontal curve increases, a phenomenon associated with both crest and sag curve combinations, but most strongly for crest vertical-horizontal curve combinations (Hassan et al. 2005). Misperceptions of speed and curvature, therefore, appear to be relatively common among drivers, with implicit (unconscious) perceptual information contributing to inaccurate judgements and deficient curve negotiation.

1.3. Maintaining lateral position

Misperceptions of speed and curvature and attentional failures associated with the road environment leading up to a curve often result in a driver being unable to maintain appropriate lane position through the curve leading to a loss of control, head-on or other crash. A number of studies have shown that a driver's control of speed and lane position is not optimal and, when combined with poor or absent preparation during a curve approach, situations can easily arise where the lateral traction limits are exceeded (Neuman 1992; Reymond et al. 2001; Zegeer et al. 1990). In an analysis of crashes on horizontal curves it was found that in most cases (64% of non-fatal and 77% of fatal crashes) the first manoeuvre was towards the outside, rather than in the direction of the curve (Zegeer et al. 1990). Similarly, researchers have shown that a driver's path through curves often increases friction demands well beyond that anticipated by road designers by overshooting the curve and producing a vehicle path that is sharper than the actual road radius (Glennon et al. 1985; Neuman 1992).

1.4. Speed selection

The selection of an appropriate speed to traverse a curve depends not only on the curve geometry but also on the road surface condition and the performance capabilities of the vehicle. With typical friction properties between the tyres and the road, excessive speed in a passenger car will result in a loss of adhesion with the vehicle sliding. A laden heavy vehicle will generally roll over rather than slide and this rollover will occur at a substantially lower speed than the passenger car's loss of adhesion. Sport utility vehicles (SUVs) and partly laden heavy vehicles will roll over if the friction level is relatively high, or slide if it is relatively low. Again, if rollover occurs it will occur at a lower speed than the loss of adhesion. Drivers could mitigate the increased crash risk associated with poorer vehicle stability by choosing to traverse curves at lower speeds than other vehicles. However, it has been shown (de Pont et al. 2000) that there is a strong correlation between a vehicle's rollover stability and its rollover crash risk which suggests that if such a speed reduction is occurring it is not sufficient to offset the increased crash risk.

1.5. Curve treatments

Although increases in lane and shoulder width have sometimes been recommended as a means of making curves more forgiving (Zegeer et al. 1990) this can also have the effect of increasing drivers' speeds, thus negating any overall safety gains (Lewis-Evans and Charlton 2006). More often, various types of warning signs are placed along the roadway in advance of a horizontal curve to alert drivers to the change in alignment and remove the element of surprise (Donald 1997). The goal of these warning signs is to attract drivers' attention and alert them to the risks and hazards that lie ahead (Jorgensen and Wentzel-Larsen 1999). Unfortunately, the effect of these curve warning signs on drivers' perceptions of risk may be quite low, leading to overall safety impacts of only 6% (Jorgensen and Wentzel-Larsen 1999). Shinar et al. (1980) found that installation of curve warning signs on two high-accident curves failed to result in any significant change in drivers' entry speeds. It has been suggested that one of the reasons for their limited effectiveness may be due to their overuse, particularly in situations of lesser risk (Jorgensen and Wentzel-Larsen 1999).

Some advance curve warning signs also include an advisory speed plate to indicate a recommended speed through the curve. These speed advisories are designed to affect drivers' approach speeds which have been shown to be a more important predictor of curve entry speeds than the sharpness of the curve (Retting and Farmer 1998). The effectiveness of supplementary curve advisory speeds, however, has been the subject of some debate over the years. Several studies have indicated that curve warnings with advisory speed plates are no more effective than traditional curve warnings (with no recommended speeds) (Lyles 1980; Zwahlen 1983). A laboratory study of advance warning signs with advisory speed plates found that they work best for severe curves, but may not work in the presence of distractions (and severe curves produce some slowing by themselves)(Charlton 2004). A comparison of several curve warning sign configurations found that no single sign or combination of signs was consistently more effective than any other in reducing drivers' speeds or improving their lane position as they approached and negotiated horizontal curves (Lyles 1980). One study even reported a paradoxical effect in which drivers produced higher speeds when advisory speed plates were present than when they were absent (Ritchie 1972). The explanation of this finding was that advisory speed plates may provide drivers with greater certainty about the severity of the curve ahead and allow them to proceed with greater confidence and speed (Ritchie 1972).

Another reason suggested for the questionable effectiveness of advisory speed plates is that there is inconsistency in how advisory speeds are set (including the use of outdated speed criteria) that leads many drivers to disregard the recommended speeds (Chowdhury et al. 1991; Chowdhury et al. 1998; Herrstedt and Greibe 2001). The recommended speeds displayed for many curves have become outdated over the years as a result of significant improvements to vehicles, tyres and road surfaces (Donald 1997). As previously mentioned, there also appear to be differences in how drivers comply with the advisory speeds at curves. Speed signs at curves are the most important variable in determining curve speeds for non-violators (those who report always or mostly obeying speed limits), but for non-violators the road-layout factor is the most important factor (Kanellaidis 1995). It has also been found that when drivers are familiar with particular curves, the lower the likelihood that curve advisory speed signs will influence their choice of speed at those curves (Jorgensen and Wentzel-Larsen 1999). One study reported that 90% of drivers exceeded the recommended speed displayed at curves and over half exceeded it by 10 to 30 km/h (Chowdhury et al. 1998). It has been pointed out that the net effect of inconsistent application of criteria and outdated curve advisory speeds is often tragic when a driver encounters a curve for which the advisory speed is accurate and realistic (Dorrestyn 2002).

In New Zealand, the driver's perspective was articulated in a magazine article that questioned the reliability of the advisory speeds. The author of the article argued that 'a safety sign that enjoins us to take more care than we need to puts us at risk of taking less care than we ought to. If a standard car can go around at 85 km/h with ease, the advisory sign should say so. Preaching safety by exaggerating risk just makes the foolhardy look foolish… it's time they [the advisory speeds] were looked at and renumbered so that the warnings mean something again.' (Calder 2003, p24).

Another approach to signifying the hazards associated with horizontal curves has been the placement of chevron sight boards at the tangent point of the curve entrance. Chevron sight boards typically consist of a series of chevron symbols on a single board with an advisory speed positioned to the outside of the arrows (Charlton 2004; Koorey et al. 2002). Chevron sight boards (with advisory speeds) have been shown to produce greater reductions in curve approach and curve entry speeds than advance warning signs, particularly for high and moderate speed curves (Charlton 2004). Koorey et al. (2002)

suggested that chevron sight boards with advisory speeds might be more effective at focusing drivers' attention on the posted speeds due to their placement directly in the drivers' line of vision.

Interestingly, drivers' detection rates for both types of curve warnings are very low, with a slight advantage for the advance warnings: 29% detection compared with 10.5% and 22.5% for black and white chevrons and fluorescent yellow and black chevrons respectively (Charlton 2006). This finding suggests that the location of chevron signs confers no greater conspicuity relative to advance warning signs, and thus part of their advantage in reducing drivers' speeds may lie in their ability to delineate the geometry of the curve. The finding that drivers who cannot recall seeing an advance curve warning sign underestimate their speeds and drive through the curve at higher speeds compared with drivers who recall seeing the sign (Milošević and Milić 1990) suggests that advance warning signs rely on explicit, attentional processes. In contrast, chevron sight boards continue to work well in reducing drivers' speeds even when drivers are distracted by secondary tasks such as cellphone conversations, whereas the effectiveness of advance warning signs declines (Charlton 2004). Taken together, these findings suggest that the beneficial effects associated with chevron sight boards may result primarily from implicit (ie unconscious) perceptual processing of the curve delineation rather than relying on explicit consideration of the warning or advisory speed (Charlton 2004; Lewis-Evans and Charlton 2006).

Other curve warning treatments have employed chevron signs without speed advisory plates, either as single chevron sight boards or as a series of individual post-mounted chevron symbols placed around the outside of the curve (Herrstedt and Greibe 2001; Zador et al. 1987; Zwahlen 1983; Zwahlen and Schnell 1996). While both of these types of chevron treatments appear to be effective, several studies have reported that a series of repeated chevron markers are more effective in reducing drivers' speeds, speed variability, and centreline encroachments through the curves, as compared with a single chevron sight board or standard edge marker posts (Gates et al. 2004; Herrstedt and Greibe 2001; Jennings and Demetsky 1985; Nielsen and Greibe 1998). One field study, however, reported that although the repeated chevrons did decrease drivers' speed variability they also had the effect of slightly increasing average night-time speeds through the curves (by approx. 0.3−1.0 m per sec or ~1−4 km/h) (Zador et al. 1987). It has been argued that when negotiating sharp curves drivers require information beyond that provided by most hazard warning signs (Bhatnagar 1994), and that chevron signs placed around the circumference of the curve meet that need by providing additional visual cues with which drivers can estimate the severity of the curve (Zwahlen and Schnell 1996). The reported effect of chevron warning signs on crashes has been very favourable (Agent et al. 1996; LTSA 1996). In New Zealand, the effect of chevrons installed at 83 rural sites and 20 urban sites on crashes was analysed using data from the LTSA Crash Investigation Monitoring System. Overall, the analysis indicated a 48% reduction in crashes at open road sites equipped with chevron signs and a 54% reduction in crashes at urban sites (although it should be noted that many of the sites included additional improvements such as raised reflective pavement markers, guard rails and edge marker posts). The study concluded that chevrons can be expected to aid in the reduction of crashes at bends (LTSA 1996).

A range of other curve warning treatments have also been evaluated with varying degrees of success. Vehicle-activated warning signs have been reported to reduce approach speeds at rural bends (Preston and Schoenecker 1999; Winnett and Wheeler 2002); as have reflective thermoplastic pavement markings that include a directional arrow and the word 'slow' prior to the curve (Retting and Farmer 1998). Pavement markings that include transverse lines with decreasing spacing prior to the curve entry have also been shown to decrease approach speeds in some situations (Agent 1980; Charlton 2004; Vest et al. 2005), but not in others (Comte 1998). Godley et al. (1999) tried various combinations of pavement markings (centreline and edgeline hatching) and post-mounted delineators placed to give the appearance of the curves being tighter than they actually were, but the results indicated no slowing due to pavement hatching and only inconclusive results for lateral positioning of post-mounted delineators.

Curve delineation treatments that provide accurate warning and guidance as drivers negotiate the curves, as with the repeated chevrons described above, have also met with some mixed success in improving lane positions and decreasing run-off-road crashes. A comparison of raised pavement markers and post-mounted delineators on two-lane rural highways found that only slight differences between the two curve delineation treatments (Krammes and Tyer 1991). In general, the two treatments were comparable for the inside lane of a curve, but on the outside lane post-mounted delineators produced the lower speeds (1.6 to 4.8 km/h) while the raised pavement markers produced better and less variable lane positions. Continuous longitudinal rumble strips placed on the edgeline and centreline have also been found to improve lane keeping (Räsänen 2005) and reduce run-off-road crashes (Torbic et al. 2004), particularly when placed on the approach to a curve where the vehicle departure angle is lowest (and rumble strip exposure time is highest).

1.6. Summary

The review of the research literature associated with curve speed management reveals three general mechanisms for human error at horizontal curves: failure of driver attention, misperception of speed and curvature and poor lane positioning. It is apparent that each of these aspects plays a role to some extent in contributing to crashes on curves and that none of them is entirely independent of the others. There is also a considerable range of curve speed management treatments that have been implemented, ranging from advance warnings of various types to delineation treatments through the curve. Advance warnings are primarily designed to attract drivers' attention, warn them of the presence of the curve ahead, and prompt them to reduce their speed during the curve approach. The success of advance warning signs in attracting drivers' attention is often limited when drivers are distracted and because of the general tendency of drivers to overlook many road signs, particularly on familiar roads. Other signage treatments (eg chevrons) may instead emphasise the perceptual features of the curve and appear to be able to work implicitly, without the conscious attention of the driver. Some authors have noted that these sorts of treatments may be the only way to produce speed reductions in drivers who regularly speed or violate traffic rules in other contexts (Fildes and Jarvis 1994). Still other treatments (eg raised reflective pavement markers and rumble strips) provide guidance through the curve to assist drivers in maintaining correct lane position.

The goal of this research was to differentiate the relative contribution of attentional, perceptual and lateral placement factors in drivers' ability to negotiate curves. The research was comprised of several related activities:

1. a survey of road geometry, camber, sight distances and signage at a representative sample of crash sites in New Zealand
2. analysis of available vehicle stability, driver behaviour and road geometry data in order to identify safety and performance envelopes for a representative range of curves and vehicle types
3. consultation with New Zealand roading engineers and road safety practitioners to select a set of curve treatments to be tested in the laboratory
4. laboratory testing of driver responses to the curve treatments using a simulated driving task
5. a review of the laboratory results with roading engineers and road safety practitioners to obtain their feedback regarding the effectiveness and practicability of the treatments in the New Zealand context.

2. Analysis of crash data

This analysis used the New Zealand Ministry of Transport's Crash Analysis System (CAS) database which was developed and is maintained by Land Transport New Zealand. The crash data considered is for the 10-year period from 1997−2006.

Crashes associated with speed through curves were selected by considering only crashes with movement codes BB, BC, BD, BF, DA and DB. A brief description of these codes is given in Table 2.1.

Table 2.1. Description of movement codes in CAS.

Movement code	Description
BB	Head-on – Cutting corner
BC	Head-on – Swinging wide
BD	Head-on – Both (above) or unknown
BF	Head-on – Lost control on curve
DA	Cornering – Lost control turning right
DB	Cornering – Lost control turning left

From these, only crashes where the cause code in the Police report identified speed (with or without alcohol) were selected. The selected crashes were compared with all crashes for the period in Table 2.2. This showed that, although curve speed-related crashes were only a small proportion of the total number of crashes (less than 5%) they were a very significant proportion of the more serious crashes (more than 20% of the fatal crashes and 13% of the serious injury crashes). This is as might be expected from the speed-severity relationships.

Table 2.2. Curve-speed related crashes compared with all crashes.

Crash outcome	All crashes	Curve-speed crashes	Curve speed crashes as a proportion of all crashes
Fatal	3941	820	20.8%
Serious injury	20105	2676	13.3%
Minor injury	73077	6847	9.4%
Non-injury	258744	7965	3.1%
Total	355867	18308	5.1%

The curve speed-related crashes were then separated into urban and open road crashes[3] and sorted by curve severity. The results of this are shown in Tables 2.3 and 2.4 below. Note that the sum of three curve severity categories does not equal the total in the 'all' column. The reason for this is that some crashes were categorised as occurring on straight roads. This seems strange given that the movement types used to select the crashes were all related to turning manoeuvres. However, a review of the crash reports for a small number of these crashes on straight roads indicated that they involved turning

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[3] The urban/open road classification in CAS is based on speed limits. Urban is 70 km/h or less, open road is greater than 70 km/h.

manoeuvres at intersections rather than at curves in the road. For urban roads the numbers of crashes on straights were significant while for open roads the numbers were small.

Table 2.3. Urban curve speed-related crashes by curve severity.

Crash outcome	All urban	Easy curve	Moderate curve	Severe curve
Fatal	195	80	98	11
Serious injury	922	311	401	122
Minor injury	2794	805	1244	401
Non-injury	4223	972	1591	486
Total	8134	2168	3334	1020

Table 2.4. Open road curve speed-related crashes by curve severity.

Crash outcome	All open road	Easy curve	Moderate curve	Severe curve
Fatal	625	183	363	75
Serious injury	1754	456	983	295
Minor injury	4052	1021	2256	699
Non-injury	3742	816	2022	729
Total	10173	2476	5624	1798

Open road crashes account for about 56% of curve speed crashes but as high as 76% of fatal crashes and 66% of serious injury crashes. This is, of course, not surprising given that speeds for the open road crashes are likely to be significantly higher than those on urban roads.

The classification of curves into ‘easy’, ‘moderate’ and ‘severe’ requires a subjective assessment by the attending Police officer. In extracting the CAS data we can categorise the curves using the advisory speed signs, which is a more objective approach, although there are some difficulties with this which we will discuss. The raw extracted CAS data for all crash severities are shown in Table 2.5.

Table 2.5. Crash numbers by curve advisory speed.

Advisory speed	Urban crashes	Open road crashes	All crashes	Percentage
15 km/h	5	6	11	0.34%
20 km/h	9	3	12	0.37%
25 km/h	52	89	141	4.31%
30 km/h	54	90	144	4.40%
35 km/h	93	269	362	11.07%
40 km/h	41	18	59	1.80%
45 km/h	63	377	440	13.46%
50 km/h	9	66	75	2.29%
55 km/h	32	502	534	16.33%
60 km/h	4	35	39	1.19%
65 km/h	17	638	655	20.03%
70 km/h		69	69	2.11%
75 km/h		461	461	14.10%

Advisory speed	Urban crashes	Open road crashes	All crashes	Percentage
80 km/h		60	60	1.83%
85 km/h		188	188	5.75%
90 km/h		10	10	0.31%
95 km/h		10	10	0.31%

These data in themselves are a little odd. The requirements for advisory speed sign placement in New Zealand are specified in the *Manual of traffic signs and markings* commonly called MOTSAM (Transit New Zealand 1998). This specifies that curve advisory speed signs increase in 10 km/h increments and always end in '5'. Thus 20, 30, 40, etc km/h advisory speed signs should not exist at curves on New Zealand roads, although 20 km/h advisory speed signs are used in local traffic management situations such as at speed humps. In practice, there are also some zero-ending advisory speed signs in place as illustrated in Figure 2.1 which shows two curves on Auckland's Tamaki Drive. Based on personal experience, these zero-ending signs are relatively rare but we have no data to quantify the numbers of these non-compliant signs on the network.

Figure 2.1. Advisory speed signs ending in '0'.

Although there are generally fewer data entries for the zero-ending speeds than the five-ending speeds there are still significant numbers. We believe that these numbers are disproportionately high relative to the numbers of signs but we have not proven this assertion. If we are correct then some crash data are incorrectly recorded. Reviewing the crash reports for a small selection of zero-ending advisory speeds shows that this is certainly the case in some instances. A number of the crashes attributed to 30 km/h advisory speeds occurred at roadworks sites where a 30 km/h temporary speed limit was in force but this was incorrectly recorded as an advisory speed. The crash report form does have provision for a temporary speed limit to be recorded rather than an advisory speed limit so this was a reporting error[4]. One of the crashes attributed to a 30 km/h curve was on Cobham Drive in Hamilton at the curve surveyed and reported on in section 3.2.5. We know this curve is signposted at 35 km/h. Of the six 20 km/h advisory crashes

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[4] The fact that these temporary speed restrictions at road works are recorded as advisory speeds raises the question as to whether the Police officers involved realise that these are legally binding limits that should be enforced.

reviewed, one was at a 20 km/h curve, one was at a speed hump, two were at roundabouts and two were at intersections. For these last four it appears that the 20 km/h advisory speed was the attending Police officer's view of the appropriate speed rather than a signposted value. Several 90 km/h advisory speed crash reports were also reviewed. Again, it appears that 90 km/h was the Police officer's assessment of a suitable speed for the situation rather than a posted advisory speed.

There is no simple way of resolving what the correct advisory speed should have been for the crashes attributed to zero-ending speed values. Thus two approaches were used. In the first, all of the crashes with zero-ending speeds were attributed to the next highest advisory speed. That is, 20 km/h advisory speed crashes were lumped in with 25 km/h advisory speed crashes, 30 km/h crashes with 35 km/h and so on. The results of consolidating the data in this way are shown in Table 2.6. The alternative approach is to ignore the zero-ending crashes altogether and filter them from the dataset. In this case the results are as shown in Table 2.7.

Table 2.6 Consolidated crash numbers by curve advisory speed.

Advisory speed	Urban crashes	Open road crashes	All crashes	Percentage
15	5	6	11	0.3%
25	61	92	153	4.7%
35	147	359	506	15.5%
45	104	395	499	15.3%
55	41	568	609	18.6%
65	21	673	694	21.2%
75		530	530	16.2%
85		248	248	7.6%
95		20	20	0.6%

Table 2.7. Filtered crash numbers by curve advisory speed.

Advisory speed	Urban crashes	Open road crashes	All crashes	Percentage
15	5	6	11	0.4%
25	52	89	141	5.0%
35	93	269	362	12.9%
45	63	377	440	15.7%
55	32	502	534	19.1%
65	17	638	655	23.4%
75		461	461	16.5%
85		188	188	6.7%
95		10	10	0.4%

Tables 2.3 and 2.4 show that most crashes occur on moderate curves and that more crashes occur on easy curves than on severe curves. Although it is not absolutely clear which advisory speed classifications would correspond to each of the three descriptive classifications the same trend is apparent in Tables 2.6 and 2.7.

However, these figures need to be adjusted for exposure to risk. There are likely to be significantly fewer severe curves on the network than easy bends, and severe bends are less likely to occur on more heavily trafficked roads.

The 'Signs' table in the RAMM (Road assessment and maintenance management) database can be interrogated to find the number of speed advisory signs. Data from the 2002 RAMM database were extracted for us by Koorey (2007) and are shown in Table 2.8. Ignoring the zero-ending signs and the ambiguous and unknown speed values, the distribution of speed signs is as shown in Figure 2.2.

Table 2.8 Distribution of curve signs on state highway (2002 RAMM data).

Advisory speed	No. of signs
15	19
25	114
35	436
40	1
45	726
45/55	1
50	7
55	970
55/85	1
60	5
65	1238
70	2
75	1399
85	1178
95	161
Unknown	27

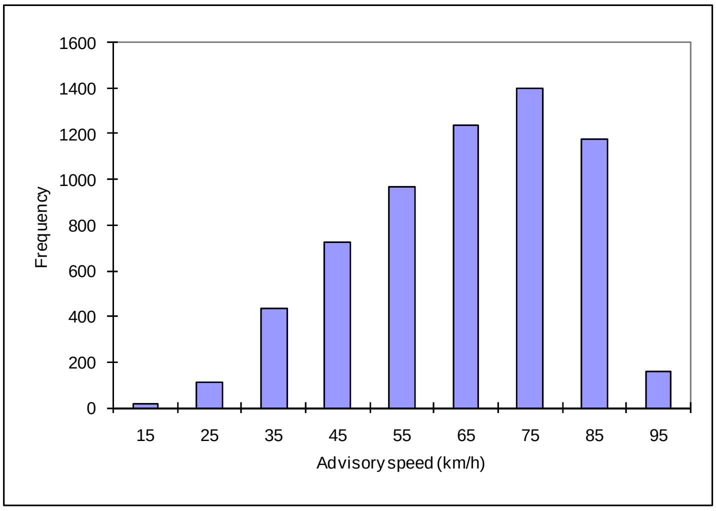

Figure 2.2 Distribution of advisory speed signs on the state highway network.

Alternatively the Road Geometry Data Acquisition System (RGDAS) data on the geometry of the state highway network provides geometry data (radius and cross-slope) from which we can calculate the theoretical advisory speed for every curve on the state highway network. The algorithm used to calculate the advisory speeds is given in Appendix A. The distribution of these theoretical speeds is shown in Figure 2.3.

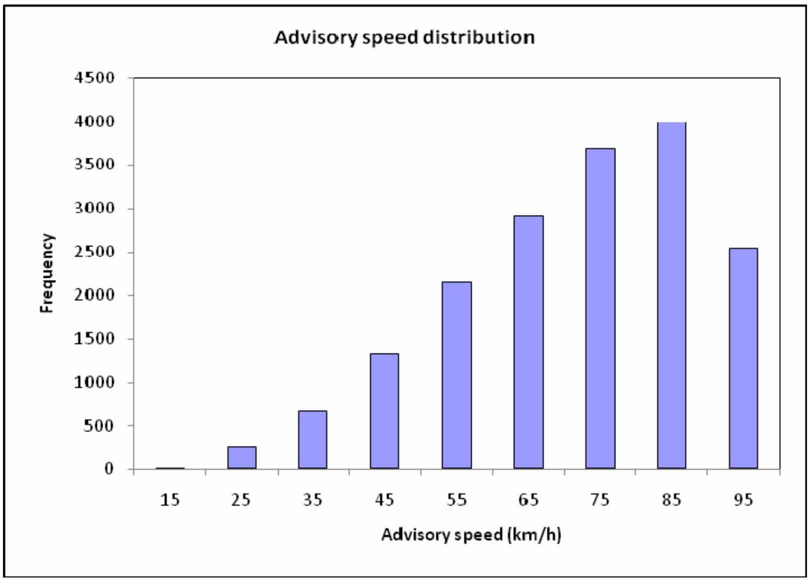

Figure 2.3 Distribution of theoretical advisory speeds for curve on state highways.

Although, for the most part, the distributions of advisory speeds shown in Figures 2.2 and 2.3 are reasonably similar, the numbers of curves at each advisory speed in Figure 2.3 are much higher than the numbers actually signposted at the same speed as shown in Figure 2.2.

There are some factors that should be taken into account when comparing these distributions. In order for a curve to be signposted with an advisory speed sign the approach speed must be significantly higher than the theoretical advisory speed as determined from the lateral acceleration criterion. The criteria for the difference between approach speed and curve speed used in MOTSAM are that the 85th percentile free-running speeds on the approaches to the curves are higher than the limit values as shown in Table 2.9. If drivers complied with the open-road speed limit these criteria should mean that no advisory speed signs of 75 km/h or above would ever be required. In practice it means that relatively few 95 km/h speed signs exist and that a significant number of 85 km/h curves are also not signposted. Comparing Figure 2.3 with Figure 2.2 we see that the theoretical proportions of 95 km/h and 85 km/h curves are higher than the actual proportion of curves signposted at these speeds as recorded in RAMM.

A further criterion that determines whether a curve is signposted relates to adjacent curves and sequences of curves. If curves are sufficiently close together they are not signposted individually but as a group with the advisory speed determined by the most severe curve in the group. The result of this is that a number of curves with a theoretical advisory speed below the open road speed limit are not signposted.

Table 2.9 85th percentile approach speeds required for advisory speed signs.

Advisory speed (km/h)	85th percentile speed (km/h)
15	30
25	40
35	50
45	60
55	80
65	90
75	110
85	120
95	130

An additional complication is that a survey of curve sites in New Zealand showed that almost half the advisory speed signs were incorrect (LTSA 1998). Most of the incorrect signs were only wrong by one speed band and the distribution was reasonably evenly spread above and below the correct value (perhaps with a slight bias below).

Taking these factors into account we would expect Figure 2.3 to be a reasonable reflection of the distribution of advisory speed signposted curves up to 75 km/h on the state highway network. For each curve, the RAMM database provides traffic data and so we can estimate the exposure to risk. This is shown in Figure 2.4.

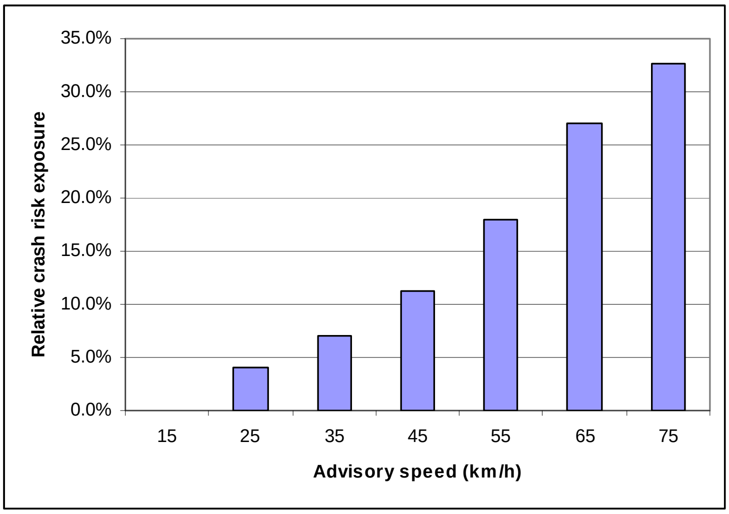

Figure 2.4 Relative exposure by advisory speed.

The results of tabulating the crash numbers, the exposure and calculating the relative crash risk all by advisory speed (without 85 and 95 km/h curves) are shown in Table 2.10. The 15 km/h curve result is not very reliable because of the small numbers of both curves and crashes involved. Beyond that it appears that the highest crash risk is on 35 km/h curves. As the curves become less severe the crash risk reduces but as they become more severe it also reduces.

The figures in Table 2.10 use the crashes for all roads while the exposure risk is calculated from curves on the state highway network. It is possible that the mix of curves on the non-state highway network is different from the state highway network so the analysis was repeated using only crashes on the state highway network. The results of this are shown in Table 2.11.

Table 2.10 Crash numbers, exposure and relative crash risk by advisory speed.

Advisory speed (km/h)	Percentage of crashes	Percentage of exposure	Relative risk
15	0.4%	0.0%	82.33
25	5.1%	4.1%	1.25
35	16.9%	7.0%	2.39
45	16.6%	11.3%	1.48
55	20.3%	18.0%	1.13
65	23.1%	27.0%	0.86
75	17.7%	32.7%	0.54

Table 2.11 Crash numbers, exposure and relative crash risk by advisory speed for state highways only.

Advisory speed (km/h)	Percentage of crashes	Percentage of exposure	Relative risk
15	0.2%	0.0%	37.62
25	3.6%	4.1%	0.89
35	13.0%	7.0%	1.84
45	14.6%	11.3%	1.29
55	20.7%	18.0%	1.15
65	26.2%	27.0%	0.97
75	21.8%	32.7%	0.67

Again the figure for 15 km/h curves is unreliable because of the small numbers involved. Otherwise the trend is very similar with the highest risk being on 35 km/h curves. More severe curves (25 km/h) appear to have a lower crash risk and with less severe curves the risk declines with reducing severity. In Table 2.11 both the crash and exposure data are based on the same set of roads and so the values for relative crash risk are likely to be more accurate than those in Table 2.10.

Possibly the most interesting result is that the crash risk appears to decrease in going from 35 km/h curves to 25 km/h curves. There are a number of possible explanations for this, such as:

- 25 km/h curves are relatively rare on the network and it may be that this rarity makes drivers more cautious when they encounter one
- As noted above, a previous survey indicated that a significant proportion of advisory speed signs showed the incorrect speed. It was not clear whether this error rate was constant across all speed levels. It may have been that a significant proportion of theoretical 25 km/h curves were actually signposted at 35 km/h. Any crashes that occurred on these bends would be recorded as occurring on a 35 km/h bend.

- Numbers of crashes were recorded as occurring on 20, 30, 40, 50, 60, 70, 80 and 90 km/h curves. Advisory speed signs at these values do not comply with MOTSAM and are likely to be rare. These crashes were allocated to the next highest value curve advisory speed. Thus the crashes identified as occurring on a 30 km/h curve were assigned to the 35 km/h group. It may be that some of these should have been assigned to the 25 km/h group.
- 25 km/h curves are quite severe and occur relatively infrequently. It may be that they occur primarily in areas where the road generally is very winding and so the mean free-running vehicle speeds in the vicinity of the curves are lower. Alternatively these curves may be more likely than others to occur in restricted speed zones and so the distribution of these curves across speed zones may be different from other curves.
- There is a degree of under-reporting of crashes, which increases as the crash severity decreases. Crashes at lower speed curves are likely to have less severe outcomes and thus have a higher rate of under-reporting. Also lower-speed curves are more likely to be on lower-volume roads which may also result in a higher rate of under-reporting. If the level of under-reporting increases more rapidly than the crash rate increases there will be an apparent reduction in crash rate. The reduction in relative crash rate is too large for this to be the only explanation.

These possible explanations are largely speculative. The result should not encourage road controlling authorities to increase the severity of curves as a method of improving safety. The underlying trend is that reducing curve severity reduces crash risk and this should be a basic principle of any road geometry improvements. Koorey and Tate (1997) found that the crash rate increased as the difference between the curve advisory speed and the approach speed increased. That is, the important factor is not the curve advisory speed itself but the difference between the advisory speed and the approach speed. In practice, more severe curves with low advisory speeds are likely to have larger differences from the approach speed than less severe curves and so will have higher crash rates.

The finding that the crash rate decreases when the curvature becomes severe (advisory speed of 25 km/h) appears to contradict the findings of numerous other authors (eg Choueiri and Lamm 1987, Cenek and Davies 2004, Cairney and McGann 2000) who have consistently found that crash risk increases with increasing curvature. However, a closer look at their work reveals that the curve groupings they used were not sufficiently fine to identify this result. Typically all curves with a radius of less than 100 m or so were grouped together. In terms of our data this would put all the curves in the 15, 25, 35, 45 and 55 km/h advisory speed categories into a single category.

Clearly from Tables 2.10 and 2.11 this group of curves has a substantially higher crash rate than the higher-speed curves which have less curvature. This is consistent with the findings of the other researchers.

3. Survey of curve sites

3.1. Introduction

The research plan originally proposed that 20 curve sites with a history of crashes be inspected to identify the characteristics that might contribute to the poor safety performance of these curves. This plan was varied slightly so that 15 curves with a poor safety record were to be inspected along with five other curves that did not have a poor safety record. The reason for this modification was to see whether there were obvious points of difference between the curves with a poor safety record and those without. All surveyed curves had advisory speeds posted. The surveyor was provided a list of more than 20 possible curves in case some were not able to be surveyed. The final tally of surveyed curves was 21 with 16 crash sites and five no-crash sites.

3.2. The curves that were surveyed

Potential curve sites for inspection were extracted from the CAS crash database using the same search criteria as for the statistical analysis described in the previous section. The curves selected were all from the Auckland−Waikato region to reduce the amount of travel required to visit the sites. There is no obvious reason to believe that factors that might lead to poor safety performance in this region would be different from those in other parts of the country.

3.2.1. Auckland sites

Three low advisory speed curves with a high-crash rate and one curve with no crashes were selected in central Auckland. These were:

1. Beach Road between old Railway Station and Stanley Street intersection. This is a 25 km/h advisory speed curve with three recorded crashes.
2. Tamaki Drive outside Kelly Tarlton's. This is a 30 km/h advisory speed curve with three recorded crashes.
3. Ngapipi Road approximately 400 m in from Tamaki Drive. This is a 45 km/h advisory speed curve with six recorded crashes.
4. Ngapipi Road approximately 200 m closer to Tamaki Drive. This curve was similar to the previous curve in many respects including the 45 km/h advisory speed but had no recorded crashes.

Figure 3.1 shows the locations of these four sites.

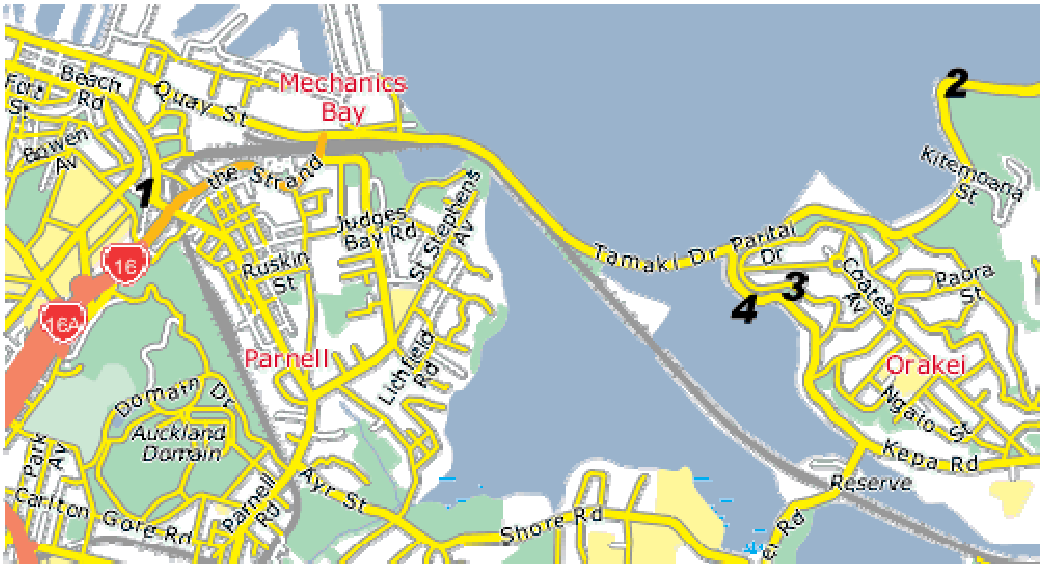

Figure 3.1 Surveyed curves in central Auckland.

3.2.2. Maramarua

Although State Highway 2 between Maramarua and Mangatawhiri has a reputation as a dangerous section of road with a high number of crashes, very few of these crashes have been identified as being caused by speed through curves. The curve sites inspected were:

1. an 85 km/h curve a few hundred metres to the east of Maramarua township. Three crashes have been recorded at this site
2. an 85 km/h curve at the intersection of Mangatangi Rd. No speed-related crashes have been recorded at this site.

Figure 3.2 shows the locations of these two sites.

Figure 3.2 Surveyed curves at Maramarua.

3.2.3. Kaihere (State Highway 27)

Travelling south from Maramarua, State Highway 2 becomes State Highway 27 (State Highway 2 turns off to the left towards Paeroa and Waihi). In the vicinity of the settlement of Kaihere there is a winding, hilly section of road several kilometres long before reaching the Hauraki Plains where the road is characterised by long straight sections. In this Kaihere hill section three curves where multiple crashes have occurred were identified. In addition two other curves with no associated crashes were selected. The curves were:

1. at the northern approach to Kaihere Hill, a 75 km/h bend with two recorded crashes
2. near the top of the ascent of Kaihere Hill, a 35 km/h bend with two recorded crashes
3. on the southern descent of Kaihere Hill, a 65 km/h bend with two recorded crashes
4. a second 35 km/h curve just north of site 2 with no associated crashes
5. an 85 km/h curve at the northern end of the section with no associated crashes.

Figure 3.3 shows the locations of these five sites.

Figure 3.3 Surveyed curves on SH27 near Kaihere.

3.2.4. Karangahake Gorge

Heading east from Kaihere on State Highway 2 between Paeroa and Waihi the road passes through the Karangahake Gorge. A number of bends in the gorge have been the sites of crashes attributed to speed. Five of these were selected for inspection. One further site with no associated crashes was also surveyed. These six curves were:

1. near the Karangahake settlement, a 65 km/h curve which was the site of a truck-trailer rollover

2. about 1 km further east, a 55 km/h curve which was the site of loss-of-control crash that resulted in a head-on collision
3. approximately 1.5 km further east, a 65 km/h curve which was the site of a loss-of-control crash. Although the crash report showed this curve as having a 65 km/h advisory speed, the survey found only a curve warning sign and chevron signs in one direction, ie the signage had been changed since the crash
4. about 1 km further on, a 65 km/h curve which was the site of three recorded crashes including a B-train rollover and two loss-of-control crashes; one resulting in a head-on
5. about 1 km further on, in the Waikino settlement, a 65 km/h curve which was the site of a loss-of-control crash. Although the crash report indicated a 65 km/h advisory speed, the surveyors found a 75 km/h sign
6. a 65 km/h advisory speed corner near Mackaytown with no associated crashes.

Figure 3.4 shows the location of these six sites.

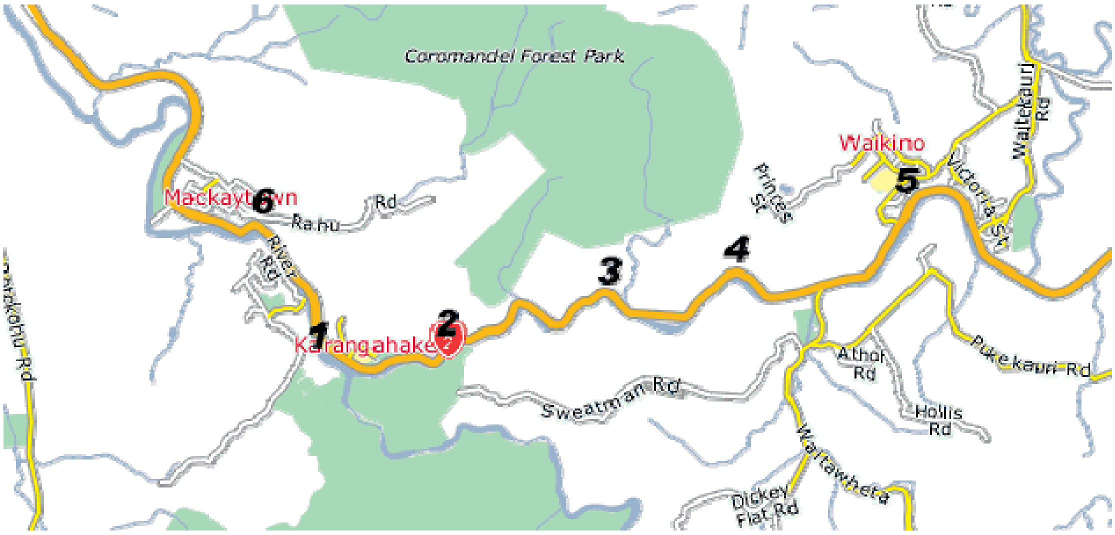

Figure 3.4 Surveyed curves in the Karangahake gorge.

3.2.5. Hamilton

Two sites in Hamilton with high numbers of curve speed-related crashes were selected. These were:

1. on Cobham Drive approaching the bridge across the Waikato River. This is a 35 km/h curve which has had eight recorded crashes
2. just south of the city, on State Highway 21, which runs from State Highway 1 towards the airport, at the Narrows Bridge over the Waikato River. This is a 45 km/h curve which has been the scene of four recorded crashes due to speed.

Figure 3.5 shows the location of these two sites.

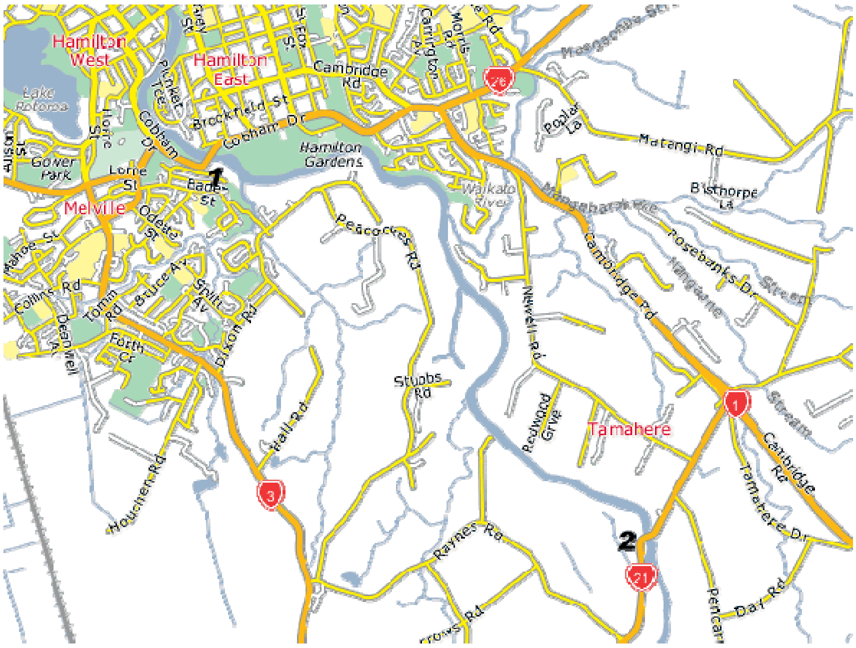

Figure 3.5 Surveyed curves in Hamilton.

3.2.6. Cambridge

Two sites in the Cambridge district were selected as follows:

1. approximately 7 km from Victoria Street Waikato River bridge on the road from Cambridge to Te Awamutu (known as Cambridge Road) just past the settlement of Monavale, a 75 km/h curve which has been the site of three recorded crashes
2. on the same road, approximately 2 km from the Waikato River bridge, a 65 km/h curve which has been the scene of two crashes.

Figure 3.6 shows the location of these two sites.

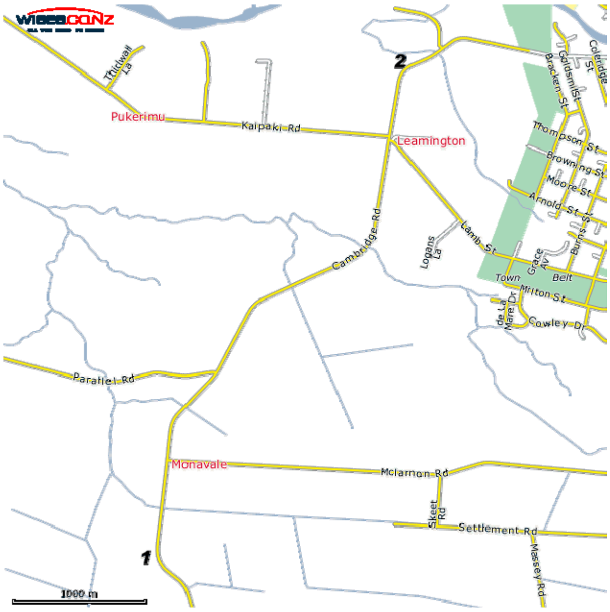

Figure 3.6 Surveyed curves in Cambridge.

3.3. Survey results

The survey was undertaken by Brenda Bendall, an experienced traffic engineer. For each curve the assessment form shown in Appendix B was completed. This assessment was quite comprehensive but primarily qualitative. Some lane and shoulder-width measurements were taken. As well as the environmental evaluation, where possible, a brief survey of vehicle speeds using a laser speed gun was also undertaken. The speed surveys recorded approach speeds and curve speeds for both directions of travel, that is, four sets of data at each location. Each of the four data sets consisted of between 12 and 20 vehicles. Time and cost constraints precluded obtaining bigger samples. The sample sizes were too small to be able to estimate average speeds with high precision but did provide a reasonable insight to the speed behaviour at each curve.

Speed measurements were undertaken at 16 of the sites including five sites with no associated curve speed crashes. A summary of the results of this speed survey is shown in Table 3.1. Comparing the average speeds through the curve with the advisory speed, the ratio varied between 0.98 and 1.58. That is, at some curves the average curve speed was approximately equal to the advisory speed while at other curves it was substantially higher. In no cases was it significantly lower. In general, the higher-speed ratios were associated with lower advisory speed values. On 11 of the curves there was no significant difference in the curve speed for the two directions of travel (using a two-tailed t-test at the 5% significance level). With a larger sample it is possible that a few of these 11 curves would be found to have a statistically significant difference in curve speed between the two travel directions but this difference would almost certainly be small. On the other five curves there was a difference in average speed between the two directions of 5−8 km/h which was statistically significant. The difference between the average speed approaching the curve and the average speed through the curve was calculated. This variable ranged from -5 km/h (ie the vehicles were accelerating through the curve) to 34 km/h which represents a substantial deceleration. Large values for this variable indicate that there was a relatively large difference between the curve design speed and the speed environment, which is usually expected to have an adverse safety impact. Although it could be argued that this factor might be a contributor to the crash rate at the Hamilton 2, Cambridge 2 and Auckland 2 (Tamaki Drive) curves, we see similar slowdown levels at Kaihere 4 (southbound) and Karangahake 6 (westbound) which are curves without a history of crashes.

The sites without crashes can be compared to neighbouring sites that did have crashes:

- Auckland 3 (six crashes) and Auckland 4 (no crashes) were both 45 km/h curves on Ngapipi Rd. The signage at both curves was very similar. The main difference noted by the surveyor was that Auckland 4 was level while Auckland 3 was near the bottom of a hill when approached from the south. This led to higher approach speeds as shown by the magnitude of the slowdown in Table 3.1.
- Karangahake 6 was similar in character to the other five sites in the Karangahake Gorge. Karangahake 6 had 3.75 m lane widths, 1.2 m wide shoulders, and was well delineated with painted edgelines and raised reflective pavement markers (RRPM)

on the centreline. It was signposted with a curve shape sign marker with the advisory speed and with a chevron board also giving the advisory speed. In the westbound travel direction there was a guardrail. In terms of these basic descriptors most of the other sites were broadly similar with some differences in detail. All sites had painted edgelines and RRPMs on the centreline. Three of the sites had less sealed shoulder width than Karangahake 6 (0.5 m – 0.8 m) and there were some variations in the signage. Overall, however, there were no obvious points of difference that would distinguish the curves with crashes from the one without crashes.

- On State Highway 2 in the vicinity of Maramarua, two 85 km/h curves were surveyed of which one was the site of three crashes while the other had none. The curve without crashes had an intersection with a major side road at its western end. Other than that both curves were well delineated with painted edgelines, RRPMs along the centreline and with a solid yellow no passing line applying to westbound traffic. Both curves had 3.5–4 m lane widths with sealed shoulders of 1.5 m. Both curves had similar vertical curvature characteristics (level approach going to downhill in the eastbound direction).
- At Kaihere, two of the five curves surveyed had no associated crashes. One of these was a 35 km/h curve which is adjacent to another 35 km/h curve that had two recorded crashes. The signage, seal width and shoulder width for these two curves were almost identical. The delineation was similar but, on the curve with crashes, the RRPMs had been covered by a pavement re-seal and thus were not effective. Both curves were 'blind' with drivers unable to see oncoming vehicles until they were quite close. The main difference between the curves appeared to be that the curve with crashes had an exit to a rest area/lookout midway through it. Both the crashes were attributed to excessive speed through the curve and neither of them involved any interaction with other vehicles. The other curve without crashes was Kaihere 5 which was an 85 km/h curve at the northern end of the section. This curve was well signposted and well delineated but had relatively narrow sealed shoulders (0.5 m). The Kaihere 1 curve, which had three crashes associated with it, was a 75 km/h curve southbound and a 65 km/h curve northbound. It had similar delineation to Kaihere 5, slightly more extensive signage (an additional chevron board) and wider sealed shoulders (1.6 m–2.2 m). The Kaihere 3 curve, which was a 65 km/h curve, also had similar delineation, more signage (additional chevrons northbound) and had similar shoulder width to Kaihere 5 (0.5 m).

Table 3.1 Summary of surveyed curve speeds.

Advisory speed	Average speed	Std error	Average/ advisory speed	Average approach speed – average curve speed	Site	Direction
25	36.8	1.0	1.47	5.5	Auckland 1	Northbound
25	35.3	1.2	1.41	10.9	Auckland 1	Southbound
30	39.9	0.7	1.33	9.8	Auckland 2	Eastbound
30	37.9	0.8	1.26	13.3	Auckland 2	Westbound
35	49.5	1.7	1.41	5.5	Kaihere 2	Northbound

Advisory speed	Average speed	Std error	Average/ advisory speed	Average approach speed – average curve speed	Site	Direction
35	55.5	2.0	1.58	-3.2	Kaihere 2	Southbound
35	45.6	1.2	1.30	7.1	Kaihere 4	Northbound
35	49.5	1.8	1.41	24.2	Kaihere 4	Southbound
45	61.9	2.0	1.38	23.6	Hamilton 2	Northbound
45	54.3	2.3	1.21	34.3	Hamilton 2	Southbound
45	49.4	1.9	1.10	-1.4	Auckland 4	Northbound
45	52.8	0.9	1.17	-0.1	Auckland 4	Southbound
45	48.2	1.4	1.07	12.1	Auckland 3	Northbound
45	52.8	1.7	1.17	-4.9	Auckland 3	Southbound
65	74.3	2.2	1.14	11.6	Cambridge 2	Northbound
65	73.9	2.1	1.14	15.9	Cambridge 2	Southbound
65	68.5	2.1	1.05	7.0	Kaihere 3	Northbound
65	64.0	2.0	0.98	-3.4	Kaihere 3	Southbound
65	73.6	1.4	1.13	7.3	Kaihere 1	Northbound
65	73.6	1.8	1.13	8.5	Karangahake 6	Eastbound
65	65.9	0.9	1.01	18.0	Karangahake 6	Westbound
75	78.9	1.0	1.05	10.4	Kaihere 1	Southbound
75	81.3	1.5	1.08	2.1	Karangahake 5	Eastbound
75	77.2	1.4	1.03	9.8	Karangahake 5	Westbound
75	89.5	2.4	1.19	1.2	Cambridge 1	Northbound
75	88.8	2.3	1.18	2.4	Cambridge 1	Southbound
85	93.0	2.0	1.09	3.3	Kaihere 5	Northbound
85	91.8	1.4	1.08	7.9	Kaihere 5	Southbound
85	86.1	1.8	1.01	2.0	Maramarua 1	Eastbound
85	89.4	1.5	1.05	4.7	Maramarua 1	Westbound
85	87.3	2.2	1.03	-0.2	Maramarua 2	Eastbound
85	86.7	1.9	1.02	7.4	Maramarua 2	Westbound

In all cases there were no obvious features distinguishing the curves with crashes from those in a similar environment with no crashes. One complication in this assessment is that the crashes associated with a curve had occurred at some time between 1997 and the time of the survey but we do not know when the curve treatment in place at the time of the survey was installed. Thus it is possible that in some cases the treatments were applied after the crash(es). Although we had hoped to identify critical features from this survey, in hindsight it is perhaps not surprising that we failed. If there had been obvious characteristics that resulted in increased crash risk, one would hope that these would have been recognised by the appropriate road controlling authority and addressed.

It should be noted that for almost all the crash site curves that were surveyed, the surveyor was able to identify steps that could be taken to improve the safety of the curve. However, these recommended interventions were developed with the benefit of hindsight, that is, knowing that the curves had been the site of crashes and being able to review the Police crash reports describing how the crashes had occurred. Assessing a curve with no crash history and determining whether or not additional treatments are necessary is a more difficult problem.

It should also be noted that crashes are a relatively rare event. The curve with the worst crash record in the survey (Cobham Drive, Hamilton) had eight crashes recorded over an eight-year period. This curve is on State Highway 1 and according to Transit New Zealand's data has an annual average daily traffic (AADT) of more than 26,000 vehicles. Thus over the eight-year period some 76 million vehicles passed through the curve and there were eight recorded loss-of-control crashes. Thus the estimated risk is 10.5 crashes per 100 million vehicles. Most curves have much lower traffic volumes and it is quite possible for these curves to have as high a crash risk as Cobham Drive but to have experienced no crashes during the eight-year period. For example, the Karangahake Gorge has an AADT count of about 7000 and so a curve with the same crash risk as the Cobham Drive curve would have been expected to have an average of about two crashes over the eight-year period. In the Karangahake Gorge we compared a site that had no crashes with other sites that had had one crash and found no distinguishing characteristics. It is quite possible that the curve with no crashes has the same crash risk as the other curves but that purely by chance no crashes had occurred in the period considered. The probability distribution that best describes the chances of the number of occurrence of a low probability event is the Poisson distribution. Table 3.2 shows some examples of probabilities calculated using the Poisson distributions. If the expected number of crashes for a particular curve over a certain time period is one, then there is a 37% (0.368) probability there will be no crashes; exactly the same probability that there will be one crash and then reducing probabilities of 2, 3, 4 or more crashes. If the expected number of crashes is two, there is still a significant probability (13.5%) that no crashes will be observed. Thus, quite clearly, although Karangahake 6 had no crashes and Karangahake 1, 2, 3, and 5 all had one crash, we do not know whether there is any difference in crash risk between these curves. Even with Karangahake 4 which has three crashes, we cannot be certain that it has a higher crash risk than the other curves.

Table 3.2 Example values of Poisson probability distribution.

Expected number of events	**1**	**2**
Actual number of events	**Probability**	**Probability**
0	0.368	0.135
1	0.368	0.271
2	0.184	0.271
3	0.061	0.180
4	0.015	0.090
more than 4	0.004	0.053

4. Performance envelope of curves

4.1. Introduction

The aim of this portion of the project was to develop a methodology for determining the safe speed for a curve based on its characteristics. This speed will vary with vehicle type and with curve properties and road and traffic environment. The level of safety (or not) achieved on a curve is determined not just by the 'safe speed' but also whether or not the cues that drivers receive lead them to select a speed that is no greater than the safe speed. To a degree, the signage and other curve treatments investigated in this project are mechanisms to assist the driver to select a safe speed when the other cues they are receiving would lead them to an unsafe speed.

4.2. Vehicle factors

There is a large range of performance variation between the different vehicles on the road. It is not practical to consider the full range of these characteristics so a set of reference vehicle classes have been selected for this analysis. These are:

- passenger car
- rigid truck or bus
- truck and trailer combination
- B-train/ semitrailer.

Even within these vehicle classes there is a large range of possible performance characteristics. When determining safe speeds for these vehicle classes, the lower end of performance is used to give a conservative estimate.

Vehicle performance characteristics that affect safe curve speed include rollover stability, braking performance, tyre friction demand, off-tracking and handling characteristics.

4.2.1. Passenger car

The design speed, curvature and superelevation of curves are designed so that the side friction demand does not exceed a maximum value. This maximum friction demand coefficient varies with design speed and can range from 0.12 at high speeds (100 km/h) to 0.35 at low speeds (50 km/h). Typically the friction coefficient for a tyre on a good road surface is 0.8 or higher and so the maximum friction demand at the design speed is considerably lower than the friction available and there is no risk of sliding. The available friction can be substantially reduced through ice, snow, mud or diesel contamination when sliding can be a risk.

Rollover stability is typically characterised by a measure called Static Rollover Threshold (SRT), which is the maximum lateral acceleration (measured in units of g, where 1 g is the acceleration due to force of gravity) that the vehicle can withstand before wheel liftoff. For a passenger car the SRT is generally greater than 1. When the SRT is greater than the available friction the vehicle will slide sideways rather than roll over. For most passenger cars this is the case, although for many four wheel drive SUVs it is not. However, the vehicle needs to be travelling considerably faster than the design speed for this to occur. For example, if a curve has a design speed of 50 km/h and a maximum friction demand coefficient of 0.35, then a vehicle travelling at 75 km/h would generate a friction demand coefficient of 0.79. At this point, some SUVs would roll over, while on some road surfaces many ordinary passenger cars would be approaching the adhesion limit of their tyres.

Generally, braking performance is limited by the friction coefficient of the tyre-road interface. Most passenger cars can brake hard enough to lock the wheels. Lee et al. (2000) propose a model for predicting speed through curves based on sight distance. This model assumes that, on average, as drivers enter a curve they will slow down from their desired speed until their available sight distance is equal to their minimum stopping sight distance. As they exit the curve and the sight distance increases they will accelerate back up to the desired speed. Although Lee et al. claim that their model predicts measured speeds well, the results they present indicate that this is only true for smaller radius curves (less than 300 m). On larger radius curves the predicted speed was higher than the measured speed which suggests that sight distance is no longer the critical factor.

Off-tracking affects the vehicle’s lane width and road width requirements. For passenger cars, the additional width required (over and above the vehicle’s physical width) is negligible and much less than that of trucks. The method for determining the amount of lane widening required on a curve (Transit New Zealand 2000) includes an allowance for the difficulty of driving on a curve. This term is equal to $V/19\sqrt{R}$ per lane where V is the design speed in km/h and R is the curve radius in metres. Interestingly, this term is proportional to the square root of the lateral acceleration without superelevation effects. The equations underpinning the determination of curve advisory speeds in MOTSAM are based on passenger car comfort. The acceptable levels of lateral acceleration implicit in these equations range from about 0.18 g to 0.35 g with the higher values occurring at lower operating speeds. Intuitively this makes sense as passenger car drivers might be expected to feel they have more control of the vehicle at lower speeds and have more time to react. However, a study by Koorey et al. (2002) found that assuming a constant ball bank indicator reading equivalent to approximately 0.25 g of lateral acceleration was a better predictor of actual speed behaviour. The range of lateral accelerations implies that the allowance for the difficulty in driving around the curve should be between 250 mm and 350 mm. As the typical passenger car is at least 500 mm narrower than the typical truck and has less off-tracking as well, if the curve can accommodate trucks it will have more than sufficient road width for passenger cars.

4.2.2. Rigid truck or bus

Generally the rollover stability of buses is sufficiently high (the Passenger Service Vehicles Rule 1999 requires that buses have an SRT greater than 0.7 g) so this should not be an issue on curves. Some rigid trucks will have much lower rollover stability. The Vehicle Dimensions and Mass Rule 2002 requires large heavy trucks to have an SRT greater than

0.35 g. Smaller rigid trucks (with a gross vehicle mass (GVM) less than 12 tonnes) have no stability requirement and could potentially have a lower SRT than this. As noted in the discussion on passenger cars at lower advisory speeds, the induced lateral acceleration can approach 0.35 g which may be close to the rollover limit for some vehicles.

Although the stopping distance requirements for heavy vehicles are the same as those for passenger cars, the braking performance of heavy vehicles is generally not as good as that of a passenger car. The additional mass of the heavy vehicle means that the amount of energy that has to be dissipated by the brake system is very much higher. The difference in weight between the laden and unladen states of a heavy vehicle is much higher than it is for a passenger car and the brake system has to be able to provide adequate braking in all states of load. Finally, the tyres of heavy vehicles need to be of a much harder compound than those of a passenger car and so the friction coefficient between the tyres and the road is less. All of these factors make the braking task more difficult. Buses suffer less from these difficulties than trucks and so bus brakes perform more like passenger cars. In terms of speed through curves, this means that where stopping sight distance is the limiting factor on vehicle speed, the appropriate speed for trucks is lower than that of passenger cars.

If the load on a truck is poorly distributed, the steer axle may not be able to generate sufficient cornering forces to negotiate the bend and the vehicle will tend to plough out. This is generally an issue of vehicle design and vehicle operations rather than curve characteristics although low levels of friction can exacerbate and in some cases can cause this problem. This is primarily an issue on small radius curves at relatively low speeds.

Because of the large differences in weight and weight distribution between the laden and unladen states it is impossible to design a truck that has neutral handling characteristics. Generally trucks understeer at low levels of lateral acceleration and gradually develop more oversteer as the lateral acceleration increases. For safe operations it is desirable that this change in handling characteristic is slow and predictable. To characterise this a 3-point measure of handling characteristics has been developed by Woodrooffe and El-Gindy (1992). Although there is some debate about what the critical values of the 3-points should be, the basic principles are:

- at low levels of lateral acceleration the level of understeer should not be excessive
- the transition from understeer to oversteer should not occur below some minimum level of lateral acceleration
- critical oversteer should not occur below some higher level of lateral acceleration.

These are all vehicle-related characteristics but for curves to be consistent with these principles the level of lateral acceleration when traversing a curve should not change too suddenly, particularly when the peak lateral acceleration is expected to be relatively high.

The second point on the 3-point measure is usually set at 0.2 g so it is desirable to select truck speeds that allow the lateral acceleration to remain below 0.2 g. This should ensure a reasonable safety margin on rollover stability.

As trucks and buses normally have a greater wheelbase than passenger cars and a greater width, they require more lane width on curves, particularly those with a tighter radius. There are two counteracting factors at play here. As speed reduces and curvature increases, the off-tracking of the vehicle increases and hence lane width requirements increase. On the other hand, the additional width allowance for the difficulty of driving on the curve (referred to in the passenger car discussion) increases with increasing speed. The *State highway geometric design manual* (Transit New Zealand 2000) gives a formula for determining the lane width required on curves using a design rigid truck. This formula is quite conservative because it adds the steady state crawl speed off-tracking to the allowance for the difficulty of driving in a curve which is a high-speed term. The actual off-tracking at normal speeds will be less than the crawl speed value. If the curve is negotiated at crawl speed (eg in a traffic jam) the allowance for the difficulty of driving through the curve becomes zero.

4.2.3. Truck and trailer

For truck and trailer combinations most of the issues are the same as for rigid trucks. Each vehicle unit acts independently in a roll and may have a roll stability which (legally)can be as low as 0.35 g and so curve speeds need to be selected to provide an adequate safety margin. All the issues relating to braking performance, friction demand and handling that were discussed with rigid trucks also apply to truck and trailer combinations.

The two main areas of difference are dynamic stability and tracking. The truck and trailer combination has relatively good low-speed off-tracking characteristics which make it quite manoeuvrable and hence better suited to operations of narrow country roads than B-trains and semi-trailers. However, the penalty for this improved low-speed performance is poorer high-speed dynamics and truck and trailers tend to require more lane width at high speeds. Theoretically, the crawl speed off-tracking of typical truck and trailers is only slightly greater than that of the rigid truck. Because the road widening calculation for rigid trucks is conservative, a curve that meets this road width will also accommodate a truck and trailer.

4.2.4. B-train or semi-trailer

The key area where B-trains and semi-trailers differ from rigid trucks is off-tracking. In terms of rollover stability, the vehicles units are roll-coupled and so the rollover stability of the combination is a weighted average of the rollover stability of the individual vehicle units. Although each vehicle unit could have an SRT at the minimum allowable value of 0.35 g, in general, one or more vehicle units will be more stable than this and so the rollover stability of the combination will be greater than 0.35 g.

The low-speed off-tracking of B-trains and semi-trailers is substantially higher than that of rigid trucks on tight curves. The standard off-tracking manoeuvre is undertaken using an 11.25 m radius turn. If we consider a 50 m radius turn, the difference between a typical semi-trailer and the design rigid truck is about 200 mm. Furthermore, full off-tracking does not occur instantaneously but develops as the turn progresses. Thus lane width may be an issue for B-trains and semi-trailers on smaller radius curves with relatively large turn angles.

4.3. Road factors

The road factors that affect speed through curves are curvature and angle of turn, superelevation, friction coefficient, sight distance and lane width/seal width. The relevance of these factors to different vehicle types varies considerably.

4.3.1. Curvature

Lamm et al. (1999) have proposed a parameter called curvature change rate of single curves (CCR_s) which they claim is the most successful for explaining the variability in operating speeds and accident rates. The formula they give for CCR_s appears complicated and determines CCR_s in gon/km[5]. With some minor rearrangement CCRs can be expressed more simply as follows:

$$CCR_s = \frac{1}{2R}\left(1 + \frac{L_{CR}}{L}\right) \qquad \text{eq (1)}$$

where CCR_s = the curvature change rate for a single circular curve with transitions curves in radians/km

R = radius of the curve in km

L_{CR} = length of the circle portion of the curve

L = total length of the curve (transitions plus circular portion)

Thus CCR_s is proportional to the curvature of the curve multiplied by a factor. This factor ranges in value from 0.5 to 1, being 0.5 when the curve consists only of transition curves and 1 when the curve has no transition curves. This suggests that a curve which consists only of transition curves is equivalent to a circular curve with half the peak curvature and no transition curves. However, the curve that consists only of transition curves is twice as long. If we fix the curve length, we find that the CCR_s is proportional to the curvature of the required circular curve and independent of the length of the transition curves, ie it make no difference whether there are transition curves or not. Figure 4.1 shows a plot of curvature against distance when curve length is fixed for three cases of transition curve length. The reduction in CCR_s due to the use of transition curves is offset by the increase in peak curvature which increases the CCR_s by exactly the same amount.

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[5] gon is a measure of angle. There are 400 gon in a circle compared to 360° or 2π radians

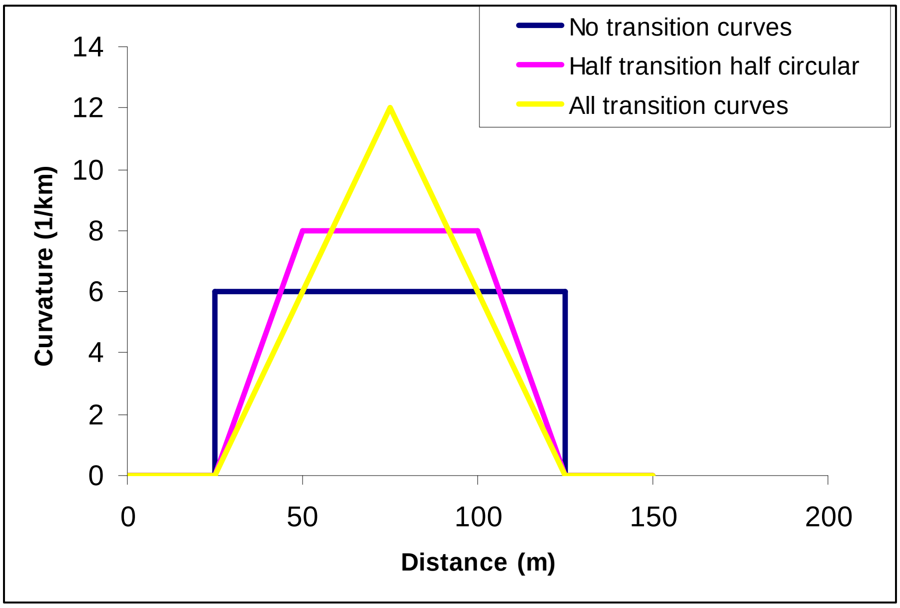


Figure 4.1 Curvature vs distance for fixed curve length.

If the peak curvature is fixed, then the CCR_s reduces as the proportion of the curve that consists of transition curves increases. In the limit case, the curve will consist entirely of transition curves and will have half the CCR_s of the circular curve with the same curvature, but it will be twice as long. A third option is to fix the location of the apex of the curve. In this case again, the greater the proportion of curve that is transition curves, the lower the CCR_s and the longer the curve. The general solution involves Fresnel integrals and so specific values for the angle turned through by the curve need to be specified to evaluate the solution. However, the solution is always between the two extremes considered previously with the lowest CCR_s occurring when the curve consists entirely of transition curves and a curve length between one and two times the length of the equivalent circular curve.

Lamm et al. analysed four databases of crashes of which they regarded two as being more accurate in terms of the calculated CCR_s. For these two the crash rate increased rapidly as CCR_s increased. As CCR_s went from 100 gon/km (1.57 radians/km) to 800 gon/km (12.57 radians/km) the accident rate increased more than five times. In the case of no transition curves 100 gon/km represented a curve radius of 640 m while 800 gon/km represented a curve radius of 80 m.

Lamm also reported on a measure called curve radii ratio which applies to multiple curves. This measure is the ratio of the curve radius to the radius of the immediately preceding curve. For ratios greater than 0.8 it has relatively little effect on the crash rate. However, for ratios less than 0.8 the crash rate rises as the ratio decreases and for values less than 0.2 it rises very rapidly. This is consistent with, although not the same as, other approaches which suggest an increase in crash risk if the design speed of the curve is significantly lower than the speed environment. Typical differences used are 10 mph or 15 km/h. Note that a 450 m radius curve can be comfortably negotiated at 100 km/h. If the curve radii ratio is 0.2 the next curve would have a radius of 90 m which would result in an advisory speed of about 50 km/h so this is a very substantial speed reduction and much greater than the 15 km/h threshold postulated by other authors.

4.3.2. Superelevation

Superelevation has the effect of applying a negative lateral acceleration and hence, for a given speed on a given curve, increases the rollover stability safety margin. Superelevation needs to be developed over some distance and transition curves are often used to also develop the superelevation. Rapid changes in superelevation can induce dynamic effects on the vehicle which may have a negative impact on stability and on road width requirements.

Although superelevation has a positive effect on rollover stability, the magnitude of the superelevation is not easily ascertained by the driver before entering the curve. Lower than normal levels of superelevation are therefore expected to have a negative impact on safety.

4.3.3. Friction coefficient

Generally speaking, appropriate speeds through curves result in tyre forces that are considerably lower than the adhesion limits, ie well below the level at which the vehicle begins to slide. However, where the friction coefficient between the road and the tyres is low this may not be the case. This can occur when the pavement surface is excessively worn (loss of skid resistance), has been contaminated with some spillage, or is affected by adverse weather (ice, snow etc).

4.4. Determining the performance envelope

4.4.1. Factors of safety

In engineering design it is standard practice to use the concept of a safety factor. If an item is being designed and one of the criteria is that the material should not yield, the designer may choose to use a safety factor of two and so will ensure that the maximum stresses in the item do not exceed half the yield stress. Safety factors are used to allow for uncertainties in the applied forces and in the assumptions made in calculations. Generally where the operating conditions are well understood and the outcomes associated with a failure are not excessive a safety factor of two is used. In cases of greater uncertainty or higher risks safety factors of three or four may be used. In design also, the designer considers the range of different loading conditions that will occur and determines the stresses associated with each one. One (or more) of these will be critical and will determine the key design parameters.

This ‘design’ approach seems to be a reasonable way to determine the maximum desirable speed for a vehicle in a curve. It seems reasonable to use a safety factor of two and so, for example, if a given value of lateral acceleration will result in the vehicle rolling over, the maximum desirable speed would generate half that lateral acceleration. In determining the speed, we need to consider rollover stability, loss of adhesion, stopping sight distance and road width requirements. The relative safety of a curve depends not only on its design speed but also on how it fits into its local speed environment. Signage and other curve treatments should reflect the relative safety of the curve not just the maximum desirable speed.

4.4.2. Lateral acceleration issues

For heavy trucks the rollover stability is legally required to be greater than 0.35 g lateral acceleration. With a safety factor of two, the maximum desirable lateral acceleration for trucks is 0.18 g. For buses with a floor height greater than 2 m (usually double deckers), the rollover stability requirement is 0.53 g while for buses with lower floors the requirement is 0.7 g. From a rollover stability point of view the maximum desirable lateral acceleration for these vehicles is 0.27 g and 0.35 g respectively. Some SUVs have rollover stabilities as low as 0.7 g although most passenger cars are much higher.

The friction coefficient between tyres and the road typically has a maximum of about 1 for dry asphalt but reduces as the amount of tyre slip increases so that the sliding friction coefficient is about 0.8. For wet asphalt the corresponding values are 0.7 and 0.55. This suggests that on dry roads the maximum desirable lateral acceleration to avoid loss of adhesion is 0.4 g on dry roads and 0.28 g on wet roads. Pavement design procedures for curves are usually based on a maximum allowable side friction. This is not constant but decreases as speed increases. The *Guide to the geometric design of rural roads* (Austroads 1999) tabulates the maximum design values of side friction against speed. This table is derived from observed driver behaviour and is based on 85th percentile speeds. This starts at 0.35 at 50 km/h and drops to 0.12 at 100 km/h. Vertical wheel forces are not constant but vary as the suspension responds to road unevenness. The magnitude of this response depends on road roughness and vehicle speed as well as the suspension characteristics. For a heavy truck with steel suspension at high speed (80 km/h plus) on a moderately rough road, the peak variations in wheel loads can be as much as half the weight of the truck. This then halves the maximum side force that can be generated for a given coefficient of friction. Although the dynamic load variations on passenger cars are less than this, it partly explains why the observed side friction demand is lower on high-speed curves.

Thus, for trucks the desirable maximum lateral acceleration is determined by rollover stability while for passenger cars it is determined by the tyre adhesion limit. For most buses and some SUVs the limit is determined by rollover on dry roads and by tyre adhesion on wet roads. On high-speed curves drivers appear to operate at lower levels of side friction force. Although in part this can be explained by vertical dynamics reducing the available side friction this is not the total explanation. At higher speeds the driver has less time available to adjust and the consequences of a failure to negotiate the curve are more severe. One option for taking this effect into account is to assume the safety factor is speed-dependent. Reaction time is directly dependent on speed while crash severity relates to energy which depends on the square of speed. Thus we can assume that the safety factor has the form:

$$\begin{aligned} &\mathrm{SF} = \mathrm{a} + \mathrm{b}.V + \mathrm{c}.V^2 \\ &where\ \ \mathrm{V\ is\ speed} \\ &\mathrm{and}\quad \mathrm{a, b, and\ c\ are\ constants} \end{aligned} \qquad \text{eq (2)}$$

If we embed this safety factor in the equation relating maximum acceptable lateral acceleration to vehicle speed we end up with a quartic equation to solve for speed. Although a quartic equation can be solved explicitly, the solution is quite complex. An alternative simpler approach is to use a safety factor of one to calculate the maximum possible speed. This speed can then be used to calculate the safety factor which can in turn be used to calculate the maximum desirable speed. Using this approach the safety factor is based on the maximum possible speed rather than the maximum desirable speed (ie V in eq (2) is the maximum possible speed rather than maximum desirable speed) but the method is simple to apply and should be consistent. Before proceeding it is necessary to establish the values of the constants a, b and c in the equation eq (2). To an extent these are arbitrary. We have selected values as follows to reflect what we believe is a reasonable approach to safety and to match observed driver behaviour. At zero speed a safety factor of one can be used. There is no need for a safety margin because at zero speed there is no additional risk. At 30 km/h we assume that the safety factor should be two while at 100 km/h it should be four. These latter two values are based approximately on the lateral acceleration associated with curve advisory speeds. The ball bank indicator equation in MOTSAM provides for readings at advisory speed of 20.4° at zero km/h, 16.65° at 30 km/h and 7.9° at 100 km/h with a 3° offset for superelevation and vehicle body roll. Thus the lateral accelerations correspond to 23.4°, 19.65° and 10.9° or 0.43 g, 0.36 g and 0.19 g respectively. If V in the equation above is in km/h then a=1, b=0.03476 and c=-4.762 x 10^{-5}. Applying this approach for a range of curve radii and superelevations to the case where the maximum lateral acceleration possible is 0.8 g gives the maximum desirable speeds shown in Figure 4.2. The effect of superelevation on desirable maximum speed is substantial particularly on the higher speed curves. However, drivers are quite limited in their ability to perceive the magnitude of the superelevation. Consequently if the superelevation differs significantly from expectations speed selection may be poor.

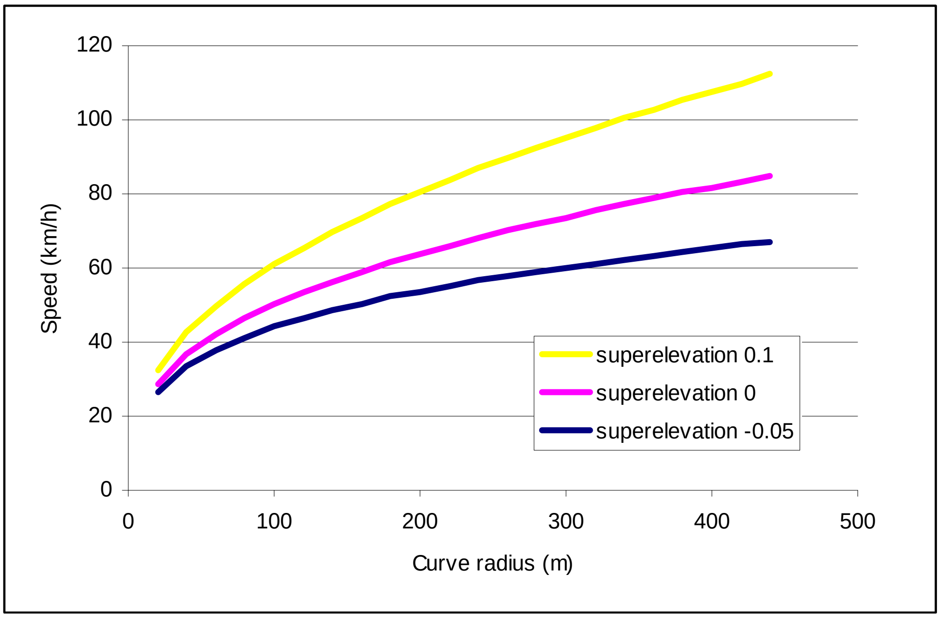


Figure 4.2 Maximum theoretical desirable speed vs curve radius and superelevation.

4.4.3. Sight distance

Stopping sight distance may be the limiting factor on curve speed selection. The stopping distance depends on the vehicle speed, the driver reaction time and braking capacity of the vehicle on the particular road surface. From simple trigonometry the sight distance on a circular horizontal curve is given by:

$$\text{Sight Distance} = 2R\cos^{-1}\left(\frac{R-O}{R}\right)$$

$$\begin{aligned} \textit{where}\ & R \text{ is the curve radius} \\ & O \text{ is the offset distance from the centre of the lane to the obstruction} \end{aligned}$$

eq (3)

The stopping distance in metres is given by:

$$\text{Stopping Distance} = \frac{\mathrm{T_r}.V}{3.6} + \frac{V^2}{254d}$$

$$\begin{aligned} \textit{where}\ & T_r \text{ is the driver reaction time in seconds} \\ & V \text{ is the vehicle speed in km/h} \\ & d \text{ is the coefficient of longitudinal deceleration} \end{aligned}$$

eq (4)

Thus for a given sight distance we can calculate the speed that results in a satisfactory stopping distance. We can then apply a safety factor to determine a maximum desirable speed that provides an adequate margin on stopping distance. As a starting point consider using a safety factor of two and a reaction time of two seconds. If we apply this to the stopping distance we find that the maximum desirable speed reduces to between 50% and 60% of the value calculated with no safety factor. This is because the safety factor effectively doubles the reaction time as well as halving the deceleration rate and reaction time is a major contributor to stopping distance. This approach appears to be too conservative. If the offset distance is 4 m, the maximum desirable speeds determined by stopping distance are less than half the speeds determined by lateral acceleration for typical passenger car parameters. If we assume that a safety factor is already included in the reaction time value and hence only apply the safety factor to the coefficient of deceleration, the maximum desirable speeds are more aligned with those determined from lateral acceleration. For small offset distances, the stopping distance speeds are lower than the lateral acceleration speeds. As the offset distance increases, the lateral acceleration determined speeds become critical particularly on the small radius curves.

4.4.4. Road width

The third factor to consider is seal width and/or lane width. This situation is complex. In principle, seal width is the important factor and lane width reflects lane marking practice. However, lane markings provide important cues to drivers and so lane width does have an impact. The lane width requirements of a vehicle vary with speed. At low speeds the rear axle of the vehicle tracks inboard of the steer axle and so the width requirement is greater than the vehicle width. As speed increases the centrifugal acceleration reduces the inboard off-tracking till at some point it becomes zero. Then as speed increases further the rear axles track outboard of the steer axle and again the width requirements are greater than the width of the vehicle.

The *State highway geometric design manual* (Transit New Zealand 2000) gives a formula for calculating the additional lane width required in a curve. This formula is based on a rigid truck with a forward distance of 8.3 m. The additional width consists of the crawl speed off-tracking that this vehicle would generate plus a width allowance for the difficulty in driving through the curve which is based on speed and curvature. In some respects this is a conservative approach because the crawl speed off-tracking is only correct at very low speeds when the difficulty factor is zero. As the speed increases the difficulty factor becomes relevant but the actual off-tracking is less than the crawl speed value. However, the 8.3 m forward length rigid truck is not the worst case for low-speed off-tracking and the crawl speed off-tracking of 18 m semi-trailers and 20 m B-trains will typically be greater.

The difficulty in using lane width to determine the desirable maximum speed is that low-speed off-tracking decreases with speed and so the lane width requirements decrease. This is offset in part by the difficulty factor which implies an increase in the width requirement. Overall, however, the lane width requirement decreases with speed until the off-tracking becomes zero. At higher speeds the off-tracking moves outboard and starts to increase again. Hence the lowest speed does not result in the lowest lane width requirement. If we consider a 30 m radius curve, then, using the *State highway geometric design manual* formula and typical passenger car dimensions we find that the passenger car requires about 1.5 m less lane width than the design rigid truck. For larger radius curves this difference is smaller but, in general, if the curve can accommodate heavy vehicles, there will be more than adequate lane width for passenger cars. For trucks the problem is that if the lane width is not adequate, reducing vehicle speed does not necessarily reduce the lane width requirements although it does increase the time available to take preventative action.

4.4.5. Procedure for determining curve speed limits

The procedure to calculate the maximum desirable speed for a vehicle through a curve is:

- determine or measure the curve radius, the superelevation and the offset distance from the centre of the lane to any visual obstruction
- establish the vehicle's cornering and stopping parameters; specifically the maximum possible lateral acceleration and the braking coefficient. The maximum lateral acceleration is limited by rollover stability for most heavy vehicles and by tyre adhesion for passenger cars. Typical values to use are 0.35 g for laden heavy vehicles, 0.7 g for buses and SUVs and 0.8 g for passenger cars. The braking coefficient reflects the maximum braking efficiency that can be achieved and should be 0.9−1 for passenger cars and 0.5−0.6 for heavy vehicles. We assume a reaction time of two seconds
- calculate the maximum possible speed (in km/h) limited by lateral acceleration using the formula:

$$V = \sqrt{(127.R(\text{lateral acc} + \text{superelevation})} \qquad \text{eq (5)}$$

- from this speed, calculate the safety factor (SF) using eq (2) where SF = 1 + $0.03476.V - 0.00004762.V^2$. Divide the maximum lateral acceleration value by the safety factor and recalculate the speed. This is the desirable maximum speed as limited by lateral acceleration.

- calculate the sight distance using eq (3). Based on a safety factor of two set the braking coefficient to half the maximum braking efficiency value. Then setting the stopping distance equal to the sight distance calculated use eq (4) to solve for speed. This is the maximum desirable speed as limited by sight distance.

The maximum desirable speed for the particular vehicle in the curve is the lesser of the two maximum speed values calculated.

As an example, consider a 50 m radius curve with 7% superelevation and an offset distance of 9 m between the centre of the inside lane and the bank which obstructs the view. For a passenger car we assume a maximum possible lateral acceleration of 0.8 g and a braking coefficient of 0.9. The maximum desirable speed due to lateral acceleration is 44 km/h while the maximum desirable speed due to stopping sight distance is 58 km/h, so the maximum desirable speed is 44 km/h. For a heavy truck we set the maximum lateral acceleration to 0.35 g and the braking coefficient to 0.6. In this case the desirable maximum speed due to lateral acceleration is 36 km/h and the desirable maximum speed due to stopping sight distance is 50 km/h. Thus the desirable maximum speed for a heavy truck is 36 km/h. Using the same assumptions for vehicle body roll of the measurement vehicle that are used in MOTSAM the advisory speed for this curve would be 45 km/h.

Although lower desirable maximum speeds are associated with greater curve severity and hence higher crash risk there are other factors that affect crash risk which need to be taken into account in determining what level of signage and other treatments are needed. These include:

- the speed environment. Curves that have a design speed that is significantly lower than the overall speed environment have a higher crash risk. There are different ways of characterising this. One is the curve radii ratio described earlier. Another is to consider curves high risk if the design speed is more than 15 km/h below the speed environment
- the presence or absence of transition curves. The desirable maximum speed based on lateral acceleration considers only the peak curvature and not the length of the curve. The CCR_s measure described earlier halves if the curve is made up entirely of transition curves rather than being only a circular arc (for the same peak curvature). This implies a substantial difference in crash risk
- the trade-off between curvature and superelevation. To generate the same lateral acceleration at a given vehicle speed, a curve can have smaller radius and a larger superelevation or a larger radius with a smaller superelevation. It is not clear that drivers perceive these two geometric features equally well. In the example above reducing the superelevation to 0.03 and increasing the radius to 60 m results in approximately the same desirable maximum speed for a passenger car.

5. Selection of curve treatments

5.1. Methodology

Based on the review of the literature, seven curve treatments were identified as candidates for laboratory testing in this research project:

1. Standard advance warning sign with advisory speed plate (black on yellow).
2. Chevron sight board with advisory speed (black on yellow).
3. Chevron sight board with 'repeater' signs installed through the curve.
4. Double yellow centre lines indicating no overtaking.
5. Rumble strips installed on centre (double yellow) and edge lines through the curve.
6. Road narrowing on curve approach achieved by adding yellow flush median striping.
7. Herringbone pavement markings installed on the curve approach.

A survey to collect practitioner ratings of the seven candidate treatments was then prepared in the hope that the survey responses would provide a basis for selecting two of the treatments (in addition to a control condition) for laboratory testing with a simulated driving task. The survey briefly described the overall goals and approach of the present project, outlined some of the relevant research literature on curve warnings, and asked the respondents to rank the seven treatments according to their interest in having each treatment included in the laboratory testing phase of the project. In addition, an eighth condition, consisting of no sign or delineation treatment, was described as a control condition. The survey also provided the opportunity for the respondents to add their comments on each of the candidate treatments. The completed survey (shown in Appendix B) was sent to 12 New Zealand road safety practitioners (transport engineers and researchers).

5.2. Results

A total of nine respondents (75%) completed and returned the survey. The respondents' rankings of the treatments are shown in Table 5.1. As can be seen in the table, there was a wide range of rankings for most of the candidate treatments and a few respondents did not rank all of the treatments. Contrary to the goal of reducing the number of candidates to two treatments, several of the respondents added their own treatments to the list. Additionally, some respondents indicated that a few of the treatments should not be included in the laboratory testing. Most noteworthy among these, six respondents commented that the control condition (no curve treatment) was so implausible that it should not be tested. These respondents argued that the standard advance warning sign (PW17) should be used as a control condition (since all curves of any consequence would include this treatment regardless of what other treatments were in place) and one respondent noted that any crashes resulting from the omission of a warning had the potential to produce carry over effects on driver behaviour associated with the other treatments.

Table 5.1 Respondents' rankings of candidate curve treatments.
(The nine respondent's individual responses are indicated by letters A to I)

Treatment	1st	2nd	3rd	4th	5th	6th	7th	Don't test
1. Control (no treatment)								A, B, C, F, G, H
2. Std. advance warning sign	F	H	A, B, I			D, E	G	
3. Chevron sight board	C	E, F, H, I			G, D			B
4. Chevron and repeaters	E	C, G, H		I		D		B
5. Double yellow centre line	I	D, H	C, E		F	G		A, B
6. Rumble strips cent. & shoulder	D	H	C, E, G	F	I			A, B
7. Road narrowing	G			D		F	H, I, E	A
8. Herringbones			D	G	E	I	A, B, F	

Additional treatments proposed by the respondents:		
Solid white centreline	B	Solid white centreline through curve as per MOTSAM.
RRPMs at centre	B	Standard centreline with raised reflective pavement markers (RRPMs).
Road narrowing II	F	Flush median through curve (but not on approach).
Road narrowing III	B	Flush median with solid lines on each side (to differentiate from turn bay).
Road narrowing IV	A	Centre flush median for right curves, shoulder hatching for left curves.
Herringbones II	H	Herringbones with progressively closer spacing (compare to equal spacing?).
Edge markers	A	Edge marker posts placed to make curve appear more severe.

Comments on the other treatments, explaining the respondents' rationale for their selection, were also very instructive. Several respondents remarked that the chevron sight boards with and without chevron repeater treatments were of considerable interest because, although anecdotal evidence regarding their effectiveness was available from site-specific crash reduction projects, further systematic data on their effects were required. A majority of these respondents added that the chevron repeater arrows should be tested by themselves owing to an increasing frequency of sites where they were erected in the absence of a chevron sight board. As regards the double yellow centreline treatment, some respondents noted that it was frequently requested by road users, and that laboratory testing was needed to assess its effects on drivers' behaviour through curves. A number of respondents indicated that although rumble strips had been reported to have beneficial effects on safety, their installation was often initially accompanied by negative public reactions concerning their likelihood of producing over-reactions or erratic steering and thus a close examination of their effects was desirable.

To assist in the comparison of the rankings for the candidate treatments, a numerical score was assigned to each rank received; a score of 7 for first place rankings, a score of 6 for second place rankings, 5 for third place rankings, and so on. Summing across all of the respondents’ rankings, five of the treatments (including the standard advance warning) had totals ranging from 32−37 and the remaining two treatments had totals of 16 and 17 points. Based on these results and the comments received regarding the control condition, the researchers elected to include the five highest-rated treatments in the laboratory testing, as well as a treatment consisting of only the repeater chevrons, with the standard advance warning treated as a control and incorporated as part of all the other treatments.

In addition, the respondents indicated substantial interest in including some variant of a road narrowing or perceptual countermeasure (PCM) treatment. Although the road narrowing and PCM (herringbone) treatments received relatively low totals when the rankings were summed, several respondents commented extensively on these options and some described alternative treatments. Taking these comments into consideration along with the results of some of our previous laboratory trials, a seventh curve treatment was developed. This treatment consisted of a single set of herringbone pavement markings placed on alternate sides of the lane so that they narrowed the lane and flattened the drivers’ path through the curve. It was also hoped that the treatment would provide some reduction in drivers’ speeds due the herringbone patterns as well as producing greater separation between the two lanes of traffic. A diagram of the new treatment is shown in Figure 5.2. Although the resulting seven treatments were far greater than the three (including control) originally planned, the researchers decided to address all seven in the laboratory testing.

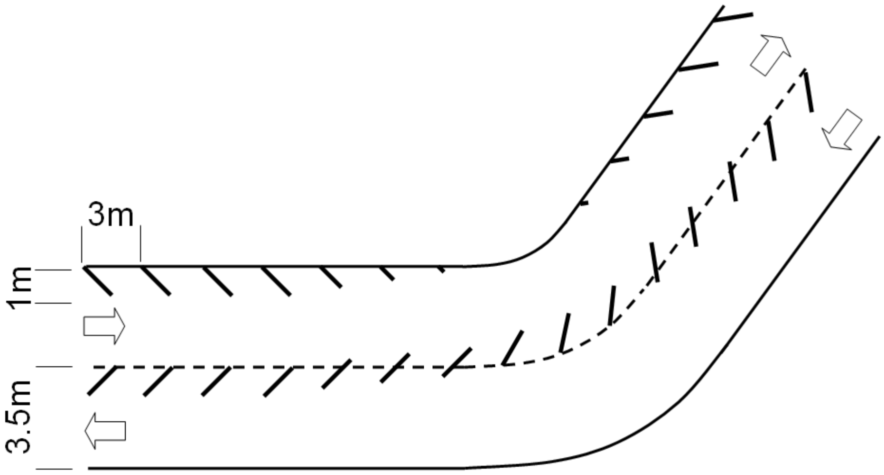


Figure 5.2. Additional herringbones − lane narrowing/guidance treatment (curve dimensions not to scale).

6. Laboratory evaluation

6.1. Methodology

6.1.1. Participants

A sample of 60 participants with unrestricted New Zealand driving licences was recruited from the local region. Forty-eight participants completed the experiment; the reasons for non-completions included participants excused due to reports of dizziness or nausea, equipment malfunctions and data loss resulting from human error. The remaining sample was comprised of 17 men and 31 women with an average age of 26.88 years (SD = 9.81) ranging from 17 to 64. The number of kilometres driven per week reported by the participants varied widely from a minimum of 10 km to a maximum of 1400 km for an average of 208.85 km (SD = 223.28). These participants reported an annual average of 0.208 traffic infringements (including speed camera fines), ranging from none to two. The participants were randomly assigned to one of two experimental groups (24 in each group). Group 1 was composed of eight men and 16 women, with an average age of 28.71 years, average weekly kms of 206.86, and average annual infringement rate of 0.261. Group 2 had nine men and 15 women with an average age of 25.04 years, average weekly kms of 211.04, and average annual infringement rate of 0.167.

6.1.2. Apparatus

The experimental apparatus was the University of Waikato driving simulator consisting of a complete automobile (BMW 314i) positioned in front of three angled projection surfaces (shown in Figure 6.1). The centre projection surface was located 2.42 m in front of the driver with two peripheral surfaces connected to the central surface at 30° angles. The entire projection surface was angled back away from the driver at 10° (from the bottom to the top of the projection surface) and produced a 200° (horizontal) by 39° (vertical) forward view of the simulated roadway from the driver's position. The image projected on the central surface measured 2.64 m wide by 2.10 m high (at a resolution of 1280 by 1024 pixels) and each of the two peripheral images measured 2.70 m by 2.10 m (at resolutions of 1024 by 768 pixels). In addition, two colour LCDs with an active area of 12.065 cm by 7.493 cm each at a resolution of 640 by 480 pixels were mounted at the centre rear-view mirror and driver's wing mirror positions to provide views looking behind the driver's vehicle. The simulated vehicle's dashboard displayed accurate speed and engine RPM data and vehicle performance was determined by a multi-body vehicle dynamics model configured as an automobile with automatic transmission, 3-litre engine (making 170 kW power), and power steering. Four speakers located inside the car and a sub-woofer underneath the car presented realistic engine and road noises as appropriate (eg engine noise synced to engine RPM and audio feedback when the simulated vehicle's wheels crossed rumble strips).

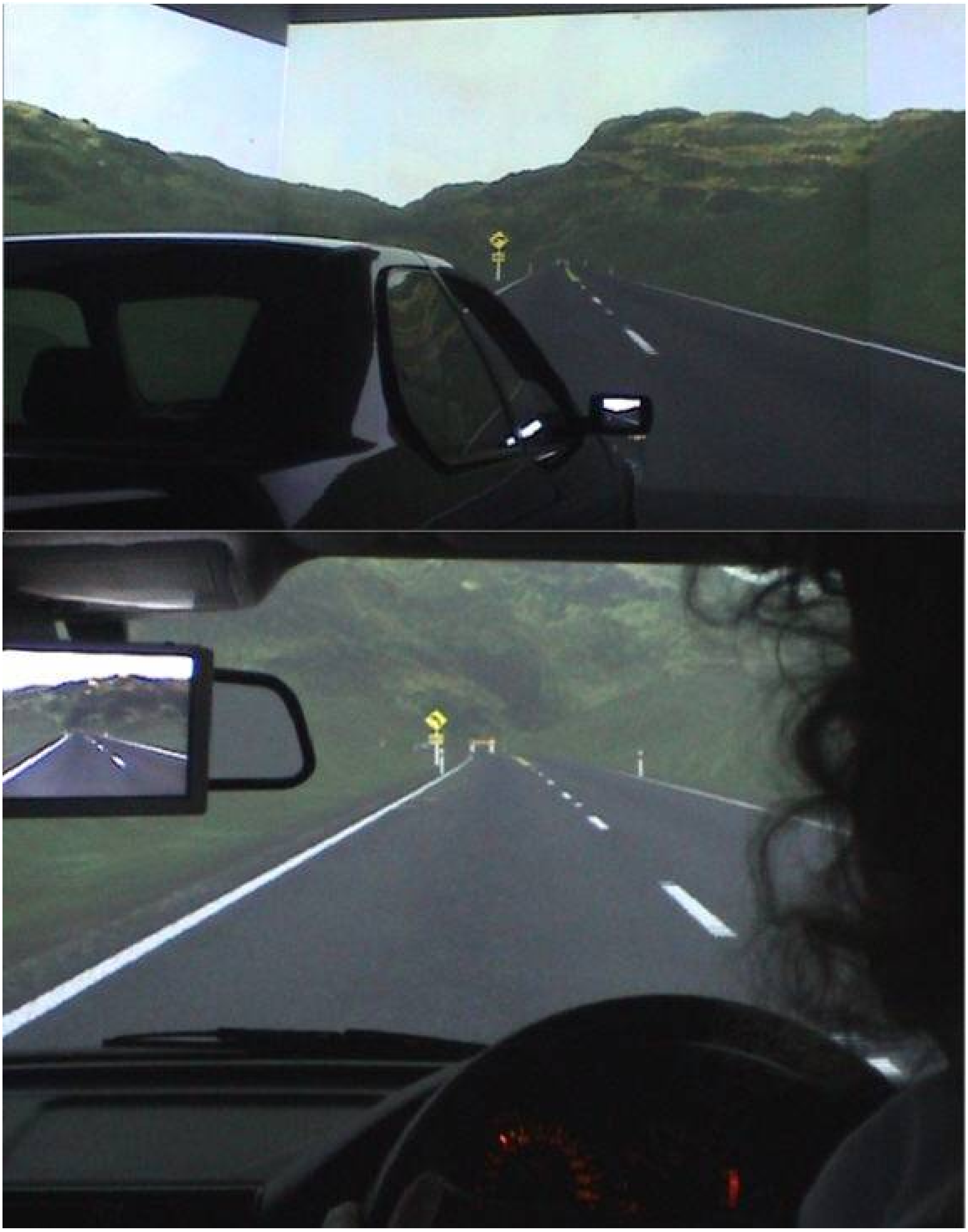


Figure 6.1 Two views of the University of Waikato driving simulator.

6.1.3. Simulation scenarios

Based on the review of the research literature and the survey of road safety practitioners and researchers, we identified seven curve speed management treatments to be tested. The seven treatments can be generally categorised into two types. Four of the treatments consisted of various types of warning signs designed to alert drivers to the presence of curves and an indication of their severity, and hopefully produce a reduction in drivers' speeds at the approach to and through horizontal curves. Thus, the first group of treatments compared was comprised of four combinations of signs as follows:

1. advance curve warning signs with arrow icons (PW17, PW 18, or PW23) and supplementary speed plates as appropriate to the individual curve's geometry
2. advance curve warning signs followed by chevron sight boards
3. advance curve warning signs followed by a series of repeater arrows
4. advance curve warning signs followed by chevron sight boards and a series of RC2 repeater arrows.

These four treatments are shown below in Figure 6.2 as they appeared in the simulations. The second group of treatments was comprised of several types of pavement markings designed to affect drivers' lateral displacement (lane position) as they drove through curves. Once again, the advance warning sign (with the standard dashed white centre line) was included as a control condition and a component of each treatment type. This second group of treatments is shown in Figure 6.3.

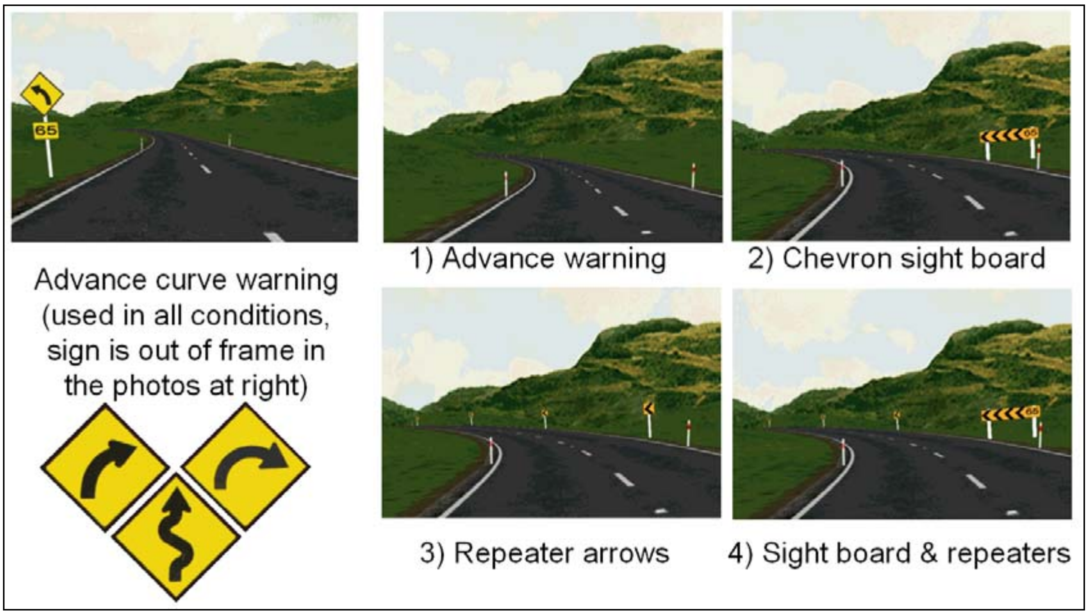
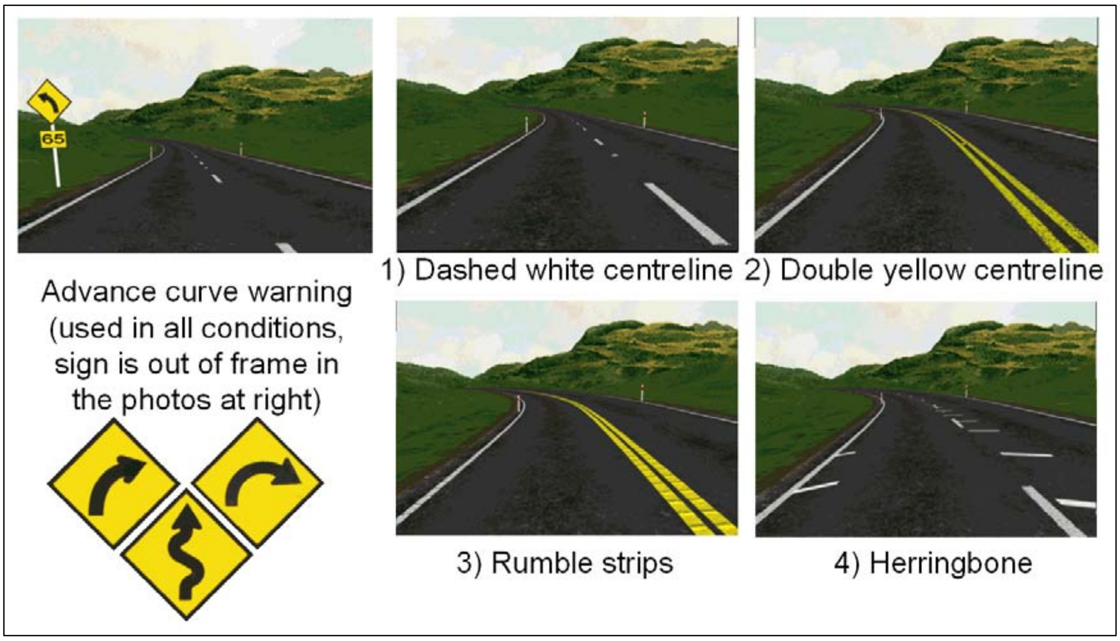


Figure 6.2 Curve warning signage treatments as depicted in simulation.
(Note that the advance warning signs included arrow icons and supplementary speed plates as appropriate to the individual curves' geometry.)



Advance curve warning (used in all conditions, sign is out of frame in the photos at right)

1) Dashed white centreline

2) Double yellow centreline

3) Rumble strips

4) Herringbone

Figure 6.3 Pavement marking treatments as depicted in simulation.

Two simulated roads were created for this study. The first road was comprised of a 3.5 km-long section containing a 1.5 km initial straight, followed by an 85 km/h right turn (45 degrees over 250 m), an 85 km/h left turn (45 degrees over 250 m), a 45 km/h right turn (45 degrees over 150 m), and a 45 km/h left turn (45 degrees over 150 m). These curves were separated from each other by 300 m straight sections of road. This first portion of the simulation was followed by a 3.4 km-long simulated section of State Highway 27 created using road survey data to reflect the actual dimensions and geometry of the highway. This section of state highway contained a range of curve types, beginning with two 65 km/h curves (right then left), a series of four tight 35 km/h curves with a 55 km/h curve in the middle, and a 65 km/h right and 75 km/h left curve near the end of the simulation. The layout of the simulated road is shown in Figure 6.4. Whereas the first half of this simulated road was on a level gradient and contained curves with constant radii, the second half of the road featured a 6.5% ascending gradient for the first 1.3 km and 3.8% descending gradient over the next 1.7 km and its curves corresponded to the irregular geometry of the state highway being represented. This simulated road was used as the main experimental scenario and seven versions were created, each containing the curve warning treatments of interest. The advance curve warning signs, with advisory speed plates and arrow icons appropriate to each curve, were placed in the simulation at distances ranging from 50 to 100 m prior to the curve entry (100 to 130 m prior to the curve tangent point) based on the specifications contained in MOTSAM (1998 and 2003). Chevron signs were located in line with, and at right angles to, the approaching traffic lane at a height of 1 m above the sealed road surface and chevron repeaters were placed at equal spacings on the outside of the curves so that three were in view of approaching vehicles at all times. Pavement marking treatments (double yellow centrelines, rumble strips and herringbones) all began 50 m prior to the curve entry.

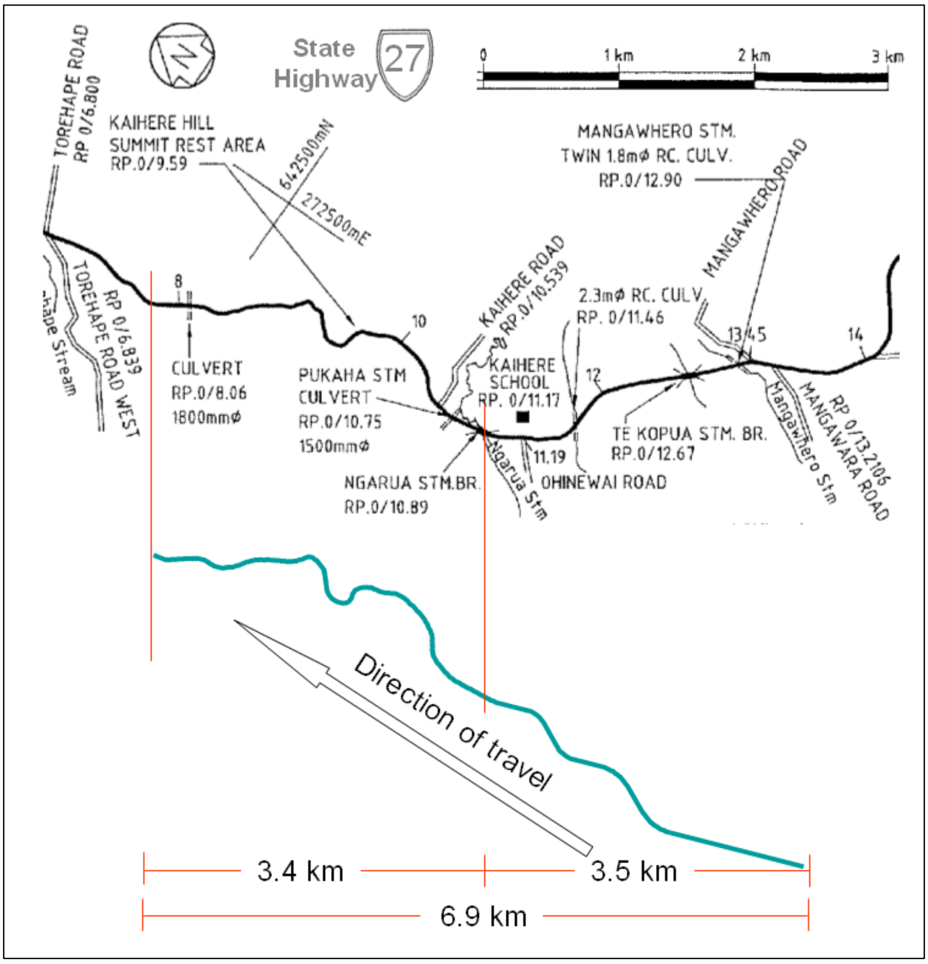


Figure 6.4 The state highway used for the experimental simulation (top portion of figure) and resulting layout of the simulated road (lower portion of figure).

The second simulated road was a 27 km-long section of gently curving and undulating road with an open road speed limit (100 km/h). The road was created using road survey data to match the dimensions and geometry of a rural two-lane state highway in New Zealand. This simulated road was used to provide the participants with practice on the simulator, and three 7 km-long sections were presented to the participants to provide some relief between repeated presentations of the experimental road. The width for both simulated roads (practice/relief and experimental) was maintained at a constant 7 m (two 3.5 m lanes) and was equipped with standard road markings, edge post delineators, and populated by a relatively light amount of oncoming traffic (a representative mix of cars and heavy vehicles equivalent to a vehicle stream of 4000−6000 vehicles per day).

6.1.4. Procedure

Participants were informed that the purpose of the experiment was 'to find out more about the attitudes and driving habits of road users in New Zealand' and that they would be asked to complete a brief questionnaire and drive several simulated roads. Participants then completed an informed consent form and a brief demographic questionnaire. The participants were then seated in the driving simulator and allowed 10 minutes to practice driving.

Upon arrival, the participants were randomly assigned to one of two experimental groups. After completion of their practice, Group 1 received the four experimental roads containing curve warning sign treatments while Group 2 received the four experimental roads containing the pavement marking treatments. The order that the experimental roads were presented for each group was counterbalanced across participants, with the 7 km-long relief roads interspersed between each experimental road. Participants' speed and lateral displacement were continuously recorded for each curve (beginning 100 m prior to curve entry) and the experimenters tallied any run-off-road or other crashes throughout each road. Immediately after completing each road, the participants were asked to rate the difficulty they had driving the road on a 7-point scale ranging from '1 = easy, no difficulty at all' to '7 = nearly impossible, unsafe' (full scale shown in Appendix C). The participants were also asked if they had any comments about the road they had just completed.

6.2. Results

The average speeds measured through the first six curves of the experimental scenarios are shown in Figure 6.5. In the top half of the figure it can be seen that the addition of the chevron sight board and repeater arrow treatments reduced the participants' speeds relative to the advance warning sign by itself. The speed difference was noticeable as early as 100 m prior to curve entry and greatest for the 85 km/h and 45 km/h curves, which were the constant radius 45° curves on level ground. The two 65 km/h curves shown in the figure were 30° variable radius curves on an uphill gradient and although the chevron treatments did produce the lowest speeds, the speeds for the advance warning sign treatment were also low throughout these curves. The relatively smaller speed differential between the advance warning signs and the other treatments may have been due to a moderating effect produced by the uphill gradient on the drivers' free-flowing speeds, resulting in somewhat of a floor effect, below which no further speed reduction was necessary. The findings that participants' curve exit and 50 m post-curve speeds did not recover are another indication of the effect of the uphill gradient associated with these curves. The lower half of the figure shows the participants' average speeds for the pavement marking treatments. Here, all of the treatments produced relatively similar speed profiles, with a slight advantage for the rumble strip treatments which were associated with the lowest speeds, particularly from the curve midpoint onwards. The differences between the treatment types on the remaining curves in the experimental scenarios were very small, again perhaps due to the lower speeds occasioned by the steep gradients and sharp curves.

A 4 (treatment type) X 3 (curve sharpness) X 2 (curve direction) repeated measures factorial analysis of variance was calculated on the curve entry speeds shown in the top half of Figure 6.5. The results indicated statistically reliable main effects of treatment type [Wilks' Lambda = 0.372, $F_{(3,21)} = 11.81$, $p < 0.001$], curve sharpness [Wilks' Lambda = 0.057, $F_{(2,22)} = 182.58$, $p < 0.001$], and an interaction between curve sharpness and curve direction [Wilks' Lambda = 0.565, $F_{(2,22)} = 8.46$, $p < 0.01$]. Post hoc analyses computed using a Bonferroni adjustment for multiple comparisons indicated that

Treatment 1 (advance warning signs) was significantly faster than any other treatment ($ps < 0.01$) but none of the other treatments differed reliably.

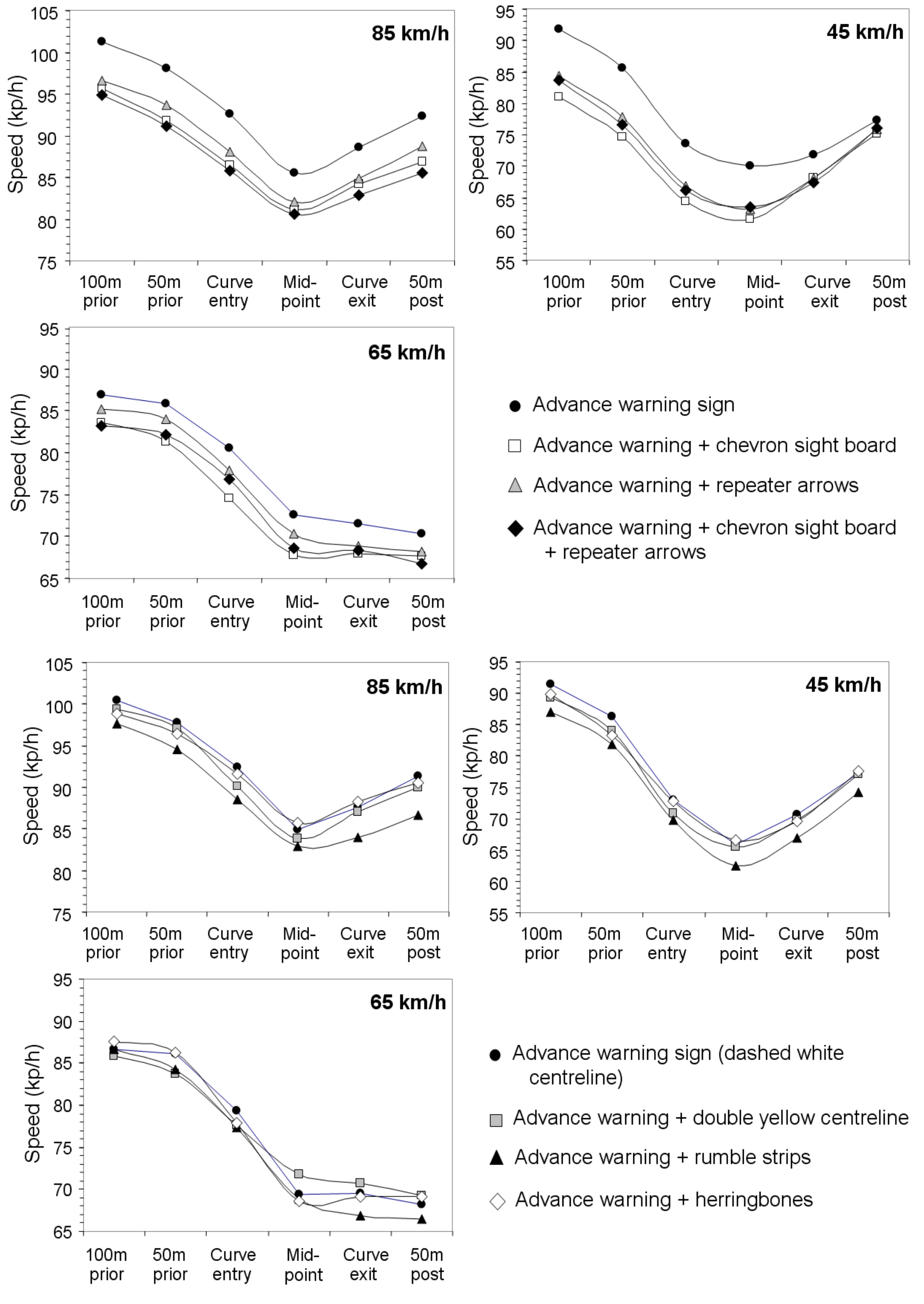


Figure 6.5 The average speeds through the first six curves in the experimental scenarios for the warning sign treatments (top half) and pavement marking treatments (lower half).

The interaction between curve sharpness and curve direction reflected the fact that right turns were an average 2.96 km/h faster for the 85 km/h curves, left turns averaged 3.202 km/h faster for the 65 km/h curves, and average speeds for the two 45 km/h curves were within 0.11 km/h of each other. It is unclear whether this pattern resulted from an order effect (the right 85 km/h curve was always the first one encountered) or was due to the uphill gradient associated with the 65 km/h curves. Analysis of the participants' demographic characteristics failed to reveal any significant differences due to gender, age, or recent history of crashes and infringements. Analysis of participants' lateral displacement) (lane positions) through the curves did not reveal any significant differences between the four treatment types.

An identical 4X3X2 analysis calculated on the curve entry speeds shown in the lower half of Figure 6.5 indicated that there were statistically reliable main effects of treatment type [Wilks' Lambda = 0.695, $F_{(3,21)} = 3.07$, $p < 0.05$], and curve sharpness [Wilks' Lambda = 0.112, $F_{(2,22)} = 86.79$, $p < 0.001$], but no effect of curve direction or any higher-order interactions. Post hoc analyses computed using a Bonferroni adjustment for multiple comparisons did not reveal any one treatment that was reliably lower than the others at the curve entry point (ps > 0.05). As with Group 1, analysis of Group 2's demographic details did not reveal any significant differences in the curve speeds associated with their personal characteristics. A between-subjects comparison of the speeds associated with the advance warning treatment failed to indicate any statistically reliable difference between the two groups ($p > 0.05$).

Another view of the effects of the pavement marking treatments can be seen in the lateral displacement data shown in Figure 6.6. The figure shows a marked effect of the herringbone treatment on the participants' lane positions (averaged separately for left and right curves across the first six curves). For right curves the herringbone pattern moved drivers an average of 0.3 m towards the outside of the curve (relative to the other treatments) at the approach and entry point. Drivers then moved towards the inside of the curve at the midpoint and then back to the outside when exiting the curve (an average of 0.83 m to the left of the control treatment). For left curves the effect of the herringbone markings was to move the participants an average of 0.32 m further left at the midpoint of the curve. Although the effect appears more dramatic in the case of right curves, the effect of the herringbones for both types of curves was to flatten out the trajectory of the drivers' paths through the curves and introduce some greater separation between the traffic in opposing lanes.

Statistical analysis of the 45, 65 and 85 km/h left curves shown in Figure 6.6 (a 4X3 repeated-measures analysis of variance) indicated a significant treatment effect for the participants' lateral displacement at the curve midpoints [Wilks' Lambda = 0.388, $F_{(3,21)} = 11.03$, $p < 0.001$], but no difference due to curve sharpness or any interaction between treatment and curve sharpness. Post hoc comparison (Bonferroni adjusted) for these left curves showed that the herringbone treatment was significantly different from the control and double yellow centreline treatments ($p < 0.001$) but was not reliably different than the rumble strip treatment ($p > 0.05$). An analysis of the lateral displacement for right curves at the point of curve entry also showed a significant treatment effect [Wilks' Lambda = 0.234, $F_{(3,21)} = 22.89$, $p < 0.001$], and a significant effect of curve sharpness [Wilks' Lambda = 0.364, $F_{(3,21)} = 19.24$, $p < 0.001$], but no interaction between treatment type and curve sharpness. Post hoc comparison (Bonferroni adjusted) for the right curves showed that the herringbone treatment was reliably different from the other three treatments ($p < 0.001$) which did not differ from one another. Post hoc comparison of the curve sharpness effect revealed that the 65 km/h right curve (30°, uphill gradient) was significantly different from the 85 and 45 km/h curves (45°, flat gradient), with drivers an average of 0.2 m further left ($p < 0.001$).

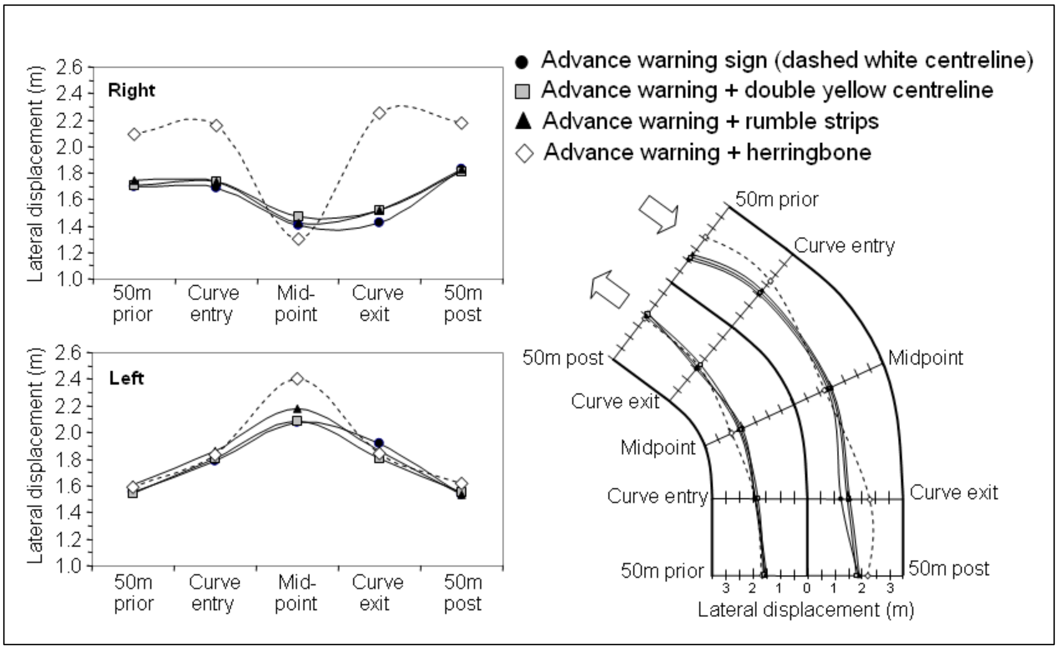


Figure 6.6 Average lateral displacement produced by the four pavement marking treatments (dashed lines indicate the path produced by the herringbone treatment).

Statistical comparison of the participants' free-flowing speeds collected from a point 1.2 km along each of the experimental roads (during the initial flat-gradient straight prior to any curves) did not display any significant differences for Group 1 [Wilks' Lambda = 0.949, $F_{(3,21)} = 0.37$, $p > 0.05$] or Group 2 [Wilks' Lambda = 0.764, $F_{(3,21)} = 2.17$, $p > 0.05$] indicating that the curve speed differences obtained were the result of the different treatments rather than other factors. The participants' ratings of driving difficulty were higher for the experimental roads (average rating of 3.41, SD = 1.14) than for the practice/relief roads (average rating of 1.09, SD = 0.97), and a few drivers did have run-off-the road crashes during the experiment, but a repeated-measures multivariate analysis of variance did not indicate any differences in the rate of occurrence of crashes, or in the participants' driving difficulty ratings, across the different curve treatments for either Group 1 [Wilks' Lambda = 0.850, $F_{(6,18)} = 0.53$, $p > 0.05$] or Group 2 [Wilks' Lambda = 0.658, $F_{(6,18)} = 1.56$, $p > 0.05$].

7. Follow-on laboratory testing

The results of the laboratory testing showed that the chevron treatment (with and without repeater arrows) was capable of producing significant reductions in participants' speeds through a range of curve types. Further, the herringbone pavement marking displayed very strong effects on participants' lane positions. In the course of reviewing the findings with fellow researchers and road safety practitioners, the question of how these two types of treatments might work in combination was raised on more than one occasion. In order to address this question, the research team decided to prepare a brief follow-on test comparing a combined chevron-herringbone treatment with the standard advance warning control treatment. The details and findings of this follow-on test are described below.

7.1. Methodology

7.1.1. Participants

A sample of 24 participants with unrestricted New Zealand driving licences was recruited from the local area. The sample was composed of 10 men and 14 women, with an average age of 26.01 years, ranging in age from 17 to 49 years (SD = 8.19 years). The average weekly kms reported by the participants was 208.75 km, ranging from 50 to 500 km (SD = 135.90).

7.1.2. Apparatus and simulation scenarios

The experimental apparatus (University of Waikato driving simulator) was the same as in the previously described laboratory testing. The simulated roads were prepared the same way as before with the exception that only two versions of the experimental road were developed. The first version consisted of the advance warning signs (and dashed white centreline) used as the control treatment in the previous experiment. The second version consisted of the advance warning signs combined with the chevron sight board and repeater arrow treatment and the herringbone pavement markings. A view of the combined treatment, as depicted in the simulation, is shown in Figure 7.1.

7.1.3. Procedure

The instructions to participants were identical to the previous test protocol and the same demographic questionnaire was administered to the participants. After a 10-minute practice drive (using the same practice scenario described previously) the participants drove the two experimental roads, the order being counterbalanced across the participants. No relief roads were used and no driving difficulty ratings were collected.

Figure 7.1 The combined chevron and herringbone treatment in simulation.

7.2. Results

The effects of the combined treatment are shown in Figure 7.2. The speeds produced by the combined treatment were well below those of the advance warning control. At the point of curve entry the speeds were an average of 3.93 km/h lower than the control treatment in the 85 km/h curves; 5.28 km/h lower for the 45 km/h curves; and 2.74 km/h lower in the 65 km/h curves. Repeated measures analysis of variance indicated that this difference was statistically reliable. As can be seen in the lower right portion of the figure, the combined treatment also produced the changes in lateral displacement characteristic of the herringbone treatment in the previous laboratory test. At the point of curve entry, the participants' lane positions in the right curves were an average of 0.37 m further left than the control treatment and for the right curves, the participants' midpoint positions were an average of 0.22 m further left. Statistical analysis of participants' speeds at the curve entry points with a 2X3X2 repeated measures analysis of variance showed a reliable difference between the two treatments [Wilks' Lambda = 0.833, $F_{(1,23)} = 4.59$, $p < 0.05$], a reliable effect of curve sharpness (Wilks' Lambda = 0.093, $F_{(2,22)} = 107.36$, $p < 0.001$), a reliable direction effect [Wilks' Lambda = 0.725, $F_{(1,23)} = 8.73$, $p < 0.01$], and a treatment by curve sharpness interaction [Wilks' Lambda = 0.725, $F_{(2,22)} = 4.16$, $p < 0.05$]. The effect of the combined chevron and herringbones treatment was to slow drivers down, for right-turning curves more than left curves, and with the largest speed reductions for the 45 and 65 km/h curves.

The statistical analysis of lateral displacement at the entry point of right curves showed that the combined treatment moved drivers significantly to the left [Wilks' Lambda = 0.256, $F_{(1,23)} = 67.01$, $p < 0.001$] relative to the advance warning treatment. There was also a reliable effect of curve sharpness [Wilks' Lambda = 0.661, $F_{(2,22)} = 5.65$, $p < 0.01$]

for which post hoc comparisons (Bonferroni adjusted) indicated that the 30° 65 km/h uphill curves once again displayed the greatest effect of the treatment ($p < 0.05$). The participants' lateral displacement at the midpoint of left curves also showed a significant treatment effect [Wilks' Lambda = 0.499, $F_{(1,23)} = 23.12$, $p < 0.001$] and a significant curve sharpness effect [Wilks' Lambda = 0.750, $F_{(2,22)} = 3.66$, $p < 0.05$]. For these left curves, however, the largest effect was for the 45 and 85 km/h curves where the combined treatment moved drivers significantly further left than at the 65 km/h curve. Bonferroni adjusted post hoc comparisons showed that the 85 km/h curve was reliably further left than the 65 km/h curve ($p < 0.05$), and that the 45 km/h curve was somewhat further than the 65 km/h curve ($p < 0.053$).

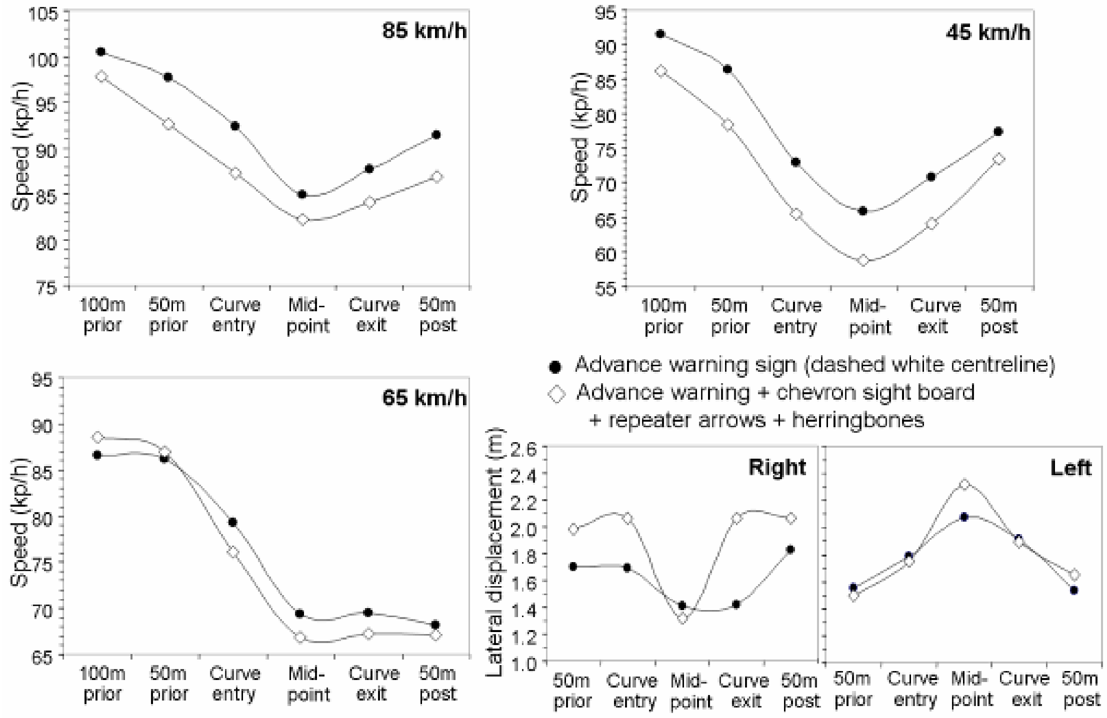


Figure 7.2 The effects of the combined chevron and herringbone treatment on participants' speeds and lane positions.

8. Practitioner consultation

8.1. Methodology

After completion of the laboratory testing, a consultation survey was prepared to advise road safety practitioners of the results of the testing and collect feedback on the practical significance of the findings. The survey briefly described the methodology employed during the testing and contained figures showing the speed and lateral displacement effects associated with the seven treatments in the primary study as well as the effects of the combined treatment investigated in the follow-on test. The survey asked the respondents to indicate their impression of the effectiveness of each treatment on a seven-point rating scale. The survey also asked them to rate the practical utility of each treatment (usefulness to road safety practitioners) and indicate any practical impediments to their implementation (eg cost and maintenance considerations). The survey (shown in Appendix D) was sent to the nine New Zealand road safety practitioners who had provided responses to the treatment selection survey and one additional practitioner with interest in the testing.

8.2. Results

Eight respondents returned completed surveys although one of them indicated that he had provided comments on each treatment but he did not want to provide numeric effectiveness and utility ratings. Figure 8.1 shows the median effectiveness and utility ratings for the seven respondents who provided numeric ratings. As can be seen in the figure, the standard advance warning signs received the lowest effectiveness ratings (ranging from a high of 4 to a low of 1). Respondent comments regarding this treatment included: ‘Drivers don’t notice these signs’ and ‘These signs should be located closer to the curves’. Of the other sign treatments, the chevron + repeater arrows received the highest effectiveness ratings (ranging from 4 to 6). Most respondents provided very similar ratings for the chevron + repeater arrows and chevron sight board treatments, with the exception of one respondent who rated the effectiveness of the chevron sight board as ‘2’ and commented that: ‘Under MOTSAM, this is not permitted unless the arrows were used as well’. Other respondents’ comments on chevron sight boards included: ‘Very cheap and surprisingly effective’; and ‘I love this sign. After coming from Australia and generally only having the PW17 and RC2s [advance warnings and repeater arrows] it was great to see the RC4s [chevron sight boards] with the curve speed on them. In fact I don't think I usually look out for PW17 signs any more because of the prevalence of RC4s around the network. It obviously works better than the PW17 … I even think they could be used without the PW17’. The repeater arrows treatment was rated the lowest (although still well above the advance warning) with ratings ranging from 3 to 5. Comments regarding the repeater arrows included: ‘I find these useful where the curvature of the road is not clear, particularly at crests or around long curves’, ‘Possibly not as noticeable as RC4’; and ‘Again quite a low-cost option, surprising it is less effective at reducing speeds, but self explains the corner’.

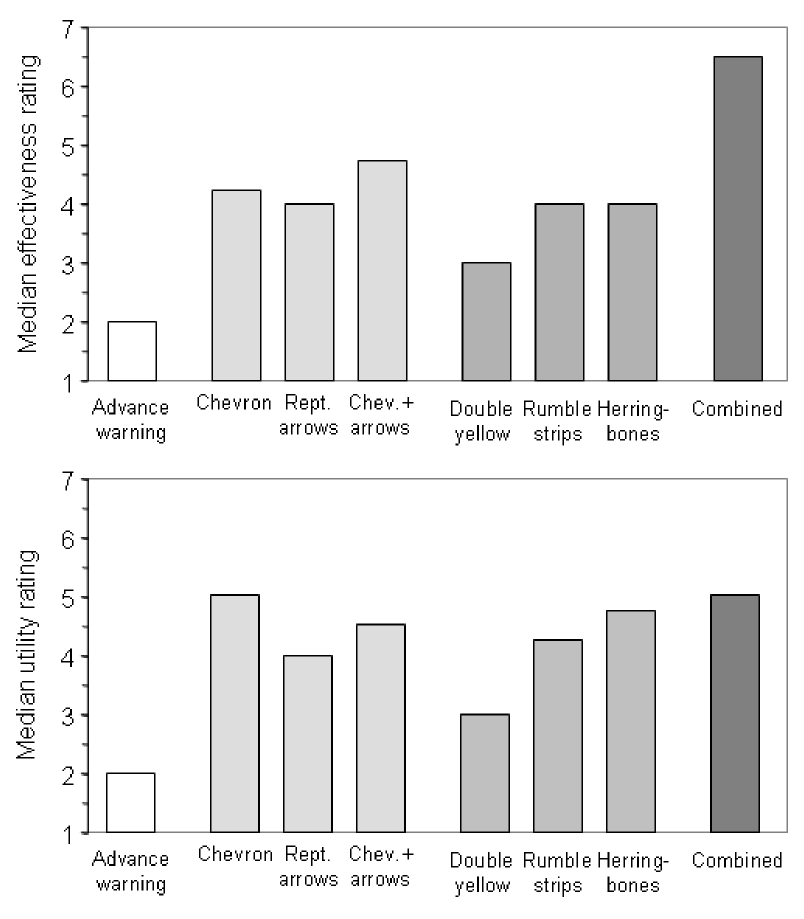


Figure 8.1 Practitioners' ratings of the effectiveness and utility of curve speed treatments.

Of the pavement marking treatments, the herringbones received the highest ratings, but were the subject of some controversy with ratings ranging from 2 to 7. Some respondents displayed considerable enthusiasm for the treatment, commenting: 'The exciting part is the new herringbone proposal, and it is the lateral displacement that really interests me ... this sort of proposal has some great opportunities for addressing the major problem of heavy vehicles leaving the road' and 'A surprisingly effective option for speed and makes a significant difference to alignment, which should reduce loss of control crashes. Very visible; on-road markings more naturally seen by drivers than signage at the edge'. Others were more wary about the potential effects on drivers: 'I like the idea of the herringbone pattern but I'm not sure it would work in practice… the pattern would be regularly driven over and wear away quickly. I guess the question that should be asked is why are curves not designed with the optimal path in mind?' and 'I have serious concerns with the path leading to the outside shoulder on right-hand curves where records show a lot of vehicles go off the road at this point. Maybe worth looking at a variation that has herring bones on entry and centre of curve but not the exit for RH bends'. One respondent identified the need for a field trial before coming to any conclusion about the treatment: 'I would support a formal trial (under Transit's control) of these markings'.

Rumble strips also received generally positive ratings (ranging from 2.5 to 6). Some representative comments included: 'The results from the rumble strips are interesting and are certainly worth noting as a possible benefit for speed management on curve' and 'Surprisingly effective in reducing curve speeds, considerable further benefits: reducing fatigue and inattention crashes, reducing inappropriate overtaking, reducing edge break'. One respondent noted with interest that: '...no adverse reactions were found to the presence of rumble strips'. Double yellow lines received the lowest effectiveness ratings of the pavement marking treatments with most respondents providing a rating of 2 or 3 with a typical response being: 'I think that the yellow double lines will make little difference and this is reflected in the results. They shouldn't be used as a speed management tool'. The exception was one respondent who rated the double yellow lines a 5 and noted that the treatment: 'Provides advance information to the motorist and provides delineation for the motorist through the curve'.

The combined treatment investigated in the follow-on test received the highest overall effectiveness ratings, and produced better agreement in the rankings (ranging from 5.5 to 7) than the herringbones by themselves. The respondent providing the lowest rating for this option noted that 'it would seem that the same level of effect could be achieved with using PW 17 and RC4 or PW 17 and RC2 (with the herringbone treatment in both cases) ... [this treatment] would appear to be 'over-engineered' for the achieved behavioural effect'. Similarly, some of the other respondents suggested combining the herringbones with chevrons and/or rumble strips without advance warning signs.

The utility ratings reflected the same general pattern as the effectiveness ratings with a reversal in the rank ordering of the chevron and chevron + repeater arrow treatments. This reversal was accompanied by the comment that the additional cost of repeater arrows did not seem justified as they didn't substantially add to the chevrons' effectiveness in reducing speeds. The utility ratings for the combined chevron + repeater arrow + herringbone treatment were not as high as the effectiveness ratings had been and this treatment was co-equal with the chevron sight board's utility ranking. Although a few respondents questioned how long the herringbone markings would last on busy highways (as noted above), others suggested that the cost of the markings was relatively low: 'Slightly higher cost but captures the two best lsot (sic) cost options of signage and markings'.

Overall, comments from the respondents on the research were complimentary and encouraging as indicated in the examples shown below:

> *Great piece of work, interesting results.*
>
> *I would say that the results do not really surprise me, and I am really glad to see some science behind the 'theories' that a lot of us had been using based on own experiences in the past.*
>
> *Overall I think this has been a worthwhile research exercise if only to confirm what we expected − although the rumble strips result is useful.*
>
> *I think the combination of these findings has practical usefulness/interest to other road safety practitioners.*

9. Discussion

The project described in this report began with a review of the research literature surrounding horizontal curves. The crash rates associated with horizontal curves are high world-wide, and the greater the severity of the curve or the difference between the surrounding speed environment and the rated curve speed, the higher the probability of a crash. While in one sense this may not appear to be a surprising finding, what is surprising is that after all the crashes and vehicle kms travelled over the years that an effective solution to the hazard has not been devised.

Driver errors associated with horizontal curves appear to be the result of three inter-related problems: failure of driver attention, misperception of speed and curvature and poor lane positioning. The first problem area arises when a driver’s attention is diverted or they fail to notice a curve ahead, either due to familiarity with the route, fatigue or some other factor. This account focuses on the conscious processing of the curve and the driver’s decision to make appropriate adjustments in their speed and trajectory. To address this issue, advance warning signs designed to attract a driver’s attention early and give them time to prepare for the curve have become the treatment of choice and have been installed widely. Unfortunately, both research findings and crash statistics indicate that advance warning signs do not provide an adequate safety measure. Part of the reason for this appears to be drivers’ tendency to rely on proceduralised or habitual motor programmes to maintain their speed and lane position (ie driving on automatic pilot) and they thus fail to attend and process most advance warning signs.

Drivers’ perceptions of speed and curvature appear to work at both a conscious (explicit) and unconscious (implicit) level. For this reason curve warnings and delineation treatments that highlight the sharpness of the curve ahead or increase a driver’s momentary sense of their apparent speed appear to offer promise in getting drivers to enter curves at a lower speed. Delineation treatments may also assist drivers with the third problem area, selecting and maintaining appropriate lane position while travelling through the curve.

The research project then examined the New Zealand crash data associated with horizontal curves. Crashes associated with excessive speed through curves were extracted from the CAS database and categorised by curve severity based on the posted advisory speed. To determine the relative exposure of traffic to these different curve severities, the RGDAS database was used to calculate the theoretical advisory speed for all curves in the state highway network. By correlating the curves with traffic count data from the RAMM database it was possible to estimate the relative exposure of traffic to each curve severity level on the state highway network. Thus it was possible to estimate the relative crash risk for each curve severity level. As has been reported by a number of other authors, generally speaking increased curvature was associated with an increased crash risk. However, when the curvature became very high (advisory speed of 25 km/h) we found a reduction in crash risk. This result has not been reported by other researchers but their studies have typically grouped all curves with a radius less than 100 m together which would hide this effect.

A survey of 21 curve sites was undertaken by an experienced traffic engineer. Sixteen of these curves had been the scene of crashes while five were similar neighbouring curves that had no recorded crashes. Although it was possible to identify treatments that would improve the crash site curves there were no obvious distinguishing points of difference between the crash sites and the non-crash sites. It was also demonstrated that the crash site curves might not have had a statistically higher crash risk than the non-crash sites. A difficult and winding section of state highway that included five of the curves surveyed was selected to be simulated in the laboratory tests.

A theoretical analysis of vehicle performance characteristics was undertaken for different vehicle types and this was used to develop a framework for determining appropriate curve speeds for different vehicle types and curve geometry based on the performance characteristics of the vehicle. The method was based on determining the speed limitations imposed on the vehicles by their lateral acceleration capabilities and the curve geometry. It then determined the speed limitations imposed by braking performance and sight distance. The overall speed limitation was the lesser of these two values. The framework used the engineering concept of a factor of safety to establish a safe operating speed which had an adequate margin for error and for unforeseen complications. The performance envelope analysis also considered the road space requirements but noted that for many vehicles on lower-speed curves, a speed reduction actually increased the road width required.

The research plan, as originally intended, was then to compare two promising curve warning treatments to a control treatment in the laboratory using the University of Waikato driving simulator to test the driving reactions of approximately 30 participants. After consultation with New Zealand road safety practitioners to select these treatments, however, it became apparent that there was keen interest in comparing many more than two or three treatments. In response to this interest, the research plan was expanded and ultimately eight treatments were tested with 84 participants.

The results of this testing re-emphasised previous findings from our laboratory that chevron warning signs were the most effective (of the methods tested) in producing substantial reductions in drivers’ curve speeds. The use of repeater arrows by themselves were just as effective for the sharpest curves and nearly as effective at higher-speed curves, providing a strong indication that a warning’s ability to highlight the curve perceptually, rather than providing an advisory speed, mattered most in controlling drivers’ speeds. During the consultation process, one of the road safety practitioners pointed out that if the spacing between repeater arrows was varied they could convey even greater information about the sharpness of curves: ‘Their spacing could also be used as an indicator that a curve is about to get sharper than it currently is’.

Of the pavement treatments, only the rumble strip treatment showed any substantial effects on drivers' speeds, and the effects were greatest in the later portions of the curves. Presumably this was because only drivers who drove on the edgeline or centreline as they traversed the curve would encounter the auditory feedback and reduce their speeds as a consequence. Reductions in the rate of run-off-road crashes reported in field trials of rumble strips would certainly seem to bear this out, and the speed reductions indicated in our laboratory tests suggested that rumble strips might be a promising delineation option for many situations. Further, there were no instances of drivers over-reacting or swerving into oncoming traffic as a result of driving on the rumble strips in our simulations, a point that will be of interest to many road safety practitioners.

It was envisaged that the herringbone pavement marking would narrow the effective lane width and reduce drivers' speeds while providing them with some guidance on the optimal path through the curve. Contrary to expectations these pavement markings did not produce any appreciable reductions in drivers' speeds. Their effects on drivers' lane position, however, were profound and it is possible that potential speed reductions due to lane narrowing were offset by indicating an optimal path through the curve (which could be traversed at higher speeds). When combined with chevron and repeater arrow signs, the herringbones did achieve both a reliable reduction in speed as well as improved lane positions.

The results of this research project suggested that further testing might be directed at identifying whether a constant placement of herringbone markings (similar to a flush median) would produce the slowing normally associated with reductions in lane width. Field trials to determine the longevity of the pavement markings under conditions of heavy use would also appear to be of considerable importance in evaluating their practical utility. The finding that the repeater arrows worked best for more severe curves also suggested that further testing to determine how sharp a curve needs to be in order to benefit from these signs would be instructive. In spite of these questions, the results did provide some immediately useful guidance for road safety practitioners, particularly regarding the benefits of chevron sight boards and rumble strips as speed management treatments at curves.

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Appendix A. Calculation of theoretical advisory speed

The *Manual of traffic signs and markings* (MOTSAM 1998) (Transit New Zealand 1998) provides a method for determining the advisory speed of a curve. Essentially this method consists of driving a test vehicle fitted with a ball-bank indicator through the curve at a steady speed and recording both the speed and ball-bank indicator reading. MOTSAM then provides a graphical method for determining the advisory speed from these readings.

The ball-bank indicator is a mechanical accelerometer that measures the lateral acceleration experienced by the vehicle in traversing the curve. Because the ball-bank indicator is mounted in the vehicle cabin, the lateral acceleration reading is the combined effect of the centrifugal acceleration due to the curve radius and vehicle speed, the superelevation of the road surface and the body roll of the vehicle. Many overseas jurisdictions require that the measurements are done iteratively with the test vehicle speed being adjusted until it matches the advisory speed. MOTSAM's method includes an adjustment for the difference between the test speed and the advisory speed so that it is not necessary to iterate.

As well as the graphical method, MOTSAM provides the following mathematical expression for determining advisory speed

$$V_M = \frac{V_o\left[\sqrt{V_o^2 + 6000(B+3)} - V_o\right]}{16\,(B+3)}$$

where:

- V_M is the measured advisory speed in km/h
- V_o is the vehicle test speed in km/h
- B is the ball-bank indicator reading in degrees.

This equation is valid when $V_o = V_M$ and, in this case, can be simplified to

$$B = 20.4 - 0.125V_o$$

The lateral acceleration generated when cornering is:

$$Lat\ acc = \frac{V_o^2}{12.95Rg}$$

where

- lat acc is the lateral acceleration measured in g
- R is the curve radius in m.

The mathematical expression from MOTSAM is based on an assumption that body roll and superelevation together contribute -3 degrees to the ball-bank reading and hence the lateral acceleration would be equivalent to a ball-bank reading of B+3 if there was no body roll or superelevation. Thus:

$$\tan(B+3) = \frac{V_o^2}{12.96Rg}$$

substituting from above

$$\tan(23.4 - 0.125V_o) = \frac{V_o^2}{12.96Rg}$$

This equation can be solved in two ways:

1. Assuming small angles the equation can be rewritten as

$$\frac{\pi(23.4 - 0.125V_o)}{180} = \frac{V_o^2}{12.96Rg}$$

This is a quadratic equation in V_o which is readily solved for particular values of R, the curve radius. The positive solution value is the theoretical advisory speed. For signposting this is rounded to the nearest speed ending in ‘five’”.

2. Alternatively the equation can be rearranged as follows:

$$R = \frac{V_o^2}{12.96g\tan(23.4 - 0.125V_o)}$$

For specific values of advisory speed, the associated curve radius can be determined. The results of doing this for speeds ending in zero are shown below.

Advisory Speed (km/h)	Radius (m)
10	1.9
20	8.2
30	19.8
40	37.9
50	63.8
60	99.5
70	147.6
80	211.5
90	296.2
100	408.9

By comparing the actual curve radius with the values in the table we can identify the advisory speed range for the curve. The appropriate sign is the mid-range value. Thus a curve with a radius of 25 m has an advisory speed between 30 and 40 km/h and should be signposted at 35 km/h.

The analysis, so far, has not taken the actual cross-slope of the road into account. The equations determining the advisory assume that the combined effect of cross-slope and vehicle body roll changes the ball bank indicator reading by -3°. From the RGDAS data, the average crossfall is 0.06, which is approximately 3.5°. This implies that the body roll contribution is 0.5° (crossfall reduces the ball bank reading while body roll increases it). The previous analysis assumes average crossfall. However, because RGDAS provides actual crossfall data for each curve we can adjust the advisory speed for the difference between the actual crossfall and the average crossfall as follows.

$$\delta_{crossfall} = \frac{(crossfall_{actual} - 0.06) * 180}{\pi}$$

The 180/п term converts the units to degrees for compatibility with the ball-bank indicator.

The formula for advisory speed then becomes:

$$\tan(B + 3 - \delta_{crossfall}) = \frac{V_g^2}{12.96R_g}$$

which can be solved as before.

Appendix B. Curve assessment survey

TERNZ
Engineering Environmental Survey
Curve Speed Management Project

Date: _______ (d/m/y) Time: _______(24 hour clock) Day of week: __________

Name of street or highway:__________ TNZ route position: _____________

Identifying characteristics (eg nearest side street, school etc.):______________

Diagram (showing curve layout and position of surveys)

1. **Road classification**

☐ 1 State highway

☐ 2 Other: _________

2. **Roadway geometric configuration** Total carriageway (sealed) width: _____ m

		North/East direction	South/West direction
☐ 1	Number of lanes:	________	_________
☐ 2	Lane widths:	________________	_________________
☐ 3	Central median islands:	Yes/No	Width: ______ m
☐ 4	Painted flush median:	Yes/No	Width: ______ m
☐ 5	Bus lanes/HOV lane:	Yes/No, Width ___	Yes/No, Width ____
☐ 6	Cycle lanes/Sealed shoulder:	Yes/No, Width ___	Yes/No, Width ____
☐ 7	Overtaking lanes:	Yes/No, Width ___	Yes/No, Width ____

Plan showing cross-section of road (show direction of north):

3. Type of roadway divider

☐ 1 Solid barrier Height: _________ m

☐ 2 Raised median Width: _________ m Height: ______m

☐ 3 Flush (painted) Width: _________ m

☐ 4 Yellow no passing lines

☐ 5 Centreline

☐ 6 None

☐ 7 Other Specify: ____________________________ Width:____ m

4. Delineation

	North/East direction	South/West direction
Lane lines:	_______	_______
Edgelines:	_______	_______
Raised Pvmt Markers:	Y/N, Width ____, Colour: ____	Y/N, Width _____ Colour: ____
	Dist from kerb: ____ m	Dist from kerb: ____ m
	Spacing: ____ m	Spacing: ____ m
Condition RRPMs?	_________	_________
Edge marker posts:	Y/N, Width ________	Y/N, Width ______
Other observations:	___________________	_________________

5. Signage

Curve warning:	_______	________
Speed advisory:	Y/N, Speed _______	Y/N, Speed _______
Location of SA sign?	Dist fm curve tangent:____m	Dist fm curve tangent:____m
Driven speed around curve	_______	________
Chevron:	_______	________
Compliance with MOTSAM	_______	________
Other:	_______	________

6. Shoulder width and type

	North/East direction	South/West direction
Total width:	_____ m	_____ m
☐ 1 Sealed pavement	Width:_____ m	Width:_____ m
☐ 2 Gravel	Width:_____ m	Width:_____ m
☐ 3 Other ___________	Width:_____ m	Width:_____ m

7. Road reserve (Width from edge seal to property boundary)

	North/East direction	**South/West direction**
Total width:	_____ m	_____ m
☐ 1 Footpath	Width: _____ m	Width: _____ m
☐ 2 Grass verge	Width: _____ m	Width: _____ m
	Dist from S/Edge: ___ m	Dist from S/Edge: ___ m
☐ 3 Drainage ditch	Width: _____ m	Width: _____ m
	Dist from S/Edge: ___ m	Dist from S/Edge: ___ m
☐ 4 Bank	Height: _____ m	Height: _____ m
	Dist from S/Edge: ___ m	Dist from S/Edge: ___ m
☐ 5 Fence/Wall/Guardrail	Height: _____ m	Height: _____ m
	Dist from S/Edge: ___ m	Dist from S/Edge:___ m

8. Other street furniture	**North/East direction**	**South/West direction**
☐ 1 Power poles	Dist from kerb: ___ m	Dist from kerb: ___ m
☐ 2 Barriers	Dist from kerb: ___ m	Dist from kerb: ___ m
☐ 3 Traffic signs	Dist from kerb: ___ m	Dist from kerb: ___ m
☐ 4 Power transformers	Dist from kerb: ___ m	Dist from kerb: ___ m

☐ 5 Other Describe: ____

9. Is there an intersection within 300 metres, in either direction?

☐ 1 No (Skip to question 12)

☐ 2 Yes

10. Type of intersection:	**North/East direction**	**South/West direction**
X Intersection	_______	_______
T Intersection	_______	_______
Y Intersection	_______	_______
Roundabout	_______	_______

Other Specify: _________________

11. Intersection control		
Uncontrolled	_______	_______
Give Way	_______	_______
Stop	_______	_______

Traffic signals _______ _______

Other Specify: ___________________________________

12. Is there street lighting?

☐ 1 No

☐ 2 Yes

☐ 3 Type of lighting _______ _______

☐ 4 Approx spacing _______ m _______ m

☐ 5 Considered appropriate? _______ _______

13. Gradient	**North/East direction**	**South/West direction**
Level *(Skip to question 14)*	_______	_______
Up	_______	_______
Down	_______	_______

14. Nature of gradient

Less than 5% (Flat)	_______	_______
5 to 15% (Rolling)	_______	_______
Greater than 15% (Steep)	_______	_______

15. Road surface

1 Unsealed *(Skip to question 17)*

2 Sealed

16. Type of seal

1 Chip

2 Paved asphalt

3 Concrete

4 Other Specify:____

17. Road curvature	**North/East direction**	**South/West direction**
☐ 1 Straight	______	______
☐ 2 Easy	______	______
☐ 3 Moderate	______	______
☐ 4 Severe	______	______

18. Roadway superelevation	**North/East direction**	**South/West direction**
☐ 1 Appropriate	______	______
☐ 2 Reverse	______	______
☐ 3 Approx. slope	______	______
☐ 4 Other	______	______

19. Approach environment	**North/East direction**	**South/West direction**
☐ 1 Composite (varying radii)	______	______
☐ 2 Reverse	______	______
☐ 3 Transitions?	______	______
☐ 4 Perception of curve?	______	______
☐ 5 Drivers perspective?	______	______

☐ 6 Describe ____

20. Predominant surround land use: **North/East direction** **South/West direction**

☐ 1 Residential

☐ 2 Commercial / Industrial

☐ 3 Schools

☐ 4 Rural

21. Sight distance North/East direction South/West direction

Use: 1 metre *(Driver's eye height)*
600 mm *(Object height)*

☐ At centre lane Distance: _____ m Distance: _____ m

22. What is the posted speed limit at this location?

☐ 1 50 km/h

☐ 2 70 km/h

☐ 3 Limited speed zone

☐ 4 100 km/h

23. Volume

Average vehicles per day (7 day ADT): ___________ vpd

Vehicle classification: % Heavy: ___% Buses: ___% Cars/Vans: ___% M/C: _____

24. Speed: Ave speed: ________ kph 85%tile speed: _________ kph

North/East direction (uphill/downhill) Ave: ____ 85%tile: ______

Successful curve negotiation: Yes / No

Braking: None / Touch / Steady / Sudden

Vehicle type: PC/Rigid Truck/ Combination Veh (semi)

South/West direction (uphill/downhill) Ave: ____ 85%tile: ______

Successful curve negotiation: Yes / No

Braking: None / Touch / Steady / Sudden

Vehicle Type: PC/Rigid Truck/ Combination Veh (semi)

Note: Successful negotiation is where driver tracks wholly within lane

25. Photos

From centreline	to North/East (road),	to South/West (road)
From N/E Edgeline or kerb	to South/East(street scene),	to South/West (street scene)
From S/E Edgeline or kerb	to North/East(street scene),	to North/West (street scene)

26. Comments on possible causes:

27. Comments on possible solutions:

28. Other comments:

* * * * * * * * * * * *

Appendix C. Curve treatment selection survey

Curve Speed Management
Transfund Project No. 909

22 August 2005

Dear Colleague,

We are currently engaged in a Transfund-sponsored project investigating ways in which drivers' speeds around curves could be managed through the manipulation of the visual cues that influence driver behaviour. This project is a continuation of our previous work in the areas of driver attention, speed management, and hazard warning signage. To date we have completed a review of the research literature, an analysis of New Zealand crash data associated with speed through curves, a survey of representative crash sites, and begun development of performance envelopes to establish safe operating limits for vehicles negotiating several surveyed curves. At this point we are about to begin the testing phase of the project in which we will begin simulation trials of several design treatments' effects on driver speeds and lane position and compare them to the performance envelopes. Based on our review of the research literature and crash data associated with speed through curves, we have identified a range of treatment options that could have beneficial effects on driver speed and lane position through curves.

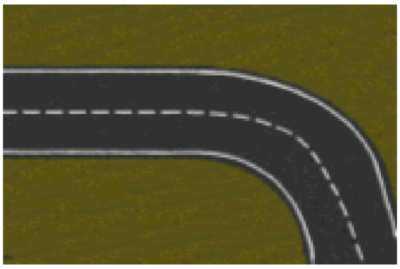
It is in this context that we now are approaching a group of experts in the area to provide us with their input in selecting the final treatments to be tested in the driving simulations. At this stage we cannot say which of the treatments will be most effective (or we wouldn't need to do any testing), but we are hoping that you and the other experts will be able to rank our treatment options on the basis of which ones offer the greatest promise in terms of their practicality and how realistically they could be implementated on NZ roads. Further, if there are other potentially important treatment options that we have not considered, we hope that you will be able to draw our attention to them. As there are some practical limits on the number of treatment options that we can test in the time available to us, we will create a refined list of treatments based on the recommendations of the group and circulate it for further comment. Although we do not plan to convene any meetings of the expert panel, we greatly value your input and will take your advice and recommendations as if they were from a formal steering committee.

By way of a very brief background, it is a well-established finding that drivers frequently underestimate their speeds on their approach to curves, underestimate their speeds through the curve, and that crashes on curves are a significant proportion of the serious crashes in New Zealand (more than 20% of the fatal crashes and 13% of the serious injury crashes). The research literature suggests three main accounts of how drivers select their curve speeds: 1) attention; 2) speed perception; and 3) curvature perception. A number of researchers have shown that attentional factors such as curve warning signs can have a high degree of influence (self-rated) on drivers' curve speed choice, but the effect may be limited to drivers identified as "non-violators" (Kanellaidis (1995). Although signage can influence drivers' estimates of curve sharpness, it often produces significant underestimates (Suzuki et. al., 2001). Drivers who cannot recall seeing the sign have the greatest probability of underestimating their curve speeds (Milosevic & Milic (1990). Our own research has shown that traditional signage works well for severe curves, but may not work well in the presence of distractions (Charlton 2004). The role of attentional factors has also been underscored with the finding that experienced drivers and drivers carrying passengers are among the most likely to underestimate their curve speeds.

Several researchers have also shown that drivers' speed perception is influenced by a range of implicit (non-attentional) roadway factors including lane width, edge rate in periphery, and road noise (Denton, 1966; Charlton, 2004). These factors appear to operate at an unconscious perceptual level, and may be the most important factor governing the speed choice of drivers from moment to moment. This account suggests that the roadway conditions present on the approach to a curve (such as road width) may be an important determinant of drivers' curve speeds and that treatments based on manipulating these perceptual properties may be particularly effective either because they provide an attentional/alerting function as well as directly affecting implicit perceptions of speed (Fildes & Jarvis, 1994). These treatments may thus be more effective than traditional warning signage (which only works when drivers are paying attention) and may be particularly important for violators (who disregard traditional signage).

Finally, some researchers have suggested that curvature misperception may be an important factor responsible for drivers' crashes through curves. Curves associated with high crash rates have been shown to be perceived as appearing closer, more visible, and wider than they actually are (Shinar, 1977). This interpretation also suggests that drivers' lateral displacement (lane position) may be at least as important to regulate as their speed in reducing crash rates at curves. However, in tests of treatments designed to make the degree of curvature easier to judge, drivers appeared to be insensitive to manipulations of inside perspective angle (Shinar, 1977). Other researchers have suggested that implicit perceptual properties associated with a curve, particularly those highlighting the outside edge of the curve to approaching drivers, may reduce curve speeds simply by presenting the curve as a barrier to approaching drivers (Godley, Fildes, Triggs, & Brown, 1999; Charlton, 2004). Curve warning treatments that emphasise the outside curvature can produce the greatest reductions in drivers' speeds, even when drivers are distracted (Charlton, 2004), but their effects on drivers' lateral displacement are unknown.

Based on these theoretical accounts of the factors governing drivers' speed selection at curves, we have identified seven treatments to be tested across a range of simulated curves (selected from the curve survey). Each of the treatments will be compared to a control condition consisting of curves delineated with standard road markings (dashed centre line and solid edge lines as shown below).

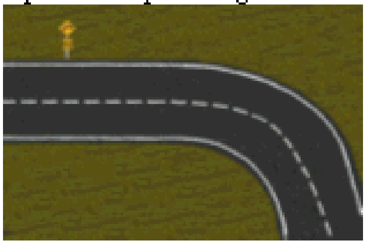


Control condition: standard road delineation only.

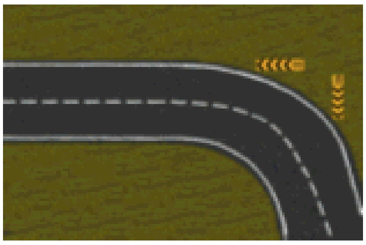
For the other seven treatment options described on the next page, we would like you to provide a ranking of each (where 1 = highest interest in testing and 7 = lowest interest in testing), and any other comments regarding the individual treatments you may wish to offer. Please return your rankings of the treatment options to us either by post or email.

Our thanks in advance,
Samuel Charlton, Peter Baas, & John dePont
Transport Engineering Research NZ Ltd.
PO Box 97846, South Auckland Mail Centre

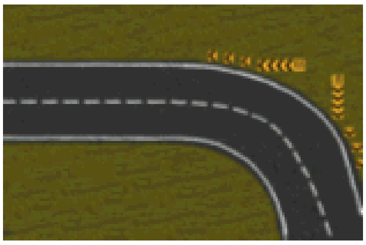
Treatments A, B, & C: These three treatments are based on existing warning signs, PW17 advance warnings, RC4 sight boards (black on orange) with and without single chevron repeaters. Each treatment has attentional and alerting functions (e.g., the advisory speeds), with the chevron repeaters emphasising the outside curvature as well.



Treatment A:
PW 17 warning sign.
Ranking (1 to 7) ______



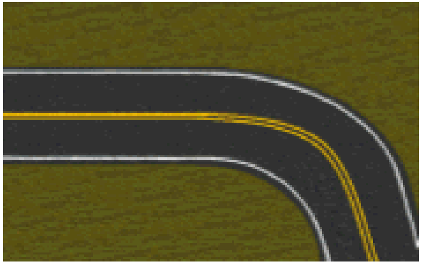
Treatment B:
RC4 sight board (no PW17).
Ranking (1 to 7) ______



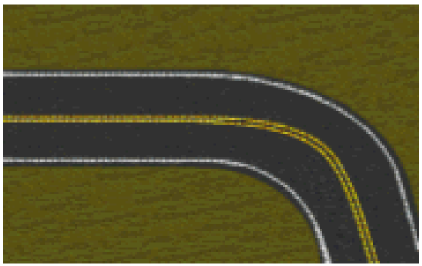
Treatment C:
RC4 with chevron repeaters
Ranking (1 to 7) ______

Comments ________________

Treatments D & E: These delineation treatments are designed to increase drivers' perception of the curvature with major effects on drivers' lateral displacement through the curves. Treatment E (rumble strips) may also reduce approach speeds if driven on.



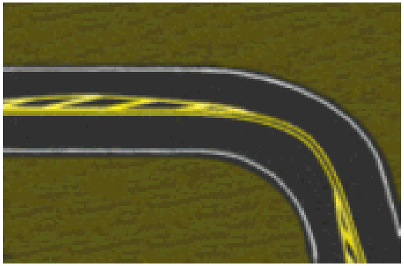
Treatment D: Double yellow centre line
Ranking (1 to 7) ______



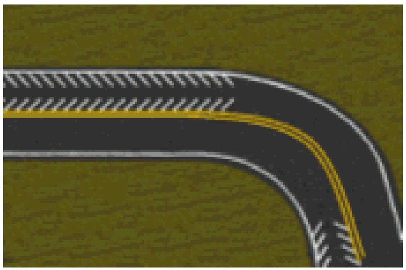
Treatment E: Profiled centre & edge lines
Ranking (1 to 7) ______

Comments ________________

Treatments F & G: These treatments are designed to affect drivers' perception of speed during the curve approach, reducing their speeds and possibly having a beneficial effect on lateral displacement through the curve as well.



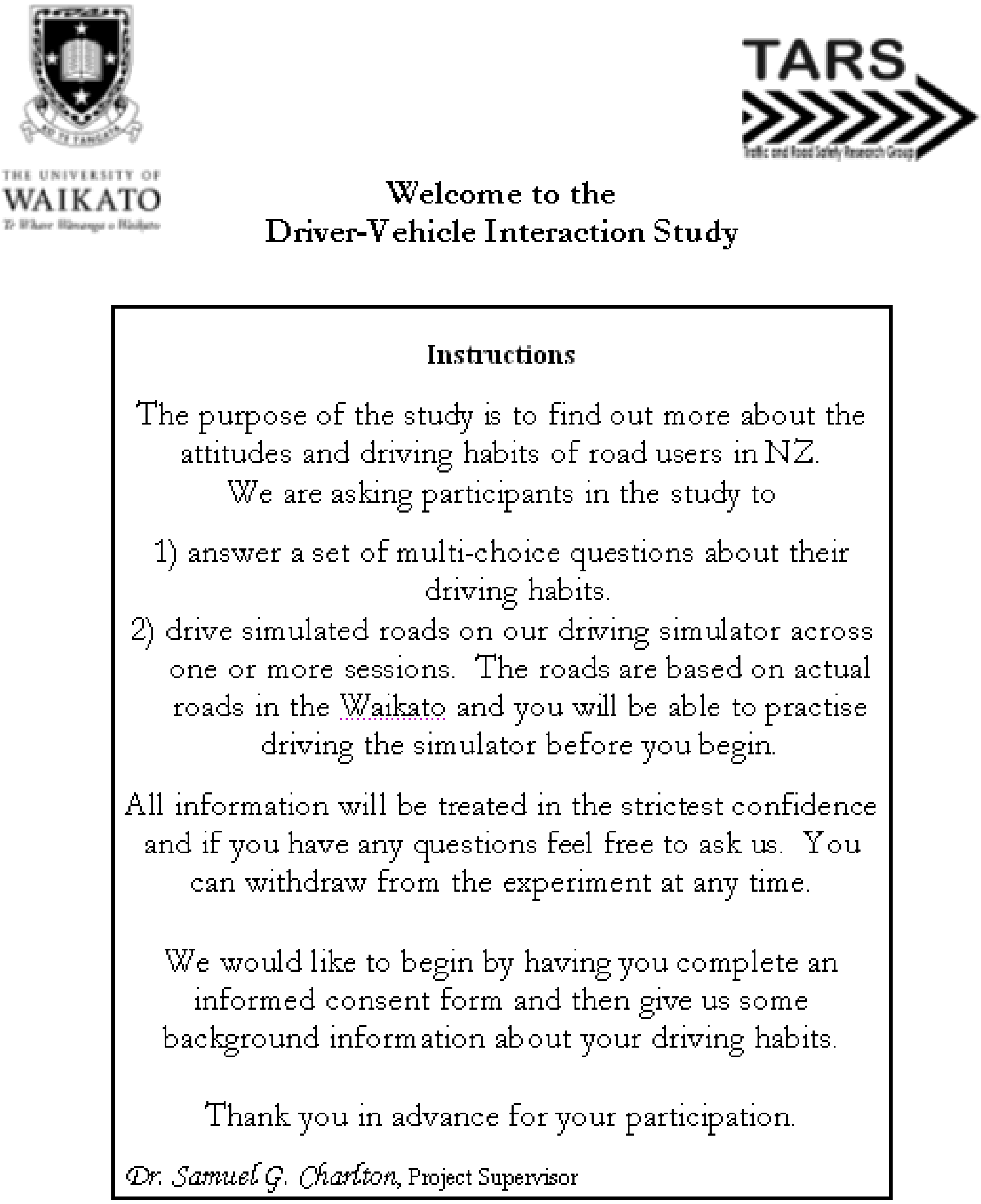
Treatment F: Road narrowing
Ranking (1 to 7) ______



Treatment G: Herringbones
Ranking (1 to 7) ______

Comments ________________

Appendix D. Laboratory participants' survey



THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

TARS
Traffic and Road Safety Research Group

Welcome to the
Driver-Vehicle Interaction Study

Instructions

The purpose of the study is to find out more about the attitudes and driving habits of road users in NZ.
We are asking participants in the study to

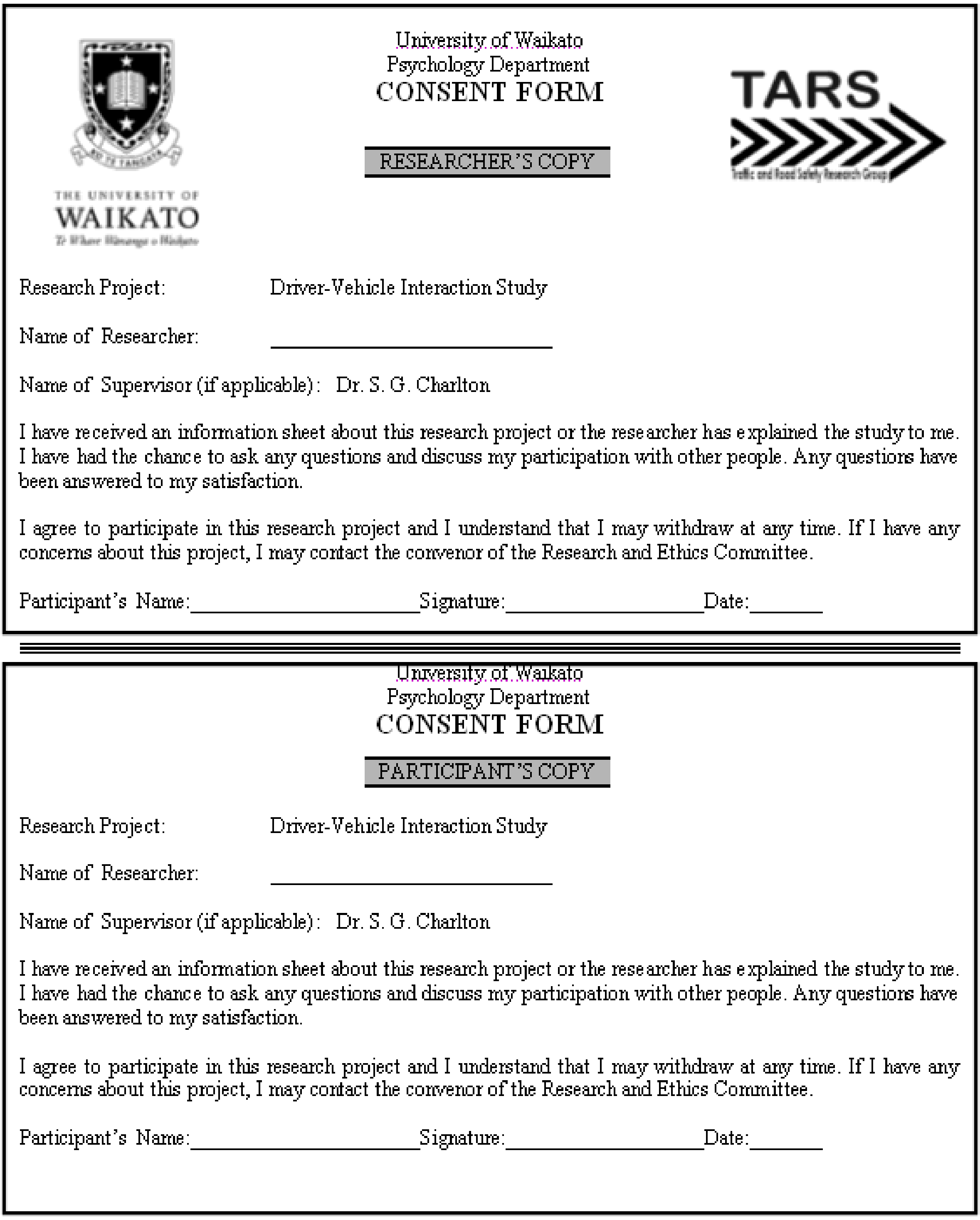
1) answer a set of multi-choice questions about their driving habits.
2) drive simulated roads on our driving simulator across one or more sessions. The roads are based on actual roads in the Waikato and you will be able to practise driving the simulator before you begin.

All information will be treated in the strictest confidence and if you have any questions feel free to ask us. You can withdraw from the experiment at any time.

We would like to begin by having you complete an informed consent form and then give us some background information about your driving habits.

Thank you in advance for your participation.

Dr. Samuel G. Charlton, Project Supervisor



THE UNIVERSITY OF
WAIKATO

University of Waikato
Psychology Department
CONSENT FORM

TARS

RESEARCHER'S COPY

Research Project: Driver-Vehicle Interaction Study

Name of Researcher: ______________________________

Name of Supervisor (if applicable): Dr. S. G. Charlton

I have received an information sheet about this research project or the researcher has explained the study to me. I have had the chance to ask any questions and discuss my participation with other people. Any questions have been answered to my satisfaction.

I agree to participate in this research project and I understand that I may withdraw at any time. If I have any concerns about this project, I may contact the convenor of the Research and Ethics Committee.

Participant's Name:________________________Signature:_____________________Date:_______

University of Waikato
Psychology Department
CONSENT FORM

PARTICIPANT'S COPY

Research Project: Driver-Vehicle Interaction Study

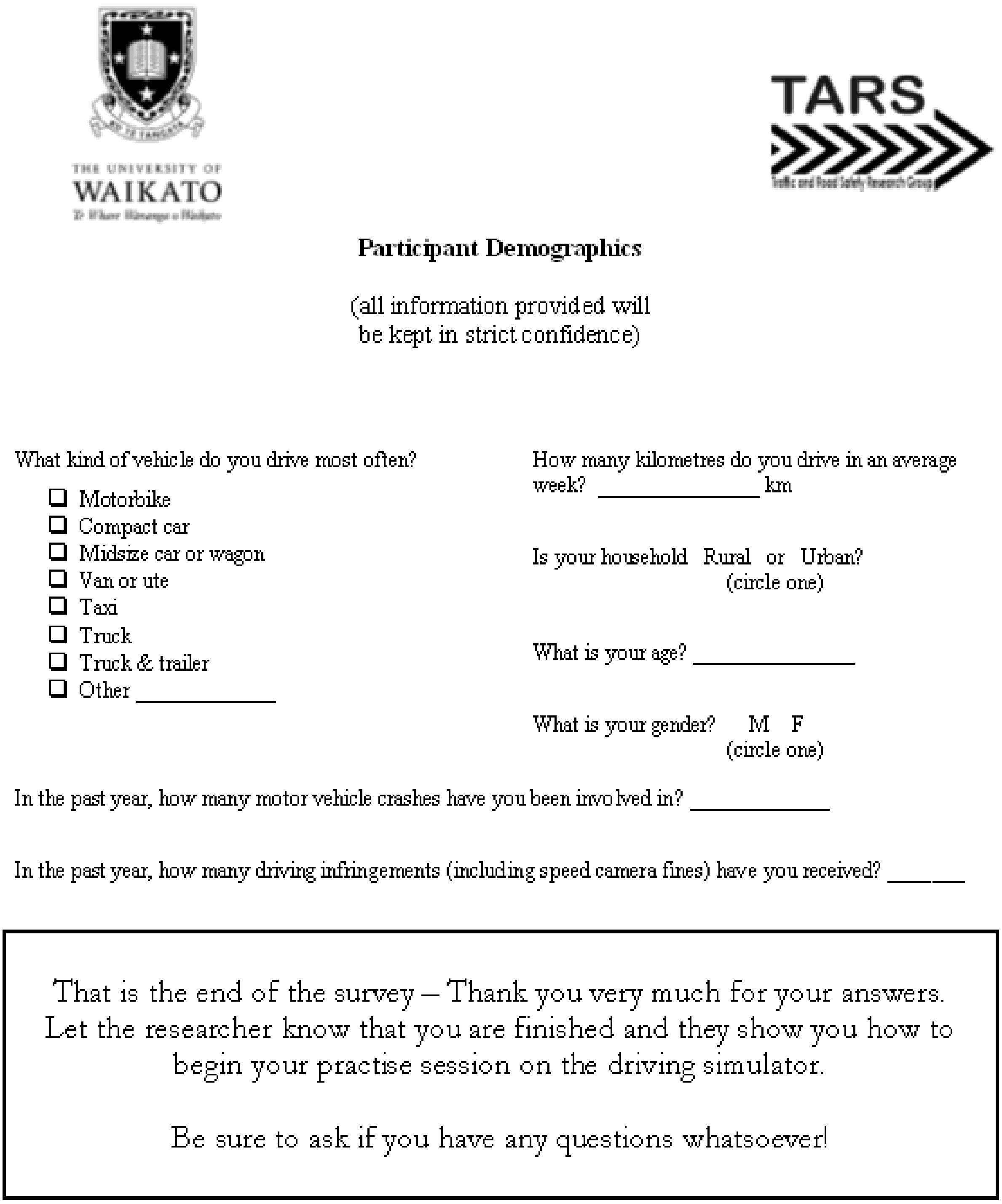
Name of Researcher: ______________________________

Name of Supervisor (if applicable): Dr. S. G. Charlton

I have received an information sheet about this research project or the researcher has explained the study to me. I have had the chance to ask any questions and discuss my participation with other people. Any questions have been answered to my satisfaction.

I agree to participate in this research project and I understand that I may withdraw at any time. If I have any concerns about this project, I may contact the convenor of the Research and Ethics Committee.

Participant's Name:________________________Signature:_____________________Date:_______



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TARS
Traffic and Road Safety Research Group

Participant Demographics

(all information provided will
be kept in strict confidence)

What kind of vehicle do you drive most often?

- ☐ Motorbike
- ☐ Compact car
- ☐ Midsize car or wagon
- ☐ Van or ute
- ☐ Taxi
- ☐ Truck
- ☐ Truck & trailer
- ☐ Other ____________

How many kilometres do you drive in an average week? ______________ km

Is your household Rural or Urban?
(circle one)

What is your age? ______________

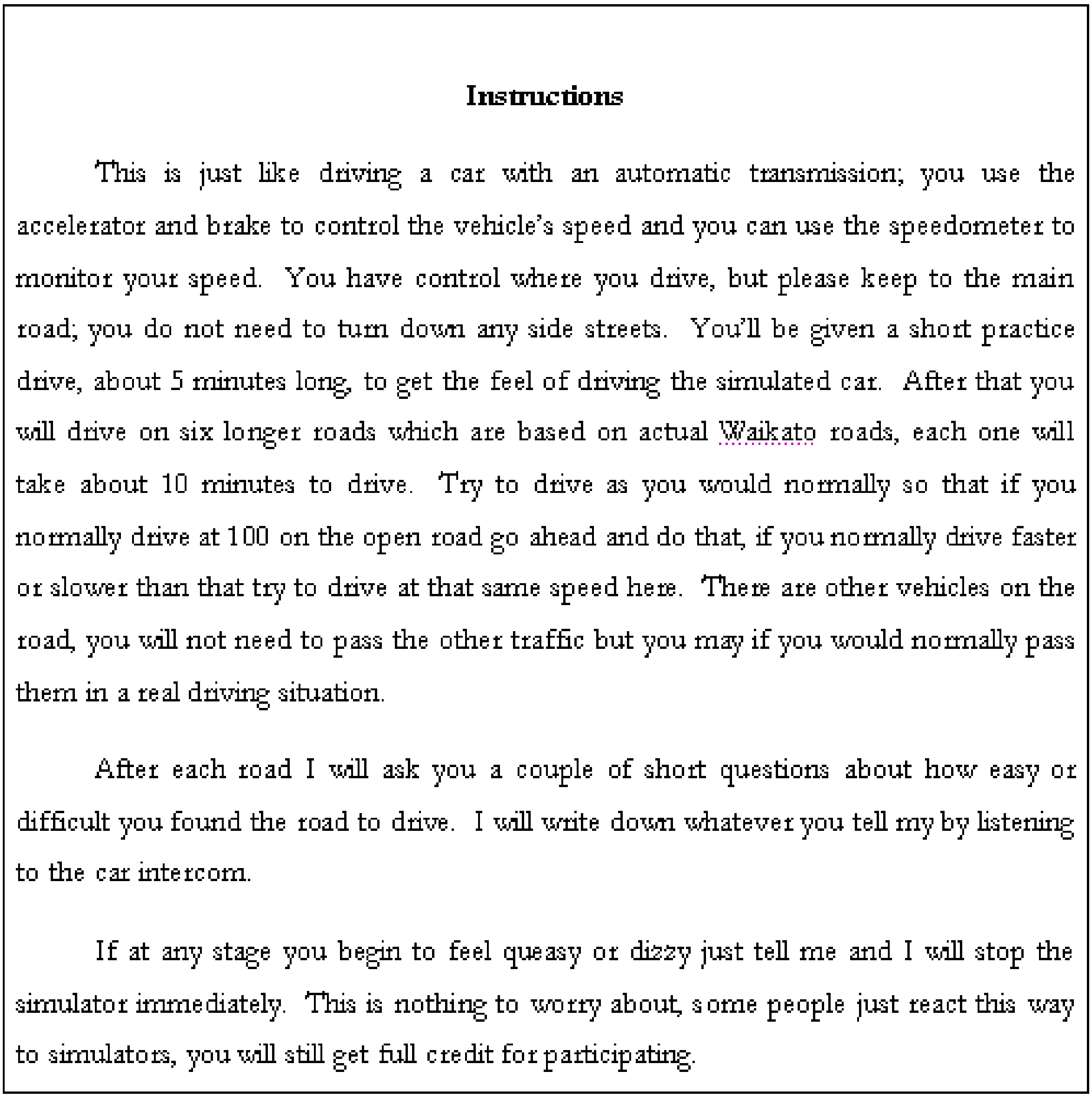
What is your gender? M F
(circle one)

In the past year, how many motor vehicle crashes have you been involved in? ____________

In the past year, how many driving infringements (including speed camera fines) have you received? _______

That is the end of the survey – Thank you very much for your answers.
Let the researcher know that you are finished and they show you how to begin your practise session on the driving simulator.

Be sure to ask if you have any questions whatsoever!

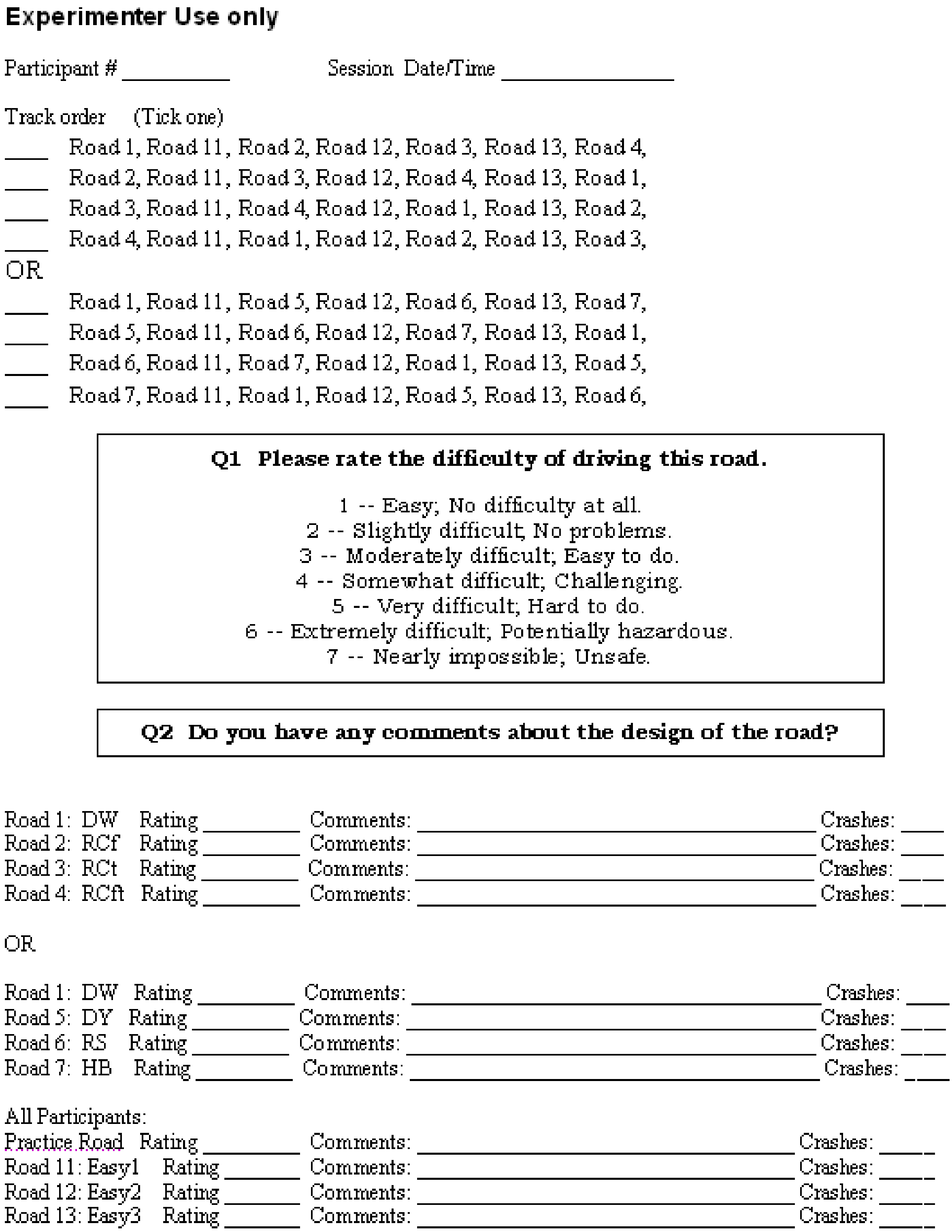


Instructions

This is just like driving a car with an automatic transmission; you use the accelerator and brake to control the vehicle's speed and you can use the speedometer to monitor your speed. You have control where you drive, but please keep to the main road; you do not need to turn down any side streets. You'll be given a short practice drive, about 5 minutes long, to get the feel of driving the simulated car. After that you will drive on six longer roads which are based on actual Waikato roads, each one will take about 10 minutes to drive. Try to drive as you would normally so that if you normally drive at 100 on the open road go ahead and do that, if you normally drive faster or slower than that try to drive at that same speed here. There are other vehicles on the road, you will not need to pass the other traffic but you may if you would normally pass them in a real driving situation.

After each road I will ask you a couple of short questions about how easy or difficult you found the road to drive. I will write down whatever you tell my by listening to the car intercom.

If at any stage you begin to feel queasy or dizzy just tell me and I will stop the simulator immediately. This is nothing to worry about, some people just react this way to simulators, you will still get full credit for participating.



Experimenter Use only

Participant # __________ Session Date/Time ________________

Track order (Tick one)

____ Road 1, Road 11, Road 2, Road 12, Road 3, Road 13, Road 4,
____ Road 2, Road 11, Road 3, Road 12, Road 4, Road 13, Road 1,
____ Road 3, Road 11, Road 4, Road 12, Road 1, Road 13, Road 2,
____ Road 4, Road 11, Road 1, Road 12, Road 2, Road 13, Road 3,

OR

____ Road 1, Road 11, Road 5, Road 12, Road 6, Road 13, Road 7,
____ Road 5, Road 11, Road 6, Road 12, Road 7, Road 13, Road 1,
____ Road 6, Road 11, Road 7, Road 12, Road 1, Road 13, Road 5,
____ Road 7, Road 11, Road 1, Road 12, Road 5, Road 13, Road 6,

Q1 Please rate the difficulty of driving this road.

1 -- Easy; No difficulty at all.
2 -- Slightly difficult; No problems.
3 -- Moderately difficult; Easy to do.
4 -- Somewhat difficult; Challenging.
5 -- Very difficult; Hard to do.
6 -- Extremely difficult; Potentially hazardous.
7 -- Nearly impossible; Unsafe.

Q2 Do you have any comments about the design of the road?

Road 1: DW Rating _________ Comments: ________________________________ Crashes: ____
Road 2: RCf Rating _________ Comments: ________________________________ Crashes: ____
Road 3: RCt Rating _________ Comments: ________________________________ Crashes: ____
Road 4: RCft Rating _________ Comments: ________________________________ Crashes: ____

OR

Road 1: DW Rating _________ Comments: ________________________________ Crashes: ____
Road 5: DY Rating _________ Comments: ________________________________ Crashes: ____
Road 6: RS Rating _________ Comments: ________________________________ Crashes: ____
Road 7: HB Rating _________ Comments: ________________________________ Crashes: ____

All Participants:
Practice Road Rating _________ Comments: ______________________________ Crashes: _____
Road 11: Easy1 Rating _______ Comments: ______________________________ Crashes: _____
Road 12: Easy2 Rating _______ Comments: ______________________________ Crashes: _____
Road 13: Easy3 Rating _______ Comments: ______________________________ Crashes: _____

Appendix E. Consultation survey

Curve Speed Management
Transfund/Land Transport NZ Project No. 909

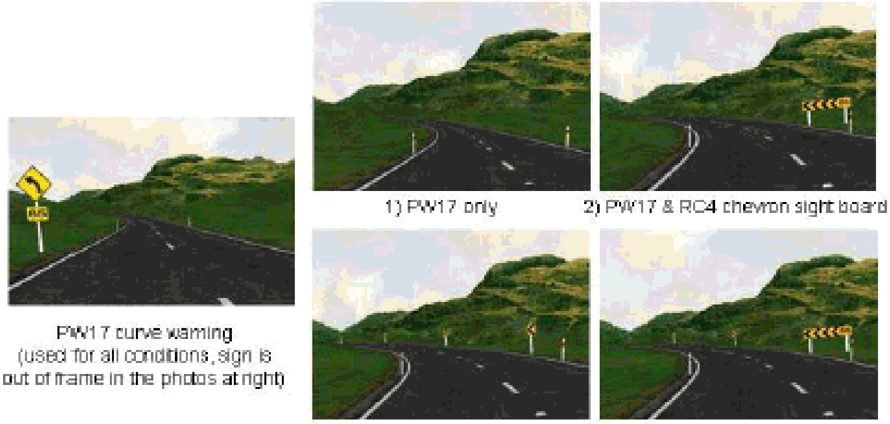
22 June 2006

Dear Road Safety Researcher/Practitioner,

We are currently bringing to a close a Transfund/Land Transport NZ project investigating ways in which drivers' speeds around curves can be better managed through the manipulation of the visual cues that influence driver behaviour. This project is a continuation of our research programme investigating a range of issues involving driver attention, speed management, and hazard warning signage. You may have already played a role in an earlier phase of the current project in which road safety practitioners and researchers provided us with their recommendations for curve treatments to be tested in our driving simulations.

We recently completed the laboratory testing phase of the research and we are now seeking reactions to the results from experienced road safety practitioners and researchers such as yourself. In particular, we are interested in your assessment of the curve speed treatments in the light of the simulator results, the practical significance of the results (i.e., are the results likely to be of use to practitioners), and any potential impediments to implementation such as cost, maintenance, or other considerations.

Based on our review of the research literature and the input we received from 12 road safety practitioners and researchers, we identifed two groups of curve speed management treatments to be tested. The first group of treatments to be compared consisted of various warning signs designed to alert drivers to the presence of curves and produce a reduction in speeds at the approach to, and through the curves. The need to test these warning signs emerged from a strong consensus among the practitioners and researchers that the use of RC4 chevron sight boards, with and without accompanying RC2 repeater arrows needed to be investigated further. Thus, the first group of treatments compared was comprised of 4 combinations of these signs as follows: 1) PW17 curve warnings; 2) PW17 curve warnings followed by RC4 chevron sight boards; 3) PW17 curve warnings followed by a series of RC2 repeater arrows; and 4) PW17 curve warnings followed by RC4 chevron sight boards and a series of RC2 repeater arrows. These four treatments are shown below in Figure 1 as they appeared in the simulations.


PW17 curve warning
(used for all conditions, sign is out of frame in the photos at right)

1) PW17 only

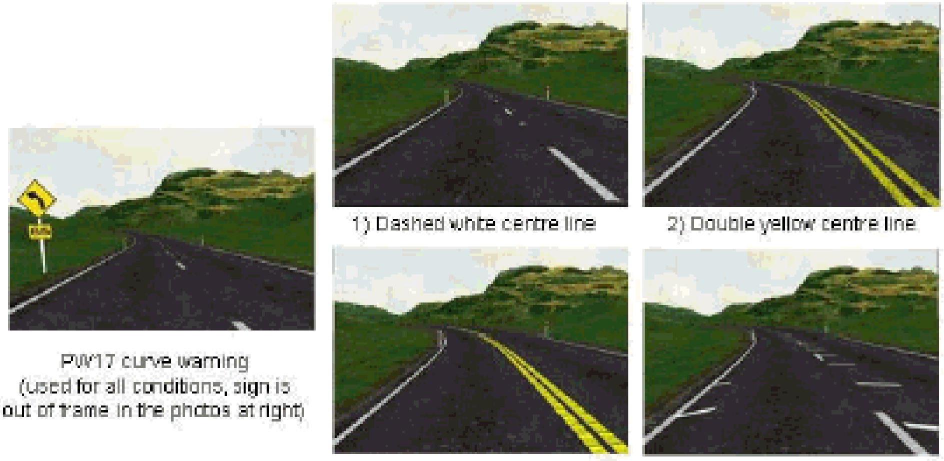
2) PW17 & RC4 chevron sight board

3) PW17 & RC2 repeater arrows

4) PW17, RC4 & RC2 repeaters

Figure 1. Curve warning signage treatments as depicted in simulation.

The second group of treatments compared was comprised of several types of road markings designed to affect drivers' lateral displacement (lane position) as they drive through curves. Testing double yellow lines was mentioned by several practitioners as being of interest given the frequency with which the need for no overtaking lines on curves is mentioned by members of the driving public. For similar reasons, the investigation of rumble strips was included due to previous reports of adverse public reaction to the use of rumble strips on the left edge line of left-hand curves. Finally, a herringbone treatment designed to "flatten" drivers' path through the curve and provide increased separation between opposing traffic was developed based on a combination of approaches suggested by the expert panel and previous research. This second group of treatments is shown in Figure 2, with some additional detail on the herringbone treatment presented in Figure 3.


PW17 curve warning (used for all conditions, sign is out of frame in the photos at right)

1) Dashed white centre line

2) Double yellow centre line

3) Left and right rumble strips

4) Herringbone treatment

Figure 2. Road marking treatments as depicted in simulation.

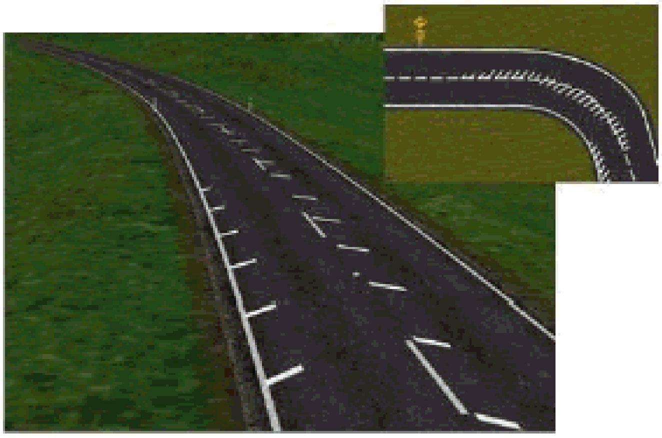


Figure 3. Herringbone delineation treatment as depicted in simulation and overhead sketch diagram(not to scale).

The two types of treatments, warning signs and road markings, were applied to a simulated 3.4 km section of State Highway 27 centred on the Kaihere Hill summit in the Hauraki District. Another 3.5 km section of level road containing four horizontal curves with consistent radii (two 85 kmh and two 45 kph curves) was added to the front of the simulated road to compare with the more challenging vertical and horizontal curves along the summit road. The road geometry used in the simulator testing is shown in Figure 4.

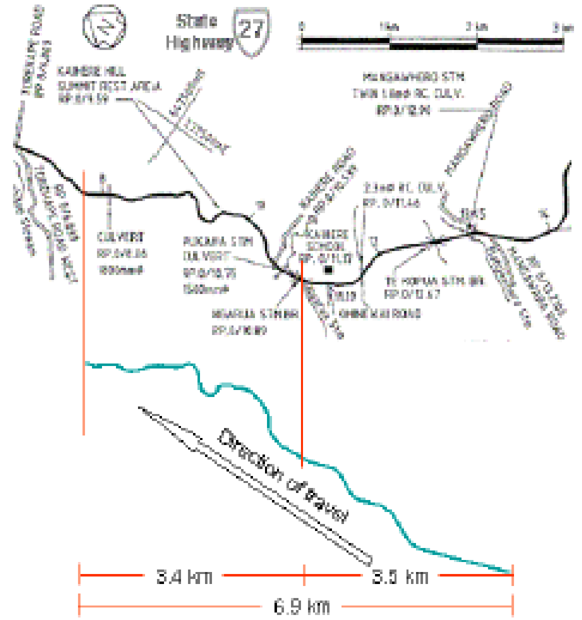


Figure 4. Road geometry used in simulation (bottom panel) compared to map of actual state highway geometry.

One group of 30 participants drove a series of simulations containing each of the four warning signage treatments and another group of 30 participants drove a series of simulations depicting each of the four road marking treatments. Figure 5 shows the the speed profiles resulting from the signage treatments averaged for two 85 kph curves (one left and one right), two 45 kph curves (one left and one right), and two 65 kph curves (one left and one right on an uphill gradient). As can be seen in the figure, PW17 warning signs by themselves were not as effective at reducing speeds as when they were used in conjunction with RC4 chevron sight boards and/or RC2 repeater arrows. Also of note is the finding that this difference was not as prominent in the presence of uphill gradients, as reflected in the results for the 65 kph curves. Not apparent in the summary results shown below is the finding that speeds for left-hand curves were marginally slower than speeds for right-hand curves, regardless of the type of warning sign present.

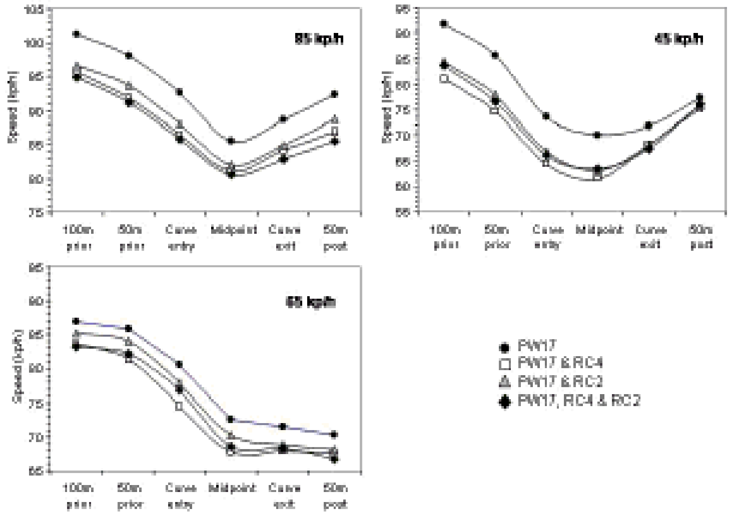


Figure 5. Speed profiles resulting from the four combinations of curve warning signs.

Figure 6 shows the the speed profiles resulting from the road marking treatments averaged for the same 85, 46, and 65 kph curves. The four types of road marking did not produce any appreciable differences in speed, with the exception of marginally slower speeds associated with the rumble strip treatment on the level grade curves (85 & 45 kph curves below). Once again, the speeds for left-hand curves were marginally slower than speeds for right-hand curves, regardless of the type of road marking. Of greater interest was the effect of the four types of road markings on drivers' lane positions as they negotiated the curves. The lateral displacement data are shown in Figure 7 and, as expected, the herringbone treatment had the effect of flattening the drivers' path through the curve, with a somewhat more substantial effect for curves to the right than curves to the left. It should also be noted that there were no adverse reactions to the presence of rumble strips on the left edge lines of left-hand curves indicated in the drivers' behaviour.

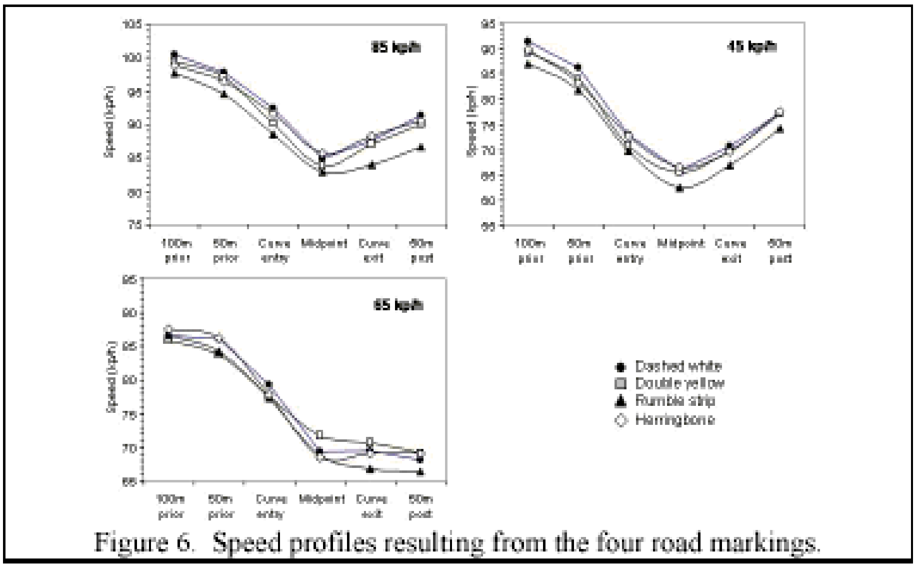


Figure 6. Speed profiles resulting from the four road markings.

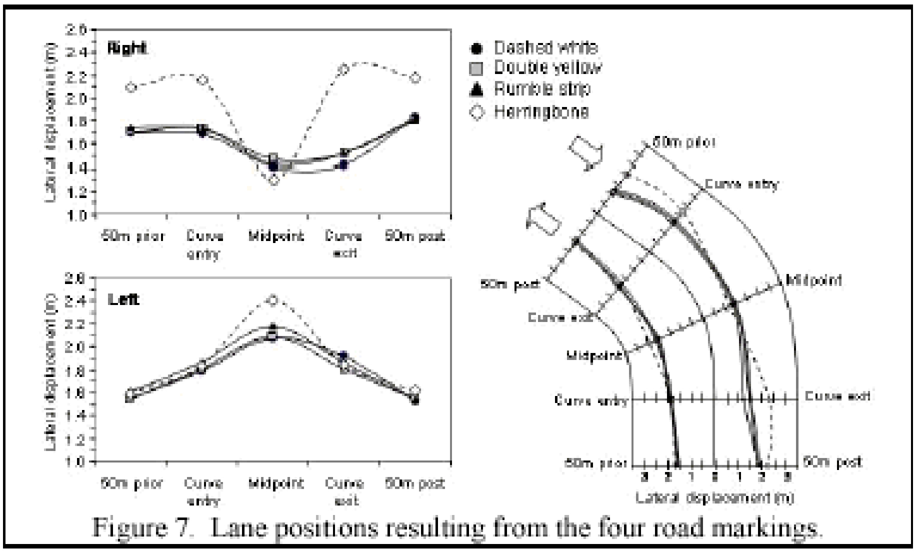


Figure 7. Lane positions resulting from the four road markings.

In response to participants' ratings and verbal feedback received on the various treatments, an additional 20 participants were tested on the same simulated road configured with the herringbone road marking and the PW17+RC4+RC2 warning sign combination (see Figure 8). The results of this configuration indicated a favorable combination of reduced curve speeds and flattened path through the curves, as shown in Figure 9 below.

Figure 8. Combination of herringbone markings and warning signs.

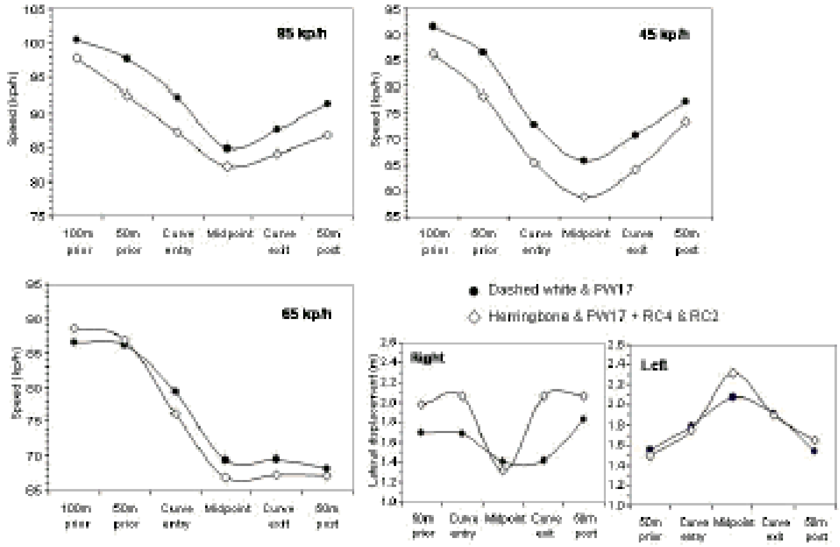


Figure 9. Speed profiles and lane positions resulting from the combination of herringbone markings and warning signs.

As mentioned earlier, we are now approaching a group of experienced road safety practitioners and researchers such as yourself in order to obtain a sense of the practical significance of the results. We are particularly interested in your reactions to the various treatments given the simulator results, your assessment of whether the results are likely to be of any use to other road safety practitioners, and whether there are any potential impediments to implementation (e.g., cost & maintenance considerations) which might mitigate their usefulness. Accordingly, we would like you to provide a ranking of each of the eight treatment types tested (where 7 = highest effectiveness and 1 = lowest effectiveness), a rating of the practical utility of each treatment (where 7 = high usefulness to road safety practitioners) and any other comments regarding the practicability of the individual treatments. As always, we greatly value your input and your advice and recommendations will be incorporated into the final report for this project. You can email your responses to me at *samiam@waikato.ac.nz* or post them to the address shown at below right.

My grateful thanks in advance,
Samuel Charlton
University of Waikato
Traffic & Road Safety Research Group
& Transport Engineering Research NZ Ltd.

Please reply to me at:
Department of Psychology
University of Waikato
Private Bag 3105
Hamilton, 3240

1: PW 17 warning sign only.
Effectiveness rating (1 to 7) ______
Practical utility rating (1 to 7) ______
Comments ____________________________

2: PW 17 & RC4 chevron sight board.
Effectiveness rating (1 to 7) ______
Practical utility rating (1 to 7) ______
Comments ____________________________

3: PW 17 & RC2 repeater arrows.
Effectiveness rating (1 to 7) ______
Practical utility rating (1 to 7) ______
Comments ____________________________

4: PW 17, RC4, & RC2 repeaters.
Effectiveness rating (1 to 7) ______
Practical utility rating (1 to 7) ______
Comments ____________________________

5: PW 17 & double yellow centre line.
Effectiveness rating (1 to 7) ______
Practical utility rating (1 to 7) ______
Comments ____________________________

6: PW 17 & left/right rumble strips.
Effectiveness rating (1 to 7) ______
Practical utility rating (1 to 7) ______
Comments ____________________________

7: PW 17 & herringbone markings.
Effectiveness rating (1 to 7) ______
Practical utility rating (1 to 7) ______
Comments ____________________________

8: PW 17, RC4, RC2 & herringbones.
Effectiveness rating (1 to 7) ______
Practical utility rating (1 to 7) ______
Comments ____________________________