Relationship between Road Geometry, Observed Travel Speed and Rural Accidents

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Abbreviations

AADT:	Annual Average Daily Traffic
CAS:	Crash Analysis System
GIS:	Geographical Information System
GLM:	Generalised Linear Models
HSD:	High Speed Data
RAMM:	Road Assessment Maintenance Management Database
RGDAS:	Road Geometry Data Acquisition System
SCRIM:	Sideways-force Coefficient Routine Investigation Machine
SH:	State Highway
SPSS:	Statistical Package for the Social Sciences
TCR:	Traffic Crash Report

Contents

Executive summary

This study has sought to investigate the relationship between road geometry, observed travel speed and crashes, using data collected on six sections of State Highway in 2005–2006.

These data include:

- the speed profiles for a sample of young, predominately male drivers,
- road geometry data (radius of curvature and pavement crossfall) collected at 10 m intervals as part of the annual pavement friction monitoring (SCRIM), and
- crash data.

The final dataset contained 488 curves where a total of 89 curve-related injury crashes and a further 128 non-injury curve-related crashes had been recorded.

Using these data, the research has investigated the relationship between road geometry and the speed choices made by the sample drivers. Based on 'calibration' data from a series of traffic speed classifiers, these investigations have been extended to consider the expected 85th percentile speed choice of the wider population.

The speed at which drivers chose to negotiate a particular curve is more strongly related to the radius of the curve than to the design speed. However, in general, the radius does not begin to effect negotiation speed until the curve radii fall below 300 m.

The best model for predicting the negotiation speed of a particular curve is based on curve radius and a term representing the approach speed environment measured over the preceding 500 m. The resulting model for predicting the 85th percentile curve negotiation speed accounts for 85% of the variation in the dependent variable.

Two models were identified as suitable for predicting the approach speed environment: one was based on the bendiness ratio (degrees/km) over the preceding 500 m; the other was based on the mean advisory speed, a synthetic estimate derived from the radius of curvature and super-elevation.

A comparison of the 85th percentile negotiation speeds predicted by this model and the relationship currently used in the design of rural roads suggests that for speed environments less than 100 km/h, drivers are, in practice, seeking to negotiate curves at higher speeds than are currently assumed in the design.

Figure XS1 illustrates this point by showing the mean curve speed of the sample set of drivers. Drivers do not generally lower their speeds from 100 km/hr until the curve radius drops below 200–300 m.

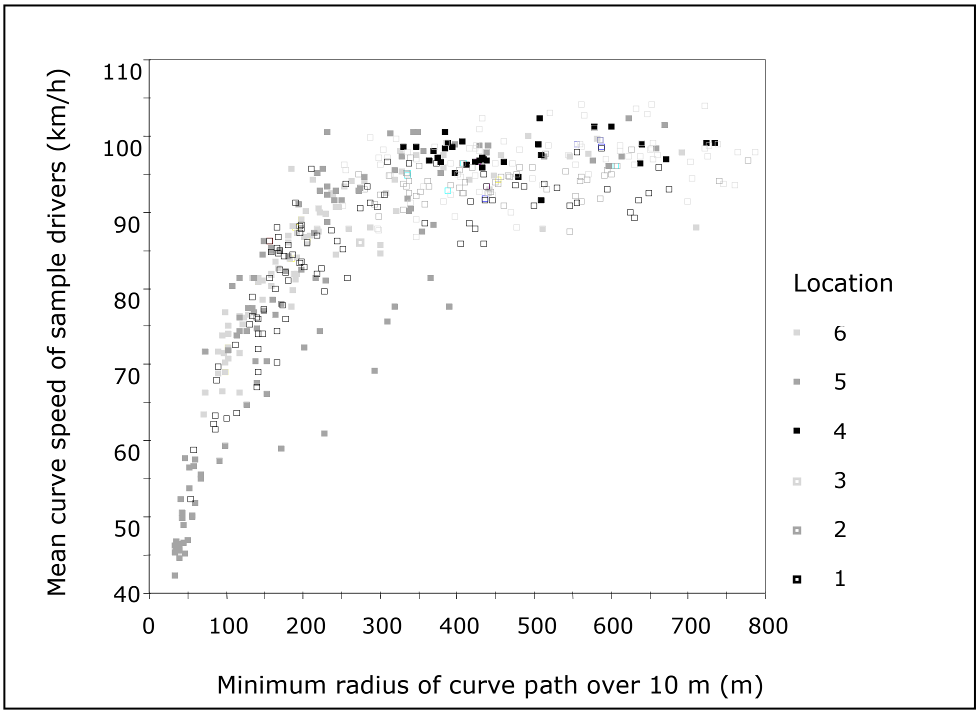


Figure XS1 Mean speed through curve from sample drivers (km/h) v. minimum curve radius (m).

A highly significant positive correlation exists between curve-related crash rates (crashes per 100 million vehicle-kilometres through curves), and the difference between the negotiation speed and the design speed (which takes curve radius and super-elevation into account). While the relatively small crash dataset precluded the development of robust crash rate prediction models, the approach used here shows considerable merit. On refinement, it could be expected to provide a useful highway network screening and crash prediction procedure.

The findings from this research are:

- It is possible to investigate drivers' speed choices using the approach developed in this research, i.e. monitoring the performance of a sample of drivers and relating their performance to that of the population using data from a number of traffic classifiers.
- The approach adopted here provides a very rich dataset that allows detailed consideration of a number of alternative variable definitions.
- It is possible to predict drivers' speed choices from highway geometry using a number of alternative measures of highway geometry. However, the best relationship is based on the 85th percentile speed and highway bendiness (absolute angular deviation measured in degrees/kilometre), measured over 1000 m.
- A driver's speed choice when negotiation a particular curve is a function of the curve radius and the approach speed, where the approach speed is established over the preceding 500 m, and may be predicted based on the bendiness of the preceding 500 m.

- We recommend that the relationship between crash risk and the difference between negotiation speed and design speed be further investigated, with a view to developing an accident prediction model that may be used in network screening and safety analysis.
- We also recommend that the design guidance regarding the relationship between speed environment, curve radius and the 85^{th} percentile speed be reviewed, as this research suggests that the current guidance underestimates drivers' speed choices.

Abstract

Speed is a major contributing factor in fatal and serious crashes in the rural environment (35% of fatal and 28% of serious crashes in 2003). In such crashes, drivers are generally described as travelling too fast for the conditions. Based on the premise that drivers do not deliberately travel too fast for conditions, what aspects of the road alignment affect drivers' speed choices?

Using highway geometry, speed and crash data collected during 2005–2006 on six 20 km road sections located in Canterbury (SH73), Blenheim (SH1), Wanganui (SH3) and Whangerei (SH1), this research investigates the relationship between curve radii, the preceding speed environment and drivers' observed curve negotiation speeds. The observed free speeds are compared to the 'safe' speed, measured as a function of the design speed of each curve; the relationship between speed and crash occurrence is examined by relating crashes to the difference between observed and 'safe' speed.

1. Introduction

1.1 Context

Speed has been identified as a contributory factor in 35% of fatal and 28% of serious accidents on rural roads in New Zealand (in 2003). In some accidents, drivers were travelling well above the speed limit. To address such accidents, the emphasis should generally be on education and enforcement. However, in many rural accidents, drivers are travelling below the speed limit but are travelling too fast for the conditions, where the safe travel speed is less than the speed limit. In such circumstances, the two matters of interest are:

- Why are drivers travelling too fast for the conditions?
- What is the increase in accident risk when drivers travel above safe driving speeds?

This study focuses on the second question (what is the increased accident risk to drivers travelling above the 'safe' speed?) and seeks to answer that question by:

- investigating factors thought to affect drivers' speed choices, and
- the crash implication of these speed choices.

To do so, Beca and MWH have investigated the relationship between highway geometry, drivers' speed choices and crash risk on six sections of State Highway which are nominally 20 km long. This research was undertaken in 2005–2006.

1.2 Purpose and objectives

The purpose of this research is to investigate the relationship between observed free speed, the 'safe' driving speed and 'speed-related' crashes on various road elements and combinations of road elements along rural roads.

The research objectives are:

- to identify how combinations of road elements, the preceding alignment and the next curve affect drivers' speed choices;
- to investigate 'safe' speed models, such as design speed, speed environment and advisory speed, and determine which model is the most appropriate for developing a crash relationship for vehicles travelling too fast for the conditions;
- to predict the increase in the accident risk as the observed travel speed (of free vehicles) through a road element (an isolated curve) approaches and exceeds the 'safe' speed of various elements; and
- to recommend how such dynamic features of rural roads can be included in a more comprehensive rural accident prediction model.

1.3 Report structure

The background to this research is given in Chapter 2, with the remaining four sections covering:

- data collection and processing (Chapter 3),
- analysis (Chapter 4),
- improvement option assessment (Chapter 5), and
- conclusions drawn from the project and recommendations for use of the research (Chapter 6).

2. Background

2.1 Crash statistics

Investigating the Crash Analysis System (CAS) crash records for five years (2001 to 2005 inclusive) reveals that curve-related crashes (loss of control and head-on) are the single biggest component of reported injury crashes on rural roads (i.e. those with speed limits greater than 70 km/h). The 9636 loss of control/head-on curve crashes made up 45% of the 21 101 reported injury crashes. This group is followed by loss of control/head-on crashes on straights, and rear-end crashes, which totalled 4101 (19%) and 3319 (16%), respectively. No other crash group exceeded 7% of the total.

While speed has been identified as a factor in 37% of the curve-related crashes and 11% of loss of control/head-on crashes on straights, the bulk of crashes are simply identified as loss of control.

2.2 Associated literature

Why do drivers make inappropriate speed choices and/or lose control on curves?

The following quotes, which are taken from a relatively recent Transportation Research Board report (Wooldridge et al. 2003), suggest that driver errors and crashes are more likely to occur when there is some disparity between what drivers may believe to be a 'safe' speed and the actual speed at which a feature can be negotiated safely.

> *Generally, drivers make fewer errors at geometric features that conform with their expectations than at features that violate their a priori and/or ad hoc expectancies.*
>
> *If a road is consistent in design, then the road should not violate the expectations of motorists or inhibit the ability of motorists to control their vehicle safely.*

The issues of driver expectations and alignment consistency are intertwined. Drivers travelling along a smooth-flowing horizontal alignment will not expect a tight low-speed curve so their speed choices will reflect that expectation. However, a driver on a tortuous alignment with numerous tight low-speed curves is more likely to expect further low-speed curves.

The key questions that must be answered are:

- How do drivers choose the speed at which they will negotiate a particular curve?
- How (or rather, over what distance) are drivers' expectations developed?
- How can we measure these expectations?
- How do we measure the difference between the 'safe speed' for the next curve and the driver's expectation as to what that might be?

To date, a limited amount of New Zealand research has supported these propositions. Jackett (1992) related crash risk (crashes per million vehicles entering a curve) to the difference between the approach speed and the ball-bank derived curve advisory speed. Although the research identified a strong positive correlation between curve crashes (head-on/loss of control on curve) and the required speed reduction, the approach speed was subjectively assessed and is understood to have focused on the immediate approach to the curve.

A subsequent study (Koorey & Tate 1997) investigated the effect of the speed environment by considering the difference between the advisory speed on a particular 200 m segment of road and the mean advisory speed over the preceding kilometre. The study included all New Zealand State Highways and sought to develop a network screening tool for use in desktop studies. To facilitate this, the advisory speed measure used in the study was a synthetic value (AS_{RGDAS}) based on the work of Rawlinson (1983), which had been used successfully in New Zealand by Wanty et al. (1995).

$$AS_{RGDAS} = -\left(\frac{107.95}{H}\right) + \sqrt{\left(\frac{107.95}{H}\right)^2 + \left[\frac{127,000}{H}\right]\left[0.3 + \frac{X}{100}\right]} \quad \text{[Equation 1]}$$

Where:

- AS_{RGDAS} = RGDAS[1] advisory speed (km/h)
- X = % crossfall (sign relative to curvature)
- H = absolute curvature (rad/km) = (1000 m/R)

2.3 Shortcomings of previous studies

However, the study by Koorey & Tate (1997) did not consider curves *per se* but 200 m segments of road, which could include parts of a curve or span multiple curves.

In this research, we seek to address some of the short-comings of the previous studies, investigating the road geometry, driver speed choice and crash risk on six segments of New Zealand State Highway, each being nominally 20 km long.

The investigation focuses on the relationship between road geometry and driver speed choices, and includes both observed and synthetic speed measures, relating these to crash risk.

[1] RGDAS = Road Geometry Data Acquisition System (Wanty et al. 1995)

3. Data collection and processing

3.1 Site selection

Beca and MWH used a 'sliding slip' Geographical Information System (GIS) procedure to identify potential survey locations, each approximately 20 km in length, that did not span urban areas. The procedure moved a 20 km analysis strip along the selected State Highway in 1 km increments, reporting the number of rural (open road speed limit) injury crashes, along with the proportion of wet road and night-time crashes.

As the focus of the research was on the role of road geometry, locations that had higher (or lower) than normal proportions of wet road crashes were excluded from consideration in order to limit the potential of skid resistance issues to confound the analysis. Locations with higher (or lower) than normal proportions of night-time crashes were also excluded so as to minimise the effect of differences in the level of delineation.

Although focusing on locations with higher traffic volumes would help to ensure that sufficient crash numbers were available for subsequent analysis, higher volumes tend to constrain vehicle speeds, so the crash rates on high-volume highways are generally lower than those for highways carrying less than 8000–10 000 vehicles per day.

Although the crash rates on lower volume State Highways (those carrying less than 5000 vehicles per day) are generally much higher than those on higher volume State Highways, the crash densities (crashes/kilometre of length) are much lower. These considerations, combined with the fact that the majority of curve-related crashes occur on highways with intermediate volumes, prompted the team to put boundaries on the traffic volumes when seeking to identify potential survey locations.

The final selection criteria for potential survey locations are set out in Table 3.1.

Table 3.1 Selection criteria for potential study locations.

Criterion	Lower bound	Upper bound
Proportion of wet crashes	25%	45%
Proportion of night-time crashes	25%	45%
Traffic volume (veh/day)	3000	8000

Having identified 100 potential survey locations, the final selection was based on:

- ensuring a reasonable geographic coverage (ensuring at least two surveys in the South Island and some in Northland, as requested by a project supporter),
- practical issues associated with the speed surveys (e.g. access to a pool of drivers), and
- local knowledge to ensure a range of alignments.

The six sections selected for the main study are listed in Table 3.2 and shown in Figure 3.1.

Table 3.1 Location of highway sections studied.

Location	Description	SH* and region
1	North of Whangerei	SH 1 (Northland)
2	South of Whangerei	SH 1 (Northland)
3	Wanagnui to Turakina	SH 3 (Manawatu)
4	Turakina to Bulls	SH 3 (Manawatu)
5	Blenheim to Seddon	SH 1 (Marlborough)
6	Tai Tapu to Birdlings Flat	SH 75 (Canterbury)

* State Highway

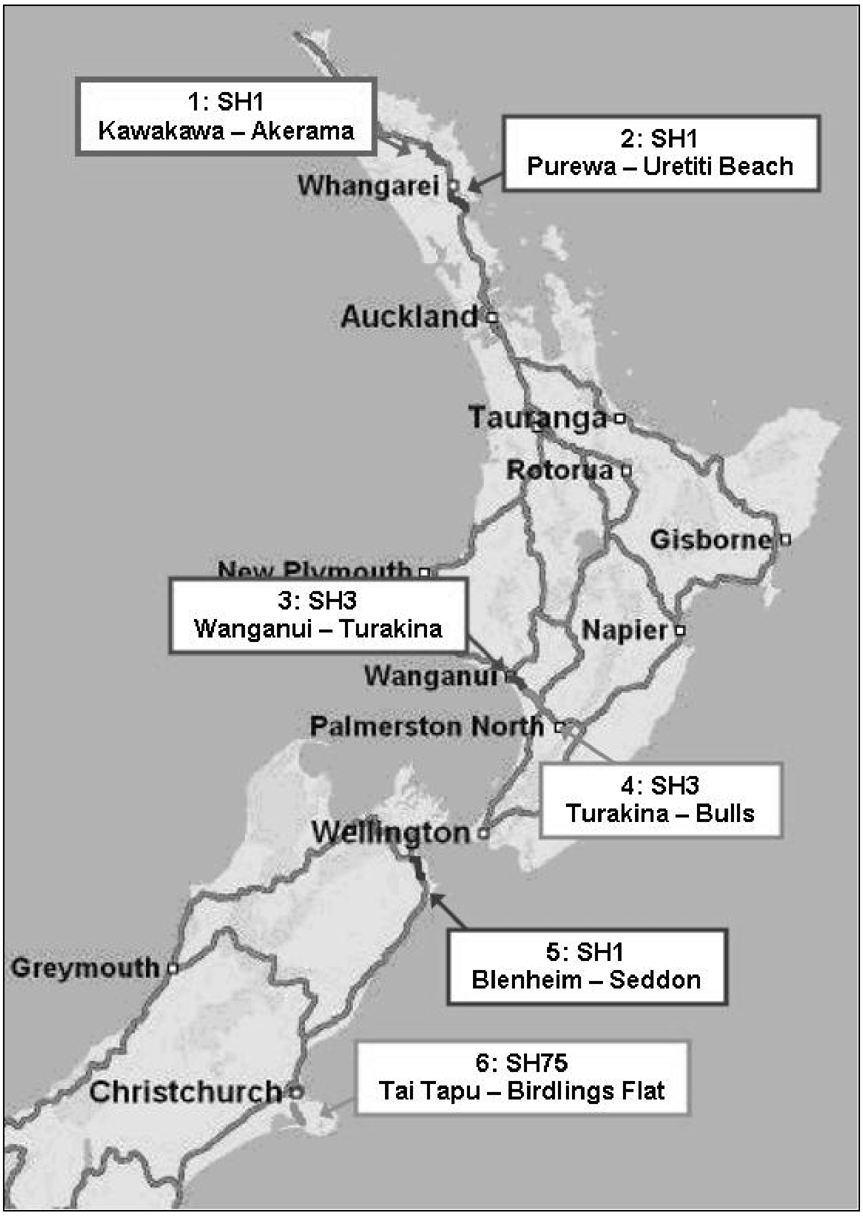


Figure 3.1 Map showing the sites selected for the speed surveys.

3.2 Road geometry data

For each location, the road geometry data were extracted from Transit New Zealand's[2] 2005 High Speed Data (HSD) holdings. These data were collected during the annual SCRIM surveys, in which an instrumented vehicle drives along the entire State Highway network in each direction. The vehicle collects details of the path radius (m) and pavement crossfall (%), and reports these every 10 m. However, since the principal aim of these SCRIM surveys is to record the road surface friction in the wheelpaths, the resulting geometric data represent the path travelled by vehicles using the road, rather than the actual design of the road alignment.

The effect of this is shown in Figure 3.2, which plots the horizontal geometry data collected by the vehicle as 1/R (R = radius).

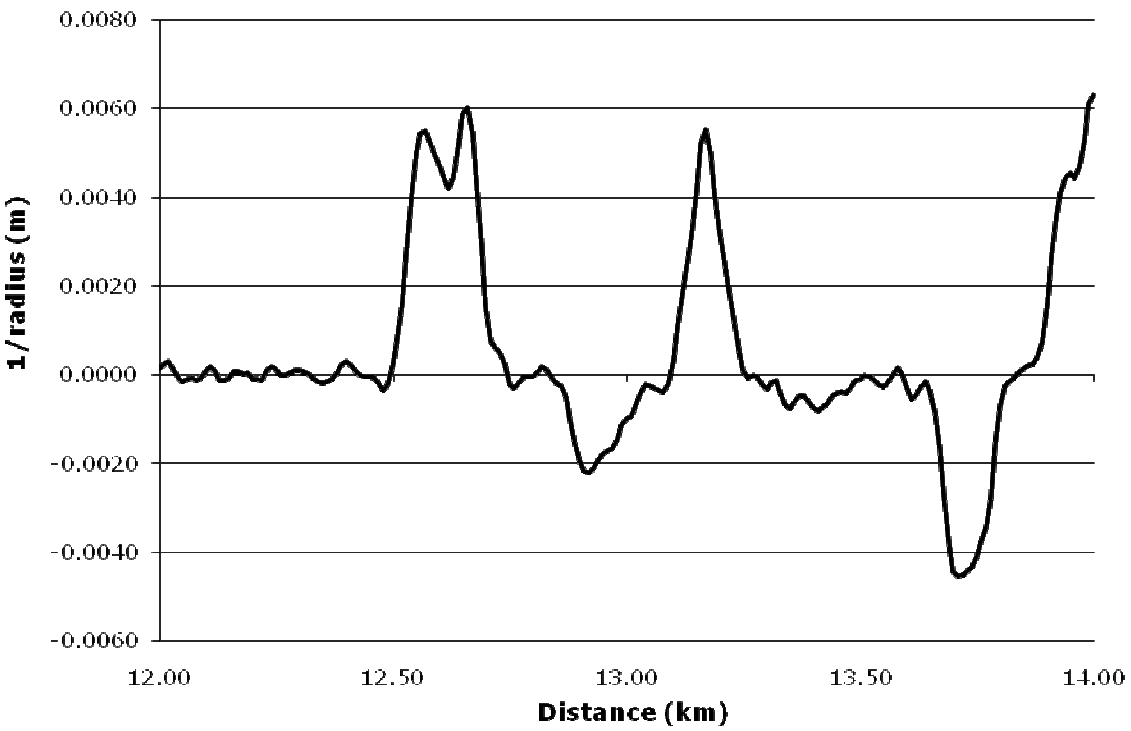


Figure 3.2 Plot of high speed geometry data collected at 10 m intervals.

The important features of Figure 3.2 are:

- the level of variability in the individual 10 m readings of a radius;
- the transition path from straight to curve, which makes determining the actual curve length difficult; and
- the fully transitional nature of short curves.

2 Transit New Zealand merged with Land Transport New Zealand in mid-2008 to become the NZ Transport Agency.

Given the level of variability in the individual 10 m data, we decided to smooth the data using a three-point running average and to report these values against the central point of the three-point series. The result was that for each 10 m road geometry reading, the following associated measures of road geometry were developed to represent the geometry at the point in question:

- the horizontal radius of the vehicle path over a particular 10 m section(R_{10}) and the absolute horizontal radius ($absR_{10}$);
- the three-point moving average of the absolute horizontal radius recorded against the running distance of the central point of the three-point series ($absR_{30}$);
- the crossfall of the particular 10 m section (X_{10});
- the three-point moving average of crossfall with the sign relative to the direction of curvature and recorded against the running distance of the central point in the three point series (X_{30}); and
- the deflection of the particular 10 m reading measured in degree of deviation (B_{10}).

The geometry of the preceding road environment was defined using the mean absolute horizontal radius over the preceding 500 m, 1000 m, 2000 m and 3000 m distances, defined as R_{500} to $R_{3000.}$ However, when deriving these measures, we limited the assumed radius for straight sections of road to 1000 m, thereby avoiding the possibility that straights where the radius was recorded as, say, 2000 m were considered to be different from one where the radius was recoded as 5000 m, potentially distorting the results.

Two additional measures of road environment geometry were also derived. The first was the 'bendiness', the average absolute change in direction per kilometre of travel expressed as degrees per kilometre (B_{500} to B_{3000}). Bendiness has been promoted by some researchers as a more complete measure of approach geometry than mean radius, as it takes better account of small radius short curves in a generally straight environment, which would produce high average values of radius (Emmerson 1970; McLean1991; Bennett1994).

The second additional measure of road environment geometry was the synthetic advisory speed (AS_{RGDAS}) proposed by Rawlinson (1983) and previously used by Wanty et al. (1995) and Koorey & Tate (1997), as discussed in Chapter 2. This measure takes both the horizontal alignment and the carriageway crossfall into account, but produces very high values of advisory speed for essentially straight sections of highway. To overcome this, the maximum value of AS_{RGDAS} was limited to the 85th percentile speeds observed in the Land Transport New Zealand regional speed surveys[3] (see Table 3.3). The average value of this variable was developed for the 500, 1000, 2000 and 3000 m preceding each element (AS_{500} to AS_{3000}).

Each road geometry variable was developed in each direction of travel, giving a total of twelve datasets (two directions for each of the six selected highways).

[3] The speed surveys used for this survey were taken from the Speed Survey Results of 2005. These were formerly available on the website http://www.transport.govt.nz/speed-index but these results are no longer available on the site, which has been updated with data from subsequent surveys.

Table 3.2 Speeds of free vehicles on rural roads (taken from the Land Transport New Zealand 2005 speed surveys).

Region	Mean free speed (km/h)	85th percentile free speed (km/h)	Difference (km/h)
Northland	95.9	105	9.1
Wanganui/Manawatu	101.2	108	6.8
Nelson/Marlborough/Tasman	91	99	8
Canterbury	99.1	104	4.9

3.3 Speed data

3.3.1 The drive-over survey

As discussed previously (in Chapter 2), one of the principal aims of the research was to investigate the impact of drivers' observed speeds on crash rates, rather than the effect of the synthetic speed measures as previously used.

To accomplish this, the research methodology proposed that a sample of 12 drivers would drive each 20 km section of highway, with each driver driving four times in each direction, giving a total of 48 speed profiles in each direction.

A key element of the study was the selection of drivers to travel each route. Although the initial research methodology proposed that a cross-section of drivers be employed for this task, the steering group were keen to see a focus on higher risk drivers, believing that such drivers would be more responsive to the subtle changes in highway geometry and would therefore provide a richer dataset.

However, focusing on a particular driver type could possibly limit the future application of the research results. To overcome this, a series of automatic traffic speed surveys were undertaken at various sites over each highway section. The data from these point surveys were then used to adjust the speed profiles from the drive-over surveys to give an estimate of the 85th percentile speed profile.

3.3.2 Data collection – observed free speed

Beca investigated rural 'loss of control' accidents by age and gender to determine the most at risk group (see Figure 3.3). The graph indicates that 17–24-year-old males are the driver group most frequently involved in crashes.

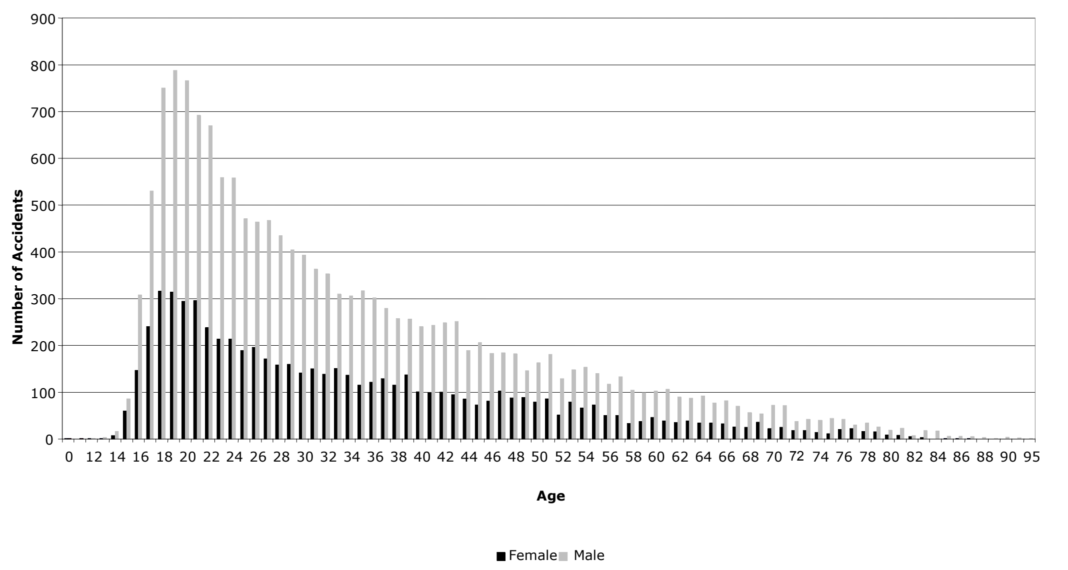


Figure 3.3 Drivers involved in rural 'loss of control' crashes by age and gender (1980–2004 inclusive).

Although employment laws prevented Beca from advertising specifically for males aged 17–24 to drive the study sections, subjects were sourced through Student Job Search. This approach was successful at targeting the higher risk group.

3.3.3 Collection of observed free speed profile data

For the surveys at each location, Beca employed twelve drivers, each of whom drove over the study section four times in each direction using a particular survey vehicle, a Mitsubishi Galant, which is a medium sized passenger car. The survey vehicle was fitted with a Nitestar trip meter, and logging equipment collected travel distance every second to produce a speed profile.

The resulting time-distance traces were then post-processed using a linear interpolation routine to provide speed values every 10m along each route. An example of the type of data collected for each of the drivers is shown in Figure 3.4.

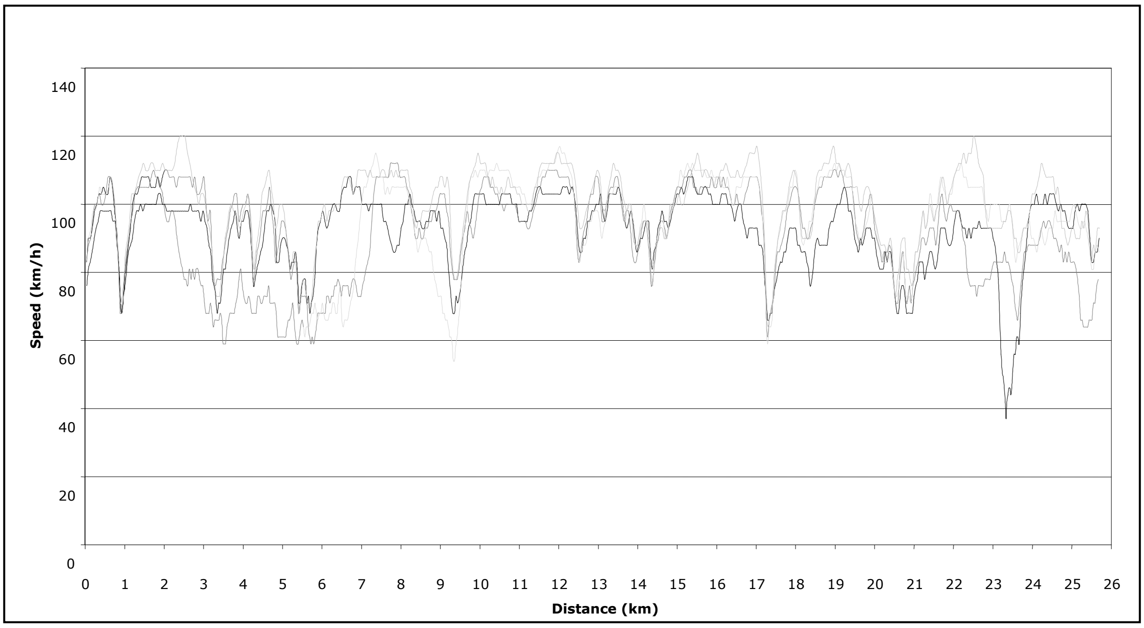


Figure 3.4 Speed v. distance for 'John Smith' while driving the eastbound run on SH 75.

The aim of the surveys was to establish the desired free speed profiles adopted by a sample of drivers in response to the road geometry. Unfortunately, problems occurred when attempting to identify the situations where the drivers were constrained by other traffic, road-works or stock movements.

In order to identify where it was likely that external factors had constrained the speed adopted by our sample drivers, the data were cleaned of all speed readings that were less than a particular limit below the mean. Following some experimentation, the limit was set at two standard deviations below the mean. Typically, these criteria resulted in relatively small data losses from particular runs, generally less than 15%. However, in some cases, where data losses for a particular run were extreme, that run was compared to the others made by the same driver and, where necessary, part or all of the particular drive was deleted.

The effect of this 'cleaning' can be seen around the 7 km mark in Figure 3.5 (where the dotted line diverges from the solid line). The 'cleaned' distance-speed trajectories were then plotted against the road geometry data to confirm that the resulting profiles were correctly positioned longitudinally and that they were sensible.

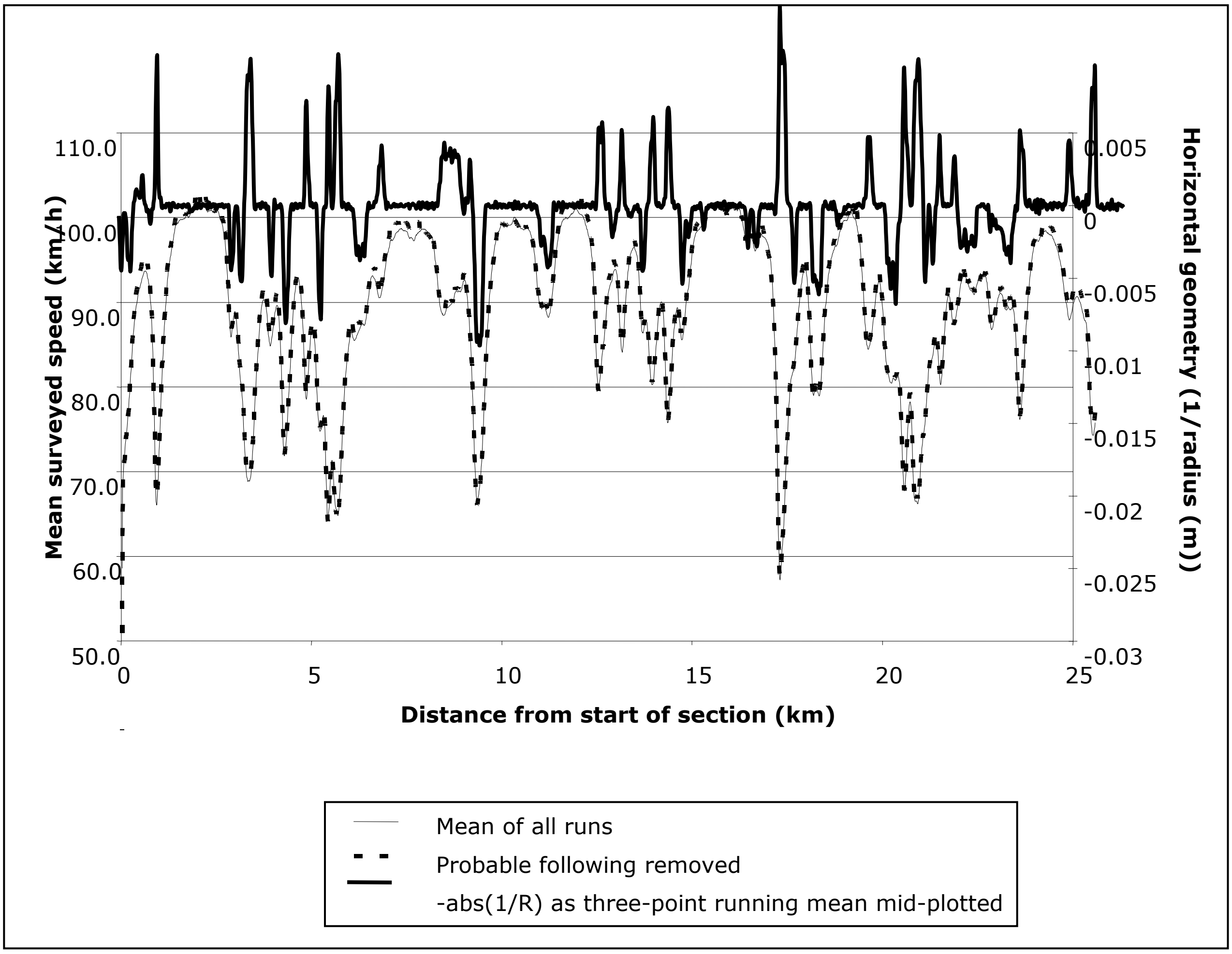


Figure 3.5 Example of a speed survey (showing distance v. mean speed and horizontal geometry) where trajectories were 'cleaned'.

Plotting the speed profiles against the road geometry proved to be a useful check, identifying that road-works at Location 1 (SH1 north of Whangarei) had affected the majority of drives along this section of highway. The result was a depressed mean speed which confounded the 'cleaning' routine. To overcome this, data for the final 4 km of the route (Location 1) were excluded from the analysis. Similarly, speeds over the final 2 km of surveys at Location 5 (SH1S Blenheim to Seddon) had been affected by the single lane Awatere Road/Rail Bridge. Again the data of the affected length was excluded from subsequent analysis.

3.3.4 Generation of the 85th percentile speed profiles

Because the sample of drivers used in the trial was intentionally biased towards younger age groups and a single vehicle was used in all trials, it is highly unlikely the free speed profiles collected are representative of the true mean free speed profile. Nor would the 85th percentile speed from the vehicle-based speed surveys be representative of the 85th percentile speed of all vehicles.

To overcome this problem, the distribution of free vehicle speeds was measured using traffic classifiers installed at a number of sites along each section of highway (see Table 3.4).

Table 3.3 Classifier speed surveys per location.

Survey location	Description	Number of speed classifier surveys
1	SH1N north of Whangerei	5
2	SH1N south of Whangerei	3
3	SH3 Wanganui to Turakina	5
4	SH3 Turakina to Bulls	3
5	SH1S Blenheim to Seddon	5
6	SH75 Tai Tapu to Little River	5

The data from each classifier were processed to establish the 85th percentile speed of free cars (short two-axle vehicles recorded by the classifiers). Free cars were defined as those with headways greater than six seconds to the vehicle in front. With the exception of Blenheim to Seddon and Tai Tapu to Little River, the speed distributions were generated for each direction. At these two sections, the counter configuration used by the contractor did not allow the data to be split directionally.

The classifier surveys were then mapped onto the speed profiles. This was not, however, a simple task. In some cases, the speed classifier surveys were undertaken a number of months after the drive-over speed profile surveys, and a number of different contractors were used to undertake the classifier surveys. Unfortunately, the exact location of some classifiers was poorly recorded and they were not always anchored to the same reference point as the speed profiles. If the study was to be repeated, it would be useful to ensure that the classifier surveys are undertaken at the same time as the drive-over speed profiles, and the position of each classifier is recorded as an offset from the start and end of the speed profile surveys.

The mean free speeds collected in the vehicle-based travel time survey and the 85th percentile speed of all free vehicles collected by the classifiers are compared in Figure 3.6.

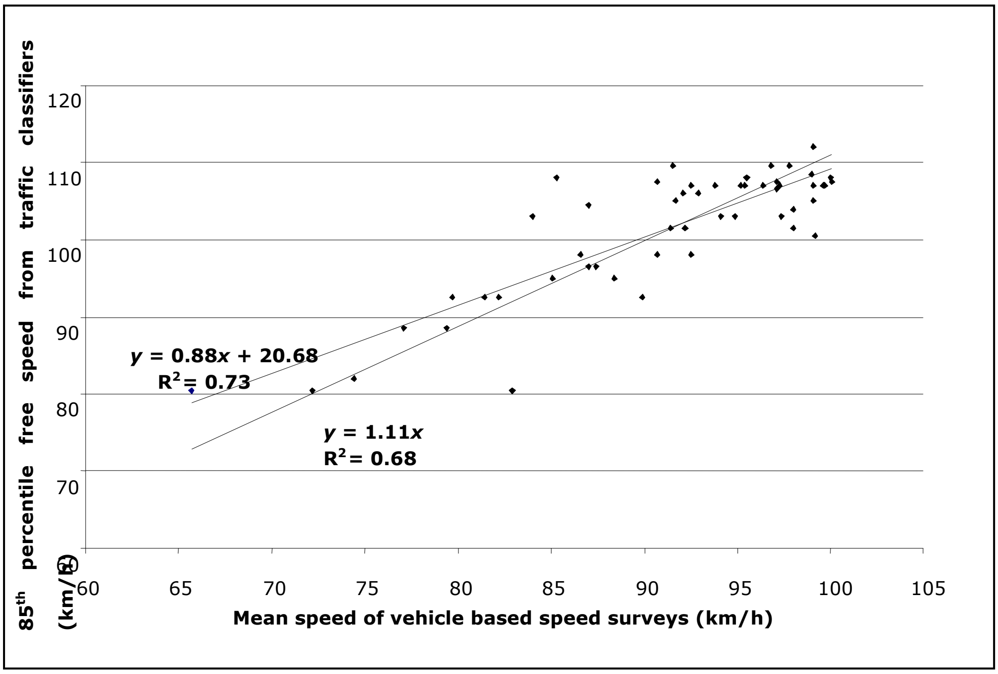


Figure 3.6 Relationship between mean speed of vehicle surveys and the 85th percentile speed from traffic classifiers.

While the relationship between the two sets of speed data is significant, when the model includes a constant ($F_{1,50}$ =132, $p < 0.001$) and when the relationship is forced through the origin ($F_{1,51}$ =24 166, $p < 0.001$), the resulting models account for approximately 70% of the variation between the data sources. One reason for this may have been the difficulties encountered when trying to locate the classification surveys accurately along the vehicle survey route.

However, further investigation found significant differences were associated with the data collected at Locations 1 and 5. A better model ($F_{3,48}$=84.128, $p < 0.001$, $R^2 = 0.84$) explaining all but 16% of the variability between the two datasets could be developed by identifying the local effects at these two locations.

$$S_{85} = 12.428 + 0.968\, V_{mean} + 5.946 L_1 - 2.966 L_5 \qquad \text{[Equation 2]}$$

Where:

- S_{85} = the 85th percentile speed of all free vehicles.
- V_{mean} = the mean speed of vehicle based surveys.
- L_x = 1 if the location of the survey is Location 1 (L_1) or Location 5 (L_5); 0 otherwise.

The overall effect of adjustment for Locations 1 and 5 is to introduce a constant shift between the mean speed for the sample and the 85th percentile speed. Although it was initially thought that the road-works at Location 1 had suppressed speeds, none of the classifiers were located close to the road-works, as shown in Figure 3.7.

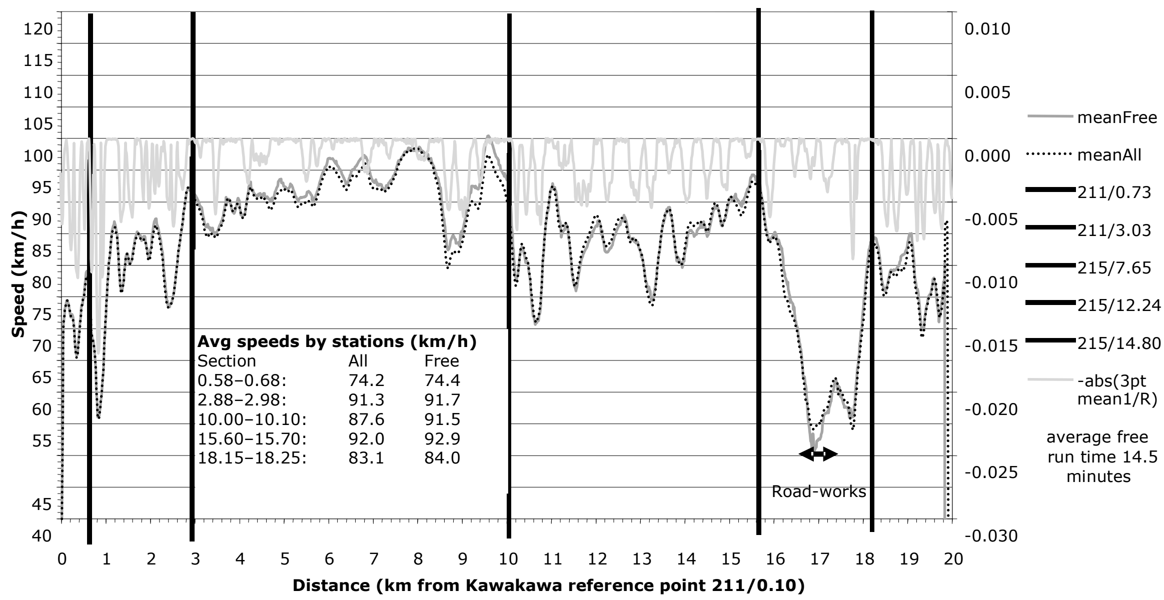


Figure 3.7 Location 1 (southbound) speed geometry profile showing traffic speed classifier locations and the road-works.

However, the differences between the mean and 85th percentile speeds recorded in Northland are typically higher than for other regions in New Zealand, while the 85th percentile speeds in the Nelson/Marlborough/Tasman region, where Location 5 is, are lower than elsewhere.

The third possibility may simply be that the twelve young divers used in the Northland surveys preferred to travel faster than those used in other areas, while the group used in Blenheim preferred to adopt slightly slower speeds. Whatever the reason, the relationship between the mean free speeds of our subjects and the 85th percentile speeds of all free cars (as measured by the classifier surveys) is robust.

3.3.5 Speed metrics

Three categories of speed measure were then considered. These dealt with drivers' speed choices:

- at a particular location;
- immediately prior to a location (or curve), i.e. the approach speed choices considered by Jackett (1992); and
- the speed environment the driver was operating in.

The following speed metrics were added for each of the twelve surveys (six locations in both directions of travel):

- To represent drivers' speed choices at each location (i.e. each 10 m) record, the following were chosen:
  - the mean free speed recorded at that 'point' by the sample of drivers who travelled the route (S_{10});
  - the three-point moving average of the mean free speed recorded by the sample of drivers (S_{30}), reported at the mid-point of the three-point series;
  - the 85th percentile free speed at that 'point' estimated from the data collected by the sample of drivers who travelled the route (V_{10});
  - the three-point moving average of the 85th percentile free speed estimated from the data collected by the sample of drivers who travelled the route (V_{30}) and reported at the mid-point of the three-point series.
- To represent drivers' speed choices immediately prior to a location, the mean estimated 85th percentile free speed recorded over 100 m was derived starting at 0 m, 100 m, 300 m and 500 m in advance of the point under consideration (A_0 to A_{500}).
- To represent the approach speed environment, the mean 85th percentile free speed was estimated over the previous 500 m, 1000 m, 2000 m and 3000 m, defined as V_{500} to V_{3000}.

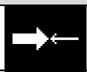
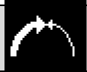
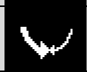
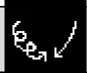
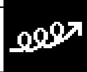
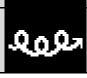
The variable naming convention is S for variables describing speed measures based on the sample drivers, V to represent the estimated 85th percentile speeds, A variables to the estimated 85th percentile speeds approaching the road element under consideration, and R is used for the radius of curves.

The variable convention includes subscripts that define the distance over which a measure was established, so that single-point estimates from the 10 m data are subscripted *10*; those collected from a mean of three consecutive 10 m readings are subscripted *30,* etc.

3.4 Crash data

Data on reported crashes along the study sections were obtained from the New Zealand CAS for 2001–2005. Given the objectives of the study, the analysis focused on crash types that are associated with a driver's inability to select the appropriate speed for the road and conditions (Table 3.5). For each section, two crash datasets were compiled as shown in Table 3.6.

Table 3.5 Loss of control and head-on crash types investigated in this research.

Abbreviation*	CAS diagram
BA	
BB	
BC	
BD	
BE	
BF	
CA	
CB	
CC	
DA	
DB	

* Grey highlight indicates a curve-related crash type.

From Table 3.6, it can be seen that for most of the study sections, the crash density is in the order of one curve-related injury crash per kilometre. This is in keeping with the crash density expected from an investigation of average State Highway densities. The two exceptions are Location 4 and Location 6. Location 4 is a section of highway with a generally high standard alignment, with numerous large radius sweeping curves. Although unlikely to have high crash rates, this section was specifically included to ensure a wide range of curve radii was investigated. While Location 6 was expected to have a relatively high crash risk, the crash density is relatively low because of the low traffic volumes.

Table 3.6 Nominal number of crashes recorded for each highway section (source: CAS 2001–2005 inclusive).

Location		Mean traffic volume (AADT*)	Nominal length (km)	Curve crashes		All loss of control	
				injury	non-injury	injury	non-injury
1	Whangarei (north)	5640	19.8	13	8	32	47
2	Whangarei (south)	10 430	25.5	29	43	48	77
3	Wanganui–Turikina	7850	19.8	23	32	29	54
4	Turikina–Bulls	5500	20.0	7	17	16	33
5	Blenheim–Seddon	3250	21.0	18	21	22	25
6	Tai Tapu–Birdlings Flat	2850	25.5	8	22	10	26
Total			131.6	98	143	157	262

* Annual average daily traffic

The crashes for each section were subsequently 'mapped' onto the road geometry data. Although the location of each crash is linearly referenced to the State Highway route position, concerns have been raised regarding the accuracy of these descriptions. The advice on the CAS website is not to rely on the route position descriptions for locating crashes. To overcome this, the location of each crash was plotted in terms of the geodetic co-ordinates, and a GIS system was used to determine the offset (to the crash) along the highway centreline from a known reference location. Given the uncertainty whether BE, CA, DA, CB or CC crashes actually occurred on curves, only the crashes of the types that did get coded on a curve were included in the analysis.

The crashes were then separated by direction of the principal vehicle, generally defined as 'Vehicle 1' in the dataset. The State Highway linear referencing system adopts the convention of using numbers that get larger with increasing southward distance. However, the direction in which vehicles were travelling is recorded on site by the police attending the crash, and frequently reflects the direction of the highway at the crash location. The result is that a vehicle involved in a crash may be travelling east or west at that location while travelling along the highway that, globally, is heading south, in the direction of increasing route position.

A scan of the highway alignments indicated that none of the surveyed highways 'turned back on themselves' and that those vehicles recorded as travelling southeast or northwest would, in the absence of recording errors, be travelling on the increasing and decreasing route positions, respectively.

3.5 Data processing

While readers of this report may be tempted to believe that combining the three datasets (geometry, speed profiles and crashes) was a relatively simple mechanical task, this was not the case, and some considerable effort was required to ensure these base data were correctly aligned. Even though the speed surveys started and finished at known points – typically roadside signs or markers, the position of which could be obtained from the State Highway Information Sheets and cross-referenced to the highway geometry – matching these two datasets presented some problems. A certain amount of 'drift' is thought to exist in both the speed profile distances recorded by the Nitestar equipment used in the speed profile surveys and also in the High Speed Data (HSD) equipment that records the geometry data. Although the latter has been 'rubber banded' to ensure the reported lengths match those in the State Highway Road Assessment Maintenance Management (RAMM) database, a trial and error process was required to match minimum speeds onto curves. The result was that for some locations, distances in one direction were adjusted by different amounts to those used for distances in the other direction.

Having matched the speed and geometry profiles, and removed (where necessary) the start and end sections over which the speed profile was distorted, the 10 metre data were then processed to identify the extent of each curve along the highway. Curves were defined as those locations where the absolute value of the radius (R_{10}) dropped below 800 m for two or more successive 10 m readings. Once identified, a curve continued until the minimum radius was identified or the sign of the radius changed. Although this process was initially automated, the variability of the 10 m data did at times create 'phantom' curves in situations where the 10 m radius data increased and then decreased; for example, the following sequence of radius readings – 250, 255, 260, 245, 250 – would be defined as two curves.

An alternative, based on a running average to smooth the data, also encountered problems and it was generally more reliable to code the curves manually. However, some problems remained when seeking to define 'broken back' curves. In this situation, two 'curves' occurred in the same direction separated by a small straight or a small section of large radius curve (500–800 m) in the same direction. Although we adopted the convention of coding these as separate curves, in retrospect, it may have been better to code these as a single curves and flag their 'broken-back' nature.

Once we had identified each curve, the data were then aggregated to provide a single record for each curve using the structure shown in Table 3.7 and the variables as described in Appendix A.

Table 3.7 Structure of final dataset for the curves investigated.

Site	Direction	Curve number	Start dist	End dist	Length	A range of data as described in Appendix A				
1	s	2	140	270	130					
1	s	3	290	420	130					
6	n	46	23030	22960	70					

Unfortunately the aggregation process resulted in the loss of many of the curve-related crashes, which, although identified by the Police as having occurred on curves, were located on straights when the crashes were matched onto the geometry. Although various automated routines were trialled, in the end, it was more reliable to allocate crashes to curves manually without reference to the traffic crash report (TCR), but based on the distance along the highway, the location of adjacent curves and the following rules:

- Where a crash was identified as occurring in a given curve, it was allocated to that curve.
- Where a crash occurred between curves, it was either dropped from the analysis or allocated to:
  - the nearest adjacent curve within 100 m (upstream or downstream),
  - the curve immediately upstream of the reported location if it was specifically identified as a curve-related crash,
  - the curve immediately upstream in the case of a loss of control crash (not on a curve), provided the distance to that curve was less than 500 m.

The final step in data preparation was to establish a 'safe' speed for each curve. Theoretically, the maximum speed at which a particular curve can be negotiated is given by Equation 3:

$$V^2 = 127R\,(e+f) \qquad \text{[Equation 3]}$$

Where:

- V^2 = maximum negotiation speed (km/h),
- R = curve radius (m),
- e = the super-elevation (m/m),
- f = the coefficient of side friction.

While the available friction over a curve (f) may be approximated from the SCRIM data, this varies over time and is typically far greater than the value assumed for design. To overcome this, the safe speed has been determined according to the design formulae from the State Highway Geometric Design Manual (Transit 2003), based on the limiting ratio of e such that:

$$V^2 = (1.27\,Re)/S_k \qquad \text{[Equation 4]}$$

In this equation, S_k is defined on the basis of the approach speed environment approximated by the mean 85th percentile speed over the previous 1 km (V_{1000}), according to Table 3.8.

Table 3.8 Values of S_k for a range of V_{1000} approach speeds (Transit New Zealand 2003).

V_{1000} (km/h)	S_k
30, 40 and 50	0.222
60	0.223
70	0.244
80	0.278
90	0.357
100	0.417
110	0.455
120 and 130	0.476

3.6 Characteristics of the final dataset

The final dataset contained 488 individual curves and a total of 312 crashes reported for the five-year period 2001 to 2005 inclusive. The distribution of crashes and curves across the six survey sections is shown by direction of travel in Table 3.9, with the curve length and radius shown by location in Figure 3.8.

Observant readers will note that for the same survey location, the number of curves recorded in each direction of travel differs, particularly at Locations 2 and 3. Three principal reasons explain this:

- The survey lengths in each direction varied as the drivers would continue past the nominal end point until a suitable pull-off location. As data were being collected continuously, it seemed sensible to include these additional data wherever possible.
- In some cases, HSD road geometry data were not available for the highway immediately preceding that used in the study. This meant that some variables, e.g. the mean radius of the preceding 1000 m, could not be computed. The sections used in the analysis were shortened to remove this 'start-up' effect.
- The definition of a curve is based on at least two sequential readings where the radius is less than 800 m. On occasions when the SCRIM truck travels on the inside of a curve, two readings of less than 800 m radius may be recorded; however, when travelling in the opposite direction around the outside of the curve, the truck may record only one reading so a curve is not defined.

Table 3.9 Distribution of curves and crashes by location and direction of travel.

Location	Direction of travel	Number of curves	Curve crashes		All loss of control	
			injury	all	injury	all
1	N	46	9	15	19	40
	S	47	3	3	4	14
2	N	33	12	32	14	48
	S	25	14	30	19	38
3	N	51	11	28	12	34
	S	34	9	24	12	32
4	N	16	2	8	5	15
	S	16	4	13	7	20
5	N	64	11	21	12	23
	S	63	6	14	8	16
6	N	46	3	17	4	18
	S	47	5	12	5	14
Totals		488	89	217	121	312

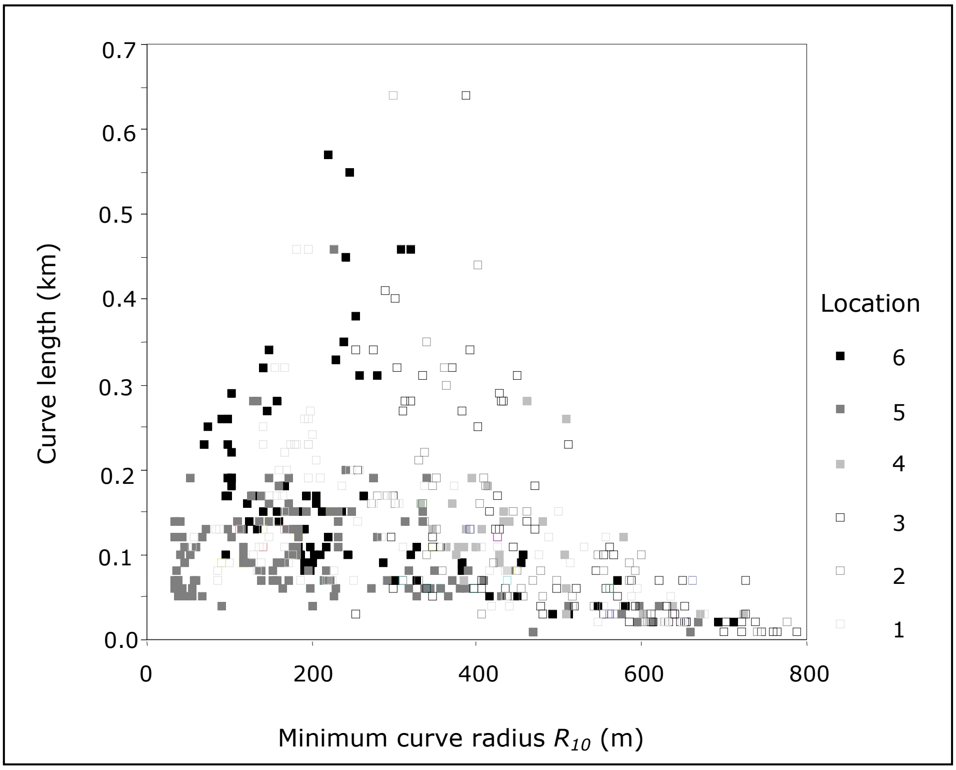


Figure 3.8 Curve length and radius by location.

The distribution of crashes across the curves for the total dataset is shown in Table 3.10. Loss of control crashes, both injury and non-injury, occurred on roughly one-third of the curves in the sample, with multiple crashes occurring on 72 of the 488 curves. Conversely, curve-related injury crashes occurred at just under 15% of curves in the sample, with multiple curve-related injury crashes occurring at only 15 curves in total.

Table 3.10 Distribution of crash groups across curves for each location.

Crash type	Crashes per curve	Frequency	Valid percent	Cumulative percent
Injury crashes on curves	0.00	417	85.5	85.5
	1.00	56	11.5	96.9
	2.00	12	2.5	99.4
	3.00	3	0.6	100.0
All curve crashes	0.00	344	70.5	70.5
	1.00	98	20.1	90.6
	2.00	33	6.8	97.3
	3.00	7	1.4	98.8
	4.00	3	0.6	99.4
	5.00	1	0.2	99.6
	6.00	1	0.2	99.8
	9.00	1	0.2	100.0
All loss of control injury crashes	0.00	396	81.1	81.1
	1.00	73	15.0	96.1
	2.00	11	2.3	98.4
	3.00	6	1.2	99.6
	4.00	2	0.4	100.0
All loss of control crashes	0.00	309	63.3	63.3
	1.00	107	21.9	85.2
	2.00	41	8.4	93.6
	3.00	17	3.5	97.1
	4.00	6	1.2	98.4
	5.00	4	0.8	99.2
	6.00	2	0.4	99.6
	7.00	1	0.2	99.8
	9.00	1	0.2	100.0

4. Data analysis

4.1 The relationship between speed and crashes

In this analysis, we sought to improve our understanding of the relationship between various speed measures and the crash rates on curves.

Given the relatively small numbers of crashes in some datasets, the approach involved aggregating the crash and exposure data across groups of curves that have similar characteristics.

Based on a series of trial analyses and the research discussed in Chapter 2, it was postulated that the safety performance of a particular curve will be related to the likelihood of drivers making speed choice errors. The likelihood of speed choice errors is defined as the difference between the negotiation speed and the 'safe speed', where the 'safe speed' is the curve design speed, as estimated from the road geometry and the surface friction assumptions provided in the *Geometric Design Manual* (Transit New Zealand 2003).

From the data, we have a range of possible negotiation speed measures including:

- the minimum speed recorded over a 10 m section, which may be subject to considerable variation;
- the mean speed over the entire curve; or
- the minimum speed measured as a mean of consecutive 10 m sections.

Each of the above can be derived from:

- the mean speed of the sample drivers, or
- the estimated 85th percentile speeds.

For each of the six predictor combinations, eight safety consequences are defined, based on crash type, severity and exposure. The crash types and severity groupings are:

- curve injury crashes,
- all curve crashes,
- loss of control and head-on injury crashes, and
- all loss of control crashes.

The exposure measures considered are:

- crashes per million vehicles entering each curve, effectively treating each curve as an individual road safety hazard;
- crashes per 100 million vehicle-kilometres travelled through curves, which takes the length of the curve into account as well as the expectation that on longer curves, drivers have less opportunity to recover from errors in speed choice.

For each curve, the difference between the 'safe speed' and the various driver speeds was calculated. The speed differences were than grouped into 5 km/h 'bins'. The size of the bins was decided following some experimentation, during which it was found that smaller 'bins' resulted in many bins having no crashes recorded against them, while larger bins reduced the number of data points available for the analysis.

For each bin, the crash consequences were then calculated, based on the total number of crashes (of each type and severity) and the total exposure (either in terms of vehicle entering the curves in that bin, or of the total vehicle-kilometres of travel around the curves allocated to the bin.

Table 4.1 provides details of the correlation between the various measures that represent the reliability of drivers' speed choice, and the crash outcomes associated with those choices that result in a positive speed difference, i.e. those situations where the negotiation speed measures were greater than the safe speed. The significant correlations ($p<0.05$) have been indicated by grey shading.

The key messages available from Table 4.1 are:

- Overall, the crash measures based on total vehicle-kilometres of travel through the curves generally perform better than those based on the total number of vehicles entering the curve. This would appear to support the proposition that curve length affects the potential for a driver to correct errors of judgement relating to speed choice.
- The most significant correlations exist between the crash risk measures and speed measures based on the sample of drivers.

Figure 4.1 shows that a quadratic relationship relates the crash rate (crashes/100 million vehicle-kilometres of travel) to the difference between the minimum mean speed recorded by the sample drivers, measured over 30 m, and the design (or safe) speed. Plots for other crash sets are given in Appendix B and confirm that a reasonable fit could be obtained, using the quadratic expressions in Table 4.2, for the injury crash sets and for all crash sets, once an outlier (speed differential =30) had been removed.

Although a quadratic expression provides the best fit to the data, this type of expression can, at times, predict an increasing crash rate for low values of speed differential. It is therefore necessary to bound the expression at the minimum value of the quadratic and assume that for speed differentials below this value, the crash rates will remain constant.

Table 4.1 Correlation of crash measures and measures of speed within curves.

Exposure measure	Crash measure	Statistic*	Mean speed of subjects over entire curve less design speed	Minimum speed of subjects in curve less design speed	Minimum three-point mean speed of subjects in curve less design speed	Mean 85th percentile Speed over entire curve less design speed	Minimum 85th percentile speed in curve less design speed	Minimum three-point 85th percentile speed in curve less design speed
Total vehicles entering the curves	Curve injury	Pearson correlation	.622	.682	.691	.560	.513	.488
		Sig. (1-tailed)	.068	.046	.043	.058	.079	.091
		N	7	7	7	9	9	9
	All curve	Pearson correlation	.673	.616	.629	.549	.816	.801
		Sig. (1-tailed)	.034	.052	.047	.050	.004	.005
		N	8	8	8	10	9	9
	Lost control injury	Pearson correlation	.492	.842	.852	.493	.569	.553
		Sig. (1-tailed)	.108	.009	.007	.074	.043	.049
		N	8	7	7	10	10	10
	All lost control.	Pearson correlation	.820	.732	.744	.790	.520	.517
		Sig. (1-tailed)	.006	.019	.017	.003	.062	.063
		N	8	8	8	10	10	10
Total vehicle kilometers of travel negotiating the curves	Curve injury crashes	Pearson correlation	.807	.854	.855	.713	.602	.515
		Sig. (1-tailed)	.014	.007	.007	.016	.043	.078
		N	7	7	7	9	9	9
	All curve crashes	Pearson correlation	.775	.758	.762	.642	.822	.755
		Sig. (1-tailed)	.012	.015	.014	.023	.003	.009
		N	8	8	8	10	9	9
	Lost control injury crashes	Pearson correlation	.617	.889	.887	.589	.769	.712
		Sig. (1-tailed)	.052	.004	.004	.036	.005	.010
		N	8	7	7	10	10	10
	All lost control crashes	Pearson correlation	.774	.756	.756	.714	.697	.719
		Sig. (1-tailed)	.012	.015	.015	.010	.012	.010
		N	8	8	8	10	10	10

* Grey highlight indicates significant correlations (p <0.05).

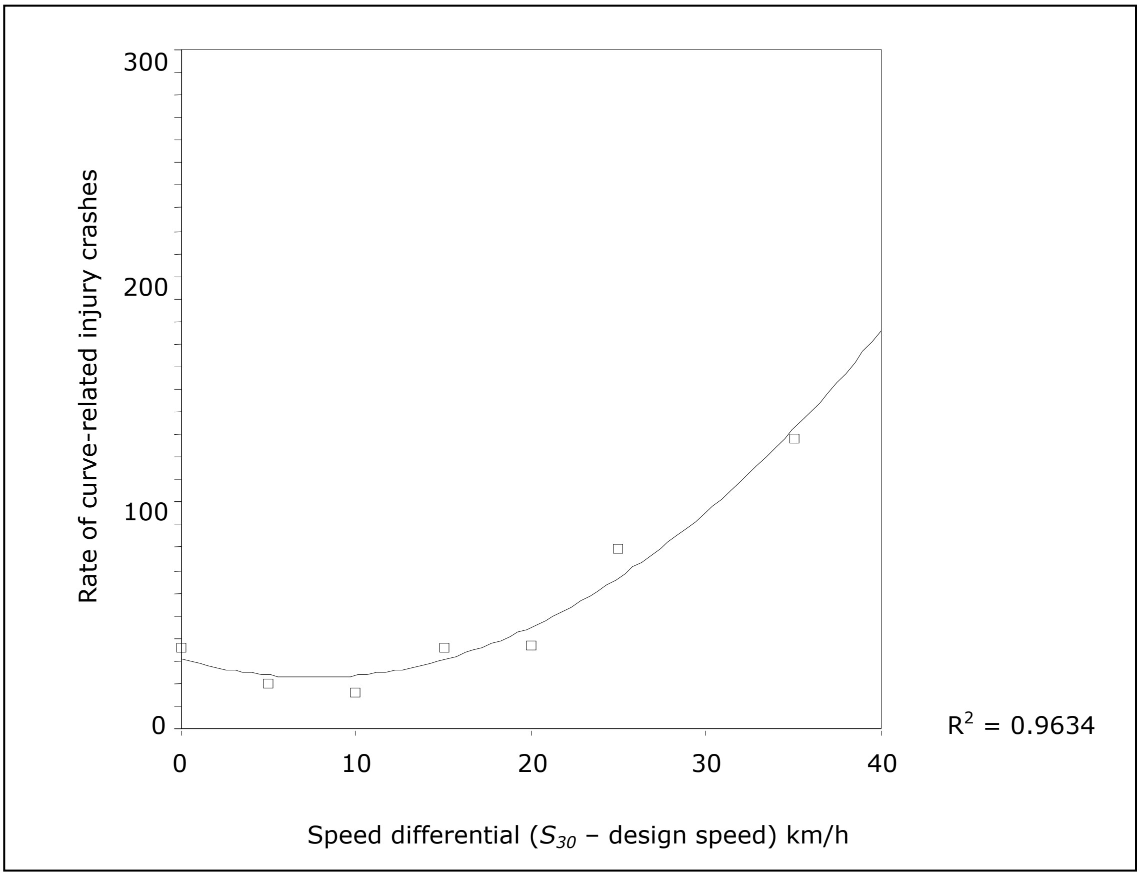


Figure 4.1 The rate of curve-related injury crashes (crashes/100 million vehicle-kilometres of travel through curves) v. speed differential.

Table 4.2 Models relating crash rate (crashes/100 million vehicle-km of travel) to the difference between the minimum mean negotation speed of subject drivers' measured over 30 m (*minS₃₀*) and design speed.

Crash set	Y=aX²+bX+c			R^2	F (df)	Lower bound	Minimum crash rate (crashes per 100 million vehicle-km)
	a	b	c				
Curve injury crashes	0.1461	-2.2205	30.9842	0.963	52.66 (4)	7.6	22.55
All curve crashes	0.1407	1.3915	46.3244	0.950	38.12 (4)	-4.9	42.88
All lost control injury crashes	0.3517	-4.9947	69.9197	0.990	199.4 (4)	7.1	52.19
All lost control crashes	0.3785	-2.7560	82.8552	0.992	249.2 (4)	3.6	77.84

The strong relationship between the subjects' speed choice and crash rates supports the decision of the research steering group to focus on the younger higher risk drivers. However, it does not assist in the development of predictive models for general analysis where data are unlikely to be collected for such a specific group of drivers.

When it came to fitting predictive relationships to the speed differential data based on measures of the 85th percentile speeds rather than observed data, the results were not particularly satisfactory. This was a little surprising, given the good fit obtained for relationships based on the mean speed of the subjects, and the strong relationship between the subjects' speed profiles and the 85th percentile speeds.

The results for speed measures based on the 85th percentile speeds were extremely sensitive to how the curves and crashes were allocated to the various bins. In a number of cases, calculating the speed differential on the basis of the 85th percentile speeds resulted in one or more curves being allocated to an adjacent 'bin'. This seriously distorted the results.

Although a number of trials were undertaken using different bin sizes, improved fitting in one part of the relationship resulted in a poorer fit in another part of the relationship.

On this basis, it must be concluded that while the approach to predicting crashes shows potential, a larger dataset is required to produce robust results. Although the possibility of including a ten-year crash history was investigated, this was discarded because of concerns regarding:

- changes in road alignment,
- the impact of the general downward trend in free speeds over the past decade, and
- difficulties in obtaining a complete set of traffic volumes for analysis.

Further research is recommended in this area, using a larger sample set. A larger sample set will enable full crash prediction models (using GLMs) to be fitted.

4.2 The relationship between road geometry and speed

4.2.1 Aims of the analysis

This second set of analyses seeks to investigate how road geometry affects the speed choices made by drivers. A number of researchers (Emmerson 1970, McLean 1991, Bennett 1994) have suggested that the speed at which a driver chooses to negotiate a particular curve is based on:

- their perception of the curve, and
- the context of the curve, i.e. the surrounding speed environment.

This section of the analysis begins by investigating the issue of speed environment, seeking to identify the geometrical characteristics that most influence drivers' speed choices on a given section of road.

The second part of the analysis looks at drivers' speed choices as they relate to a specific curve.

4.2.2 The relationship between road geometry and operating speed

New Zealand highway design uses the concept of speed environment to co-ordinate the design speed of geometric elements along the highway. While the speed environment is defined as the 85th percentile speed of free vehicles on straights or large radius curves, such features are relatively scarce in tortuous alignments. Anecdotal evidence suggests that in many cases, the speed environment is only subjectively assessed.

In this analysis, we investigate the relationship between the 85th percentile free speed (V), as estimated from the data collected for the sample of drivers who travelled the route and three measures that characterise the horizontal alignment:

- advisory speed (AS_{RGDAS}) – RGDAS advisory speed (km/h), as defined in Equation 1,
- bendiness (B) – the degrees of deviation per km, and
- Mean radius (R) – where straights are defined as radius =1000.

We investigated the performance of each measure over four distances 500 m, 1000 m, 2000 m and 3000 m immediately upstream of each curve. Scatter plots of the twelve relationships investigated are contained in Appendix C. These indicate that:

- the strongest relationships between the mean 85th percentile speed and road geometry occur over analysis lengths of 500 m and 1000 m (upstream of the start of each curve); and
- the best predictive relationships are likely to based on highway bendiness (B) and the AS_{RGDAS}.

Scatter plots of these four relationships are presented below in Figure 4.2, Figure 4.3, Figure 4.4 and Figure 4.5.

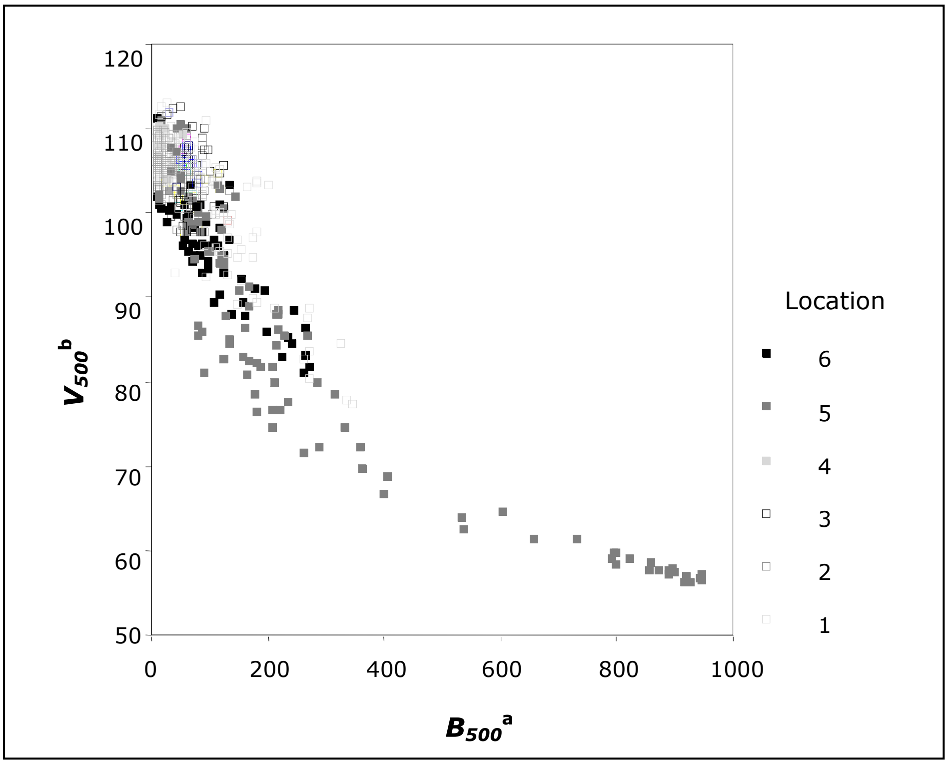


Figure 4.2 The relationship between highway 'bendiness' (degrees/km) and 85th percentile speed over 500 m.

Notes to Figure 4.2:

a The deflection angle of the curve in absolute degrees of horizontal deviation per kilometre measured over 500 m.

b The estimated 85th percentile speed averaged over 500 m approaching the curve.

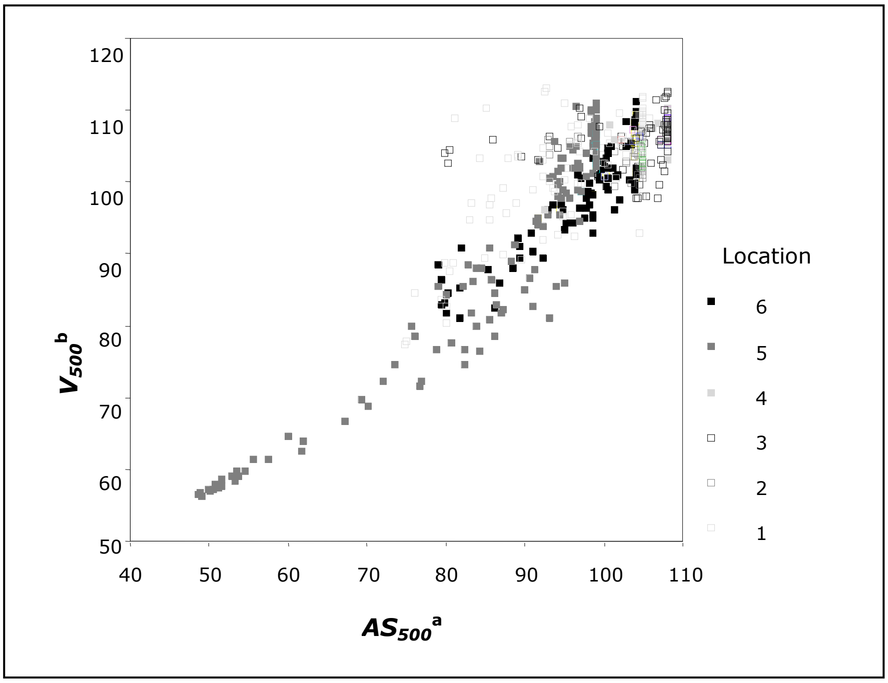


Figure 4.3 The relationship between the advisory speed AS_{RGDAS} and 85th percentile speed over 500 m.

Notes to Figure 4.3:

a AS_{RGDAS} (calculated using Equation 1)averaged over the 500 m approaching the curve.

b Estimated 85th percentile speed averaged over the 500 m approaching the curve.

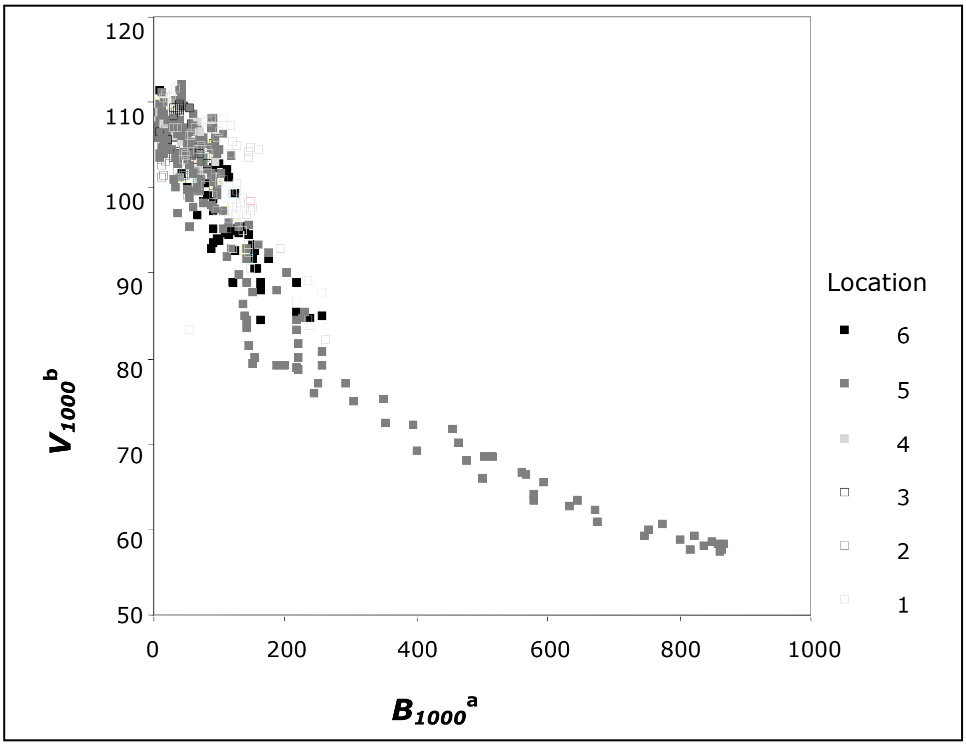


Figure 4.4 The relationship between highway 'bendiness' (degrees/km) and 85^{th} percentile speed over 1000 m.

Notes to Figure 4.4:

a Deflection angle of the curve in absolute degrees of horizontal deviation per kilometre measured over 1000 m.

b Estimated 85^{th} percentile speed averaged over the 1000 m approaching the curve.

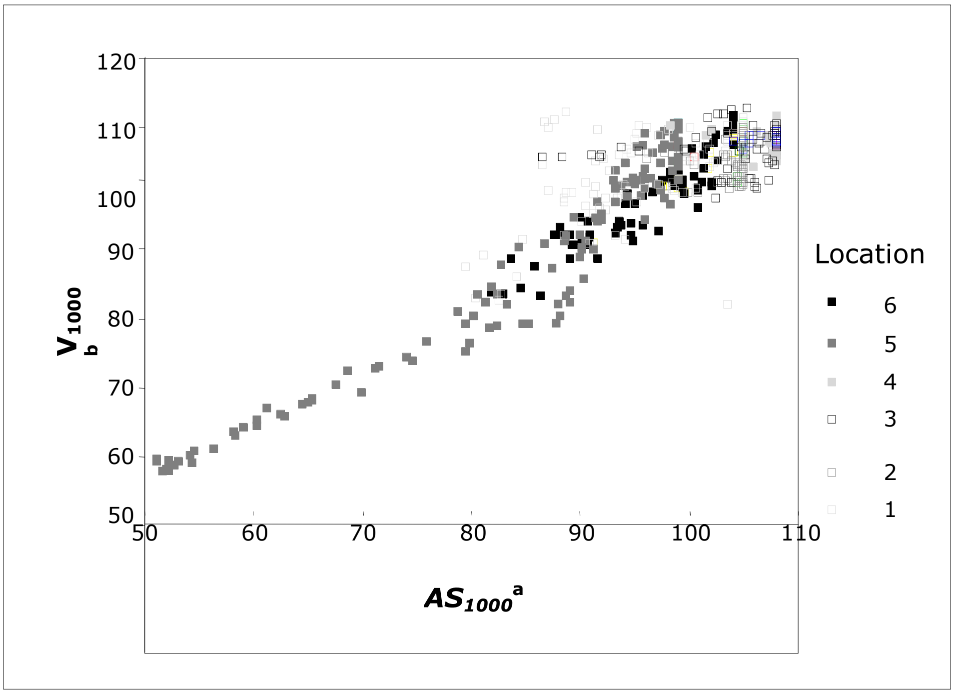


Figure 4.5 The relationship between the advisory speed AS_{RGDAS} and 85^{th} percentile speed over 1000 m.

Notes to Figure 4.5:

a AS_{RGDAS} (calculated using Equation 1) averaged over the 1000 m approaching the curve.

b Estimated 85^{th} percentile speed averaged over the 1000 m approaching the curve.

A series of relationships was then fitted to the data. Although a wide range of models were considered, the best fit for 'bendiness' was a quadratic model, while an *S* model provided the best fit for the relationship based on AS_{RGDAS}. These models and the best fitting linear models are given in Table 4.3, along with model R^2 and F statistics, and associated degrees of freedom for the model.

Table 4.3 Models relating speed environemnt (85th percentile speed or *V*) to road geometry.

Dependent variable (*Y*)	Independent variable (*X*)	Model form	a	b	c	R^2	F (df)
V_{500}	B_{500}	$Y = aX^2 + bX + c$	0.000066	-0.1179	109.565	0.860	1475 (482)
		$Y = bX + c$	–	-0.633	106.113	0.800	1929 (483)
V_{1000}	B_{1000}	$Y = aX^2 + bX + c$	0.000075	-0.1243	110.425	0.894	1992 (474)
		$Y = bX + c$	–	-0.699	106.967	0.838	2465 (475)
V_{500}	AS_{500}	$Y = bX + c$	–	0.8667	15.4414	0.824	2254 (483)
		$Y = cX^b$	2.1019	0.8432	–	0.865	3101 (483)
V_{1000}	As_{1000}	$Y = bX + c$	–	0.8933	13.1224	0.845	2583 (475)
		$Y = cX^b$	1.8347	0.8735	–	0.883	3597 (475)

4.2.3 The relationship between curve geometry and curve speed

This analysis investigates the relationship between curve negotiation speed and curve geometry. The analysis considers a range of curve speed measures for the sample drivers and the estimated 85th percentile speed of the population, and relates both of these to:

- curve deflection in degrees of horizontal deviation,
- curve design speed, and
- curve radius measures.

Although statistically significant relationships were found between the total curve deflection (a measure that combines radius and curve length) and the various curve speed measures, these relationships accounted for only around 40% of the variation between the two variables (see Figure 4.6 and Table 4.3).

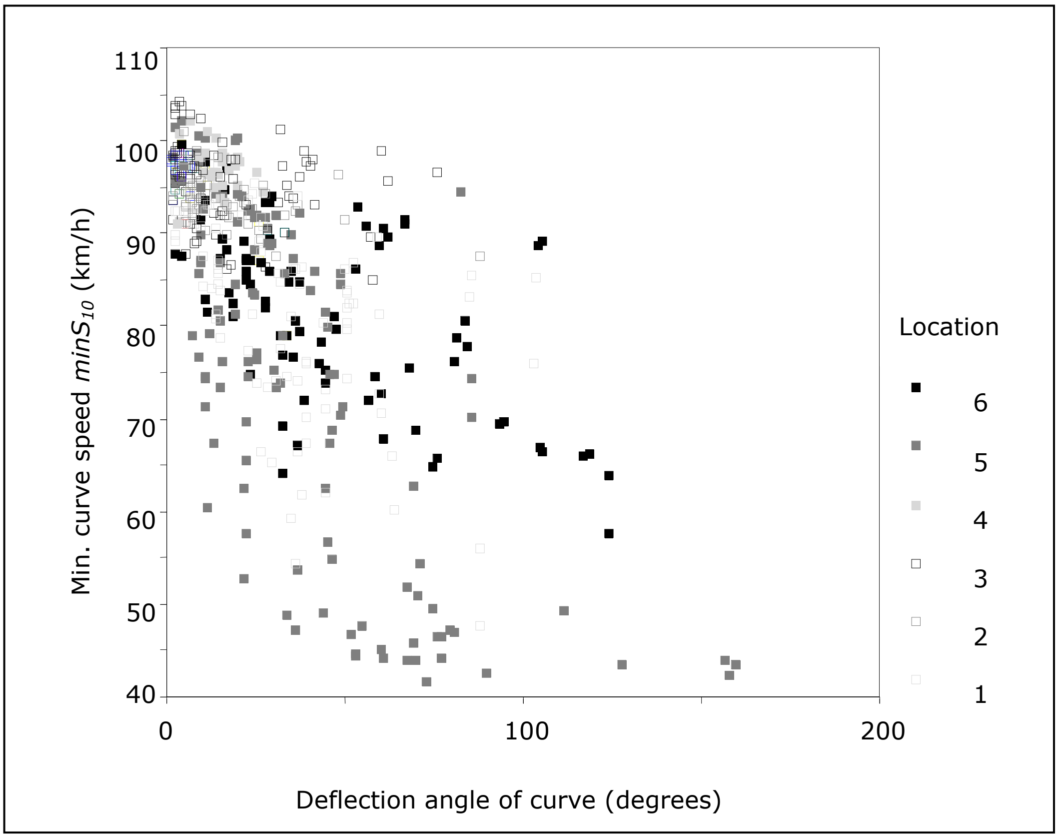


Figure 4.6 Minimum speed of sample drivers negotiating each curve v. deflection angle of curve.

Table 4.3 Predictive relationships of negotiation speed based on curve deflection angle.

Independent variable	Dependent variable	R^2	F statistic (486 df.)	p	Model parameters *Y= c + bx*	
					c	*b*
Curve deflection angle (degrees)	Mean speed over entire curve (S_c)	0.413	342	<0.001	95.811	-0.3189
	Minimum speed within curve ($minS_{10}$)	0.442	385	<0.001	95.375	-0.3487
	Minimum three-point mean speed ($minS_{30}$)*	0.441	383	<0.001	95.411	-0.3475
Curve deflection angle (degrees)	Mean 85th percentile speed over entire curve (V_c)	0.403	328	<0.001	106.71	-0.3041
	Minimum 85th percentile speed within curve ($minV_{10}$)	0.433	372	<0.001	105.750	-0.3329
	Minimum three-point mean 85th percentile speed ($minV_{30}$)*	0.432	370	<0.001	105.79	-0.3318

* This is the minimum value of S_{30} or V_{30} within the length of the curve, where S_{30} and V_{30} are the mean speeds measured over three consecutive readings taken at 10 m intervals.

After discounting curve deflection as a reliable predictor of curve negotiation speed, the analysis focused on curve design speed and curve radius. Although curve radius plays a major part in determining the design speed, Figure 4.7 shows that for any particular radius, the design speed can vary significantly, depending on the super-elevation of the curve and the available side friction.

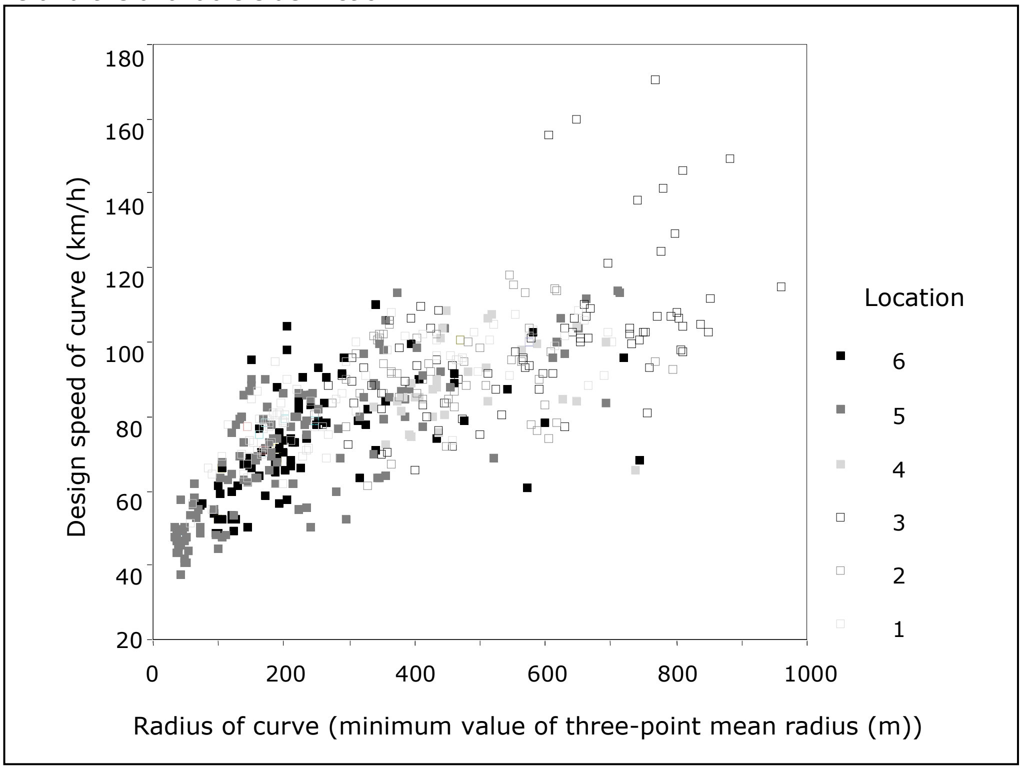


Figure 4.7 Curve design speed v. curve radius.

Although statistically significant models relating the theoretical design speed of each curve to various measures of negotiation speed are provided in Table 4.4, each still accounts for only around 65% of the variance (see Figure 4.8). It is interesting to note that in general, stronger relationships occur between design speed and the estimated 85th percentile speeds than between the mean speed of the sample drivers. This reflects the fact that design speed is intended to be the 85th percentile speed.

Table 4.4 Predictive relationships of negotiation speed based on curve design speed.

Independent variable	Dependent variable	R^2	F statistic (486 df.)	p	Model parameters $Y= e^{(c + b/X)}$	
					c	*b*
Curve design speed (km/h)	Mean speed over entire curve (S_c)	0.632	779	<0.001	5.0330	-44.988
	Minimum speed within curve ($minS_{10}$)	0.638	800	<0.001	5.0638	-48.686
	Minimum three-point mean speed ($minS_{30}$)*	0.638	799	<0.001	5.0623	-48.507
Curve design speed (km/h)	Mean 85th percentile speed over entire curve (V_c)	0.655	862	<0.001	5.0733	-38.727
	Minimum 85th percentile speed within curve ($minV_{10}$)	0.661	887	<0.001	5.0972	-41.678
	Minimum three-point mean 85th percentile speed ($minV_{30}$)*	0.661	885	<0.001	5.0961	-41.540

* This is the minimum value of S_{30} or V_{30} within the length of the curve, where S_{30} and V_{30} are the mean speeds measured over three consecutive readings taken at 10 m intervals.

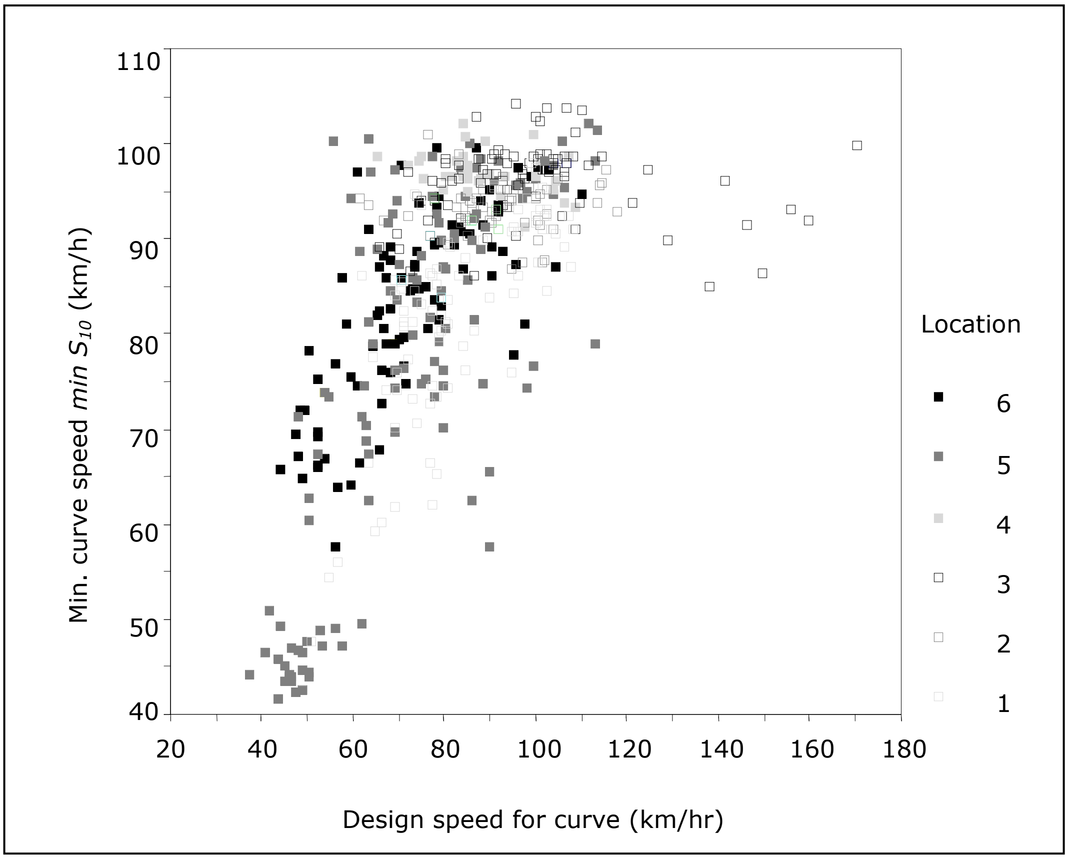


Figure 4.8 Minimum curve negotiation speed by sample drivers (min S_{10}) v. curve design speed (km/h).

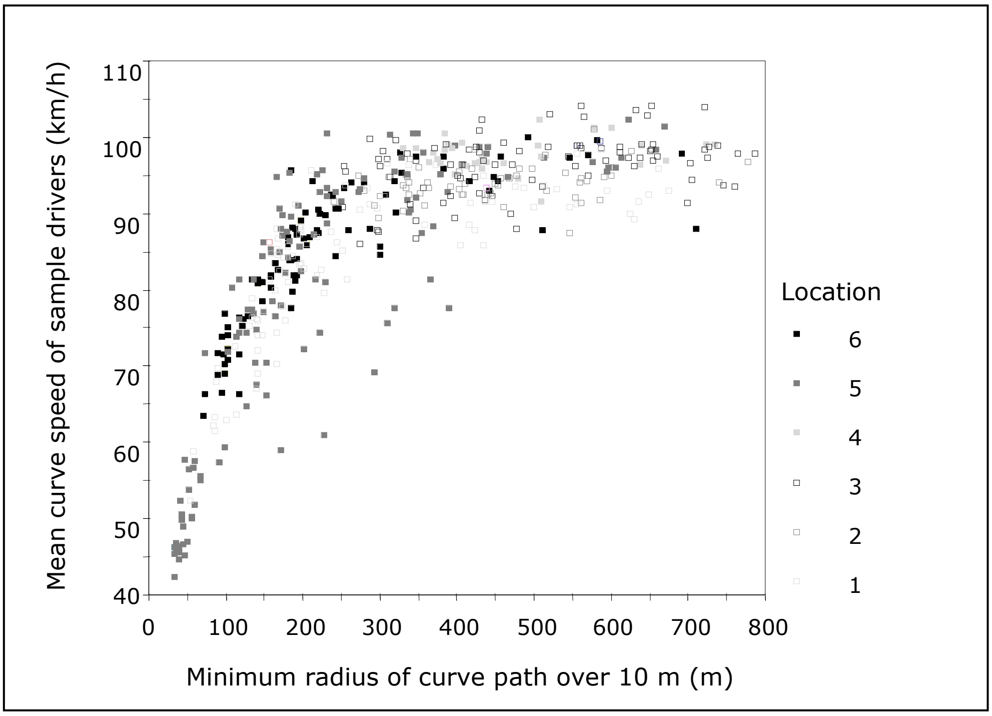


Figure 4.9 Mean speed through curve from sample drivers (km/h) v. minimum curve radius (m).

Finally in this part of the research, the relationship between curve radius and negotiation speed was investigated. Two of the three sets of predictive models described in Table 4.5, those based on the minimum curve radius and the minimum three-point mean curve radius, accounted for all but approximately 13% of the variability in the dependent variable. While the strongest relationship is between the minimum curve radius and the mean negotiation speed (Figure 4.10), this is only marginally better than others in these two groups, and the model coefficients are similar across the two sets of models.

The speed at which the sample drivers chose to negotiate a particular curve was mainly governed by the radius of that curve. Although interesting, this finding is not particularly useful in terms of being able to assess the likely negotiation speed adopted by the population as a whole. This will be best represented by the relationship between curve radius and the estimated 85th percentile speed parameter.

Table 4.5 Predictive models of curve negotiation speed by sample drivers as a function of curve radius.

Independent variable	Dependent variable	R^2	F statistic (486 df.)	p	Model parameters $Y = e^{(c + b/X)}$	
					c	*b*
Mean curve radius (over entire curve)	Mean speed over entire curve (S_c)	0.801	1961	<0.001	4.6797	-78.603
	Minimum three-point mean speed ($minS_{30}$)[a]	0.795	1881	<0.001	4.6793	-84.359
	Minimum speed within curve ($minS_{10}$)[b]	0.793	1867	<0.001	4.6791	-83.988
Minimum three-point curve radius ($minR_{30}$)	Mean speed over entire curve (S_c)	0.869	3230	<0.001	4.6138	-33.248
	Minimum three-point mean speed ($minS_{30}$)[a]	0.867	3165	<0.001	4.6091	-35.785
	Minimum speed within curve ($minS_{10}$)[b]	0.866	3133	<0.001	4.6093	-35.633
Minimum curve radius ($minR_{10}$)	Mean speed over entire curve (S_c)	0.873	3343	<0.001	4.6144	-32.009
	Minimum three-point mean speed ($minS_{30}$)[a]	0.869	3237	<0.001	4.6097	-34.426
	Minimum speed within curve ($minS_{10}$)[b]	0.868	3207	<0.001	4.6098	-34.281

Notes to Table 4.5:

a This is the minimum value of S_{30} or V_{30} within the length of the curve, where S_{30} and V_{30} are the mean speeds measured over three consecutive readings taken at 10 m intervals.

b This is the minimum value of S_{10} or V_{10} within the length of the curve, where S_{10} and V_{10} are the mean speeds measured over 10 m.

The relationships between curve radius and the negotiation speed likely to be adopted by the 85th percentile driver are almost as strong as those for our sample drivers, and again relationships based on the minimum recorded curve radius are the strongest (Table 4.6).

Table 4.6 Predictive models of 85th percentile curve negotiation speed as a function of curve radius.

Independent variable	Dependent variable	R^2	F statistic (486 df.)	p	Model parameters $Y= e^{(c+b/X)}$	
					c	*b*
Mean curve radius (over entire curve)	Mean 85th percentile speed over entire curve (V_c)	0.794	1878	<0.001	4.7636	-65.900
	Minimum three-point mean 85th percentile speed ($minV_{30}$)[a]	0.788	1807	<0.001	4.7624	-70.140
	Minimum 85th percentile speed within curve ($minV_{10}$)[b]	0.789	1821	<0.001	4.7625	-70.423
Minimum three-point curve radius ($minR_{30}$)	Mean 85th percentile speed over entire curve (V_c)	0.864	3096	<0.001	4.7086	-27.918
	Minimum three-point mean 85th percentile speed ($minV_{30}$)[a]	0.862	3038	<0.001	4.7042	-29.796
	Minimum 85th percentile speed within curve ($minV_{10}$)[b]	0.863	3070	<0.001	4.7041	-29.913
Minimum curve radius ($minR_{10}$)	Mean 85th percentile speed over entire curve (V_c)	0.869	3226	<0.001	4.7092	-26.891
	Minimum three-point mean 85th percentile speed ($minV_{30}$)[a]	0.866	3131	<0.001	4.7048	-28.680
	Minimum 85th percentile speed within curve ($minV_{10}$)[b]	0.867	3162	<0.001	4.7046	-28.791

Notes to Table 4.6:

a This is the minimum value of S_{30} or V_{30} within the length of the curve, where S_{30} and V_{30} are the mean speeds measured over three consecutive readings taken at 10 m intervals.

b This is the minimum value of S_{10} or V_{10} within the length of the curve, where S_{10} and V_{10} are the mean speeds measured over 10 m.

However, as demonstrated in Figure 4.10, the 85th percentile speeds for a number of curves are far lower than those recorded at other curves of similar radii. Clearly, some other factors are affecting speeds through these lower speed curves. In order to investigate this possibility, the data were screened and those curves where the residuals (the difference between the actual values of the mean 85th percentile speed over the entire curve (V_c) and the predicted mean 85th percentile speed using the minimum curve radius ($minR_{10}$)) exceed 10 km/h were removed.

The fit of the resulting models improved dramatically, with all models accounting for more than 90% of the variation in the datasets, as shown in Table 4.7. Furthermore, the practical differences between the prediction models for the minimum 85th percentile speed *($minV_{10}$)* and the minimum value of the three-point mean 85th percentile speed *($minV_{30}$)* became negligible. An interesting feature of Figure 4.10 is that negotiation speeds do not begin to drop until the curve radius falls below 300 m.

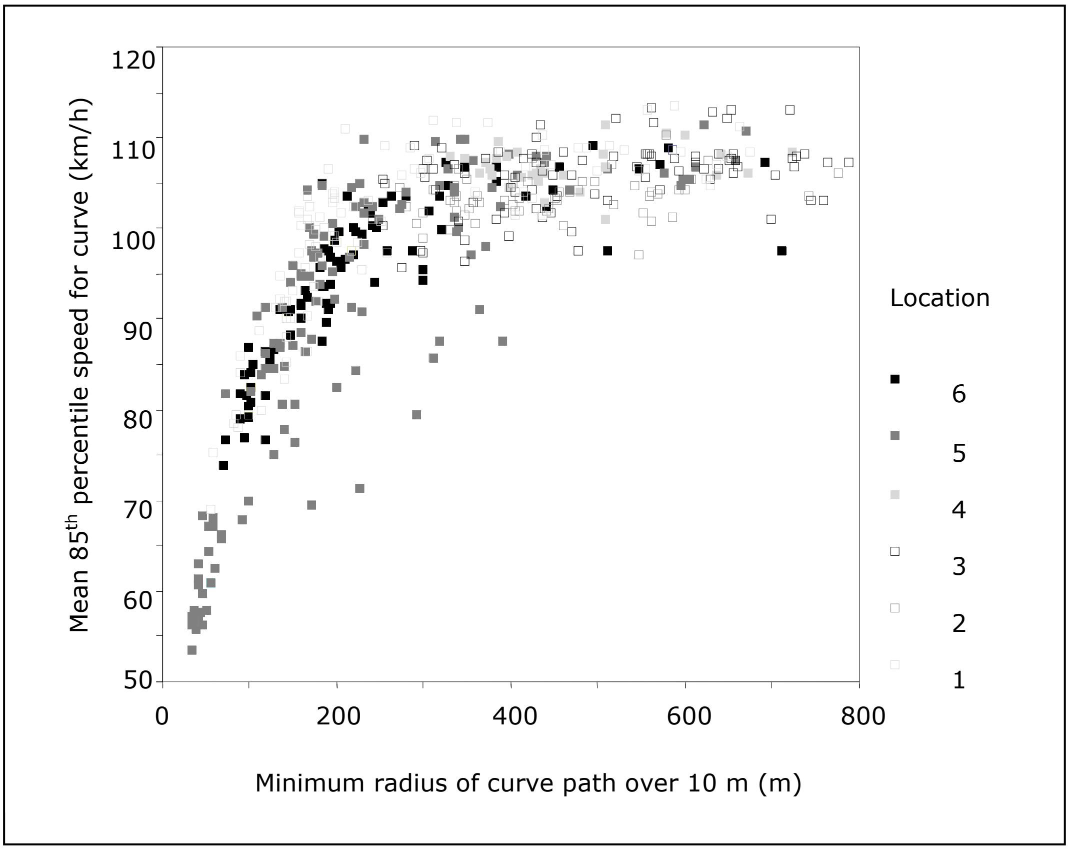


Figure 4.10 Mean 85th percentile speed throughout curve (V_c) v. minimum radius of curve path.

Table 4.7 Predictive models of 85th curve negotiation speed as a function of curve radius (following removal of outliers).

Independent variable	Dependent variable	R^2	F statistic (465 df.)	p	Model parameters $Y= e^{(c + b/X)}$	
					c	*b*
Minimum three-point curve radius($minR_{30}$)	Mean 85th percentile speed over entire curve (V_c)	0.917	5163	<0.001	4.7135	-27.752
	Minimum three-point mean 85th percentile speed ($minV_{30}$)[a]	0.913	4905	<0.001	4.7094	-29.599
	Minimum 85th percentile speed within curve ($minV_{10}$)[b]	0.914	4963	<0.001	4.7092	-29.715
Minimum curve radius ($minR_{10}$)	Mean 85th percentile speed over entire curve (V_c)	0.923	5551	<0.001	4.7142	-26.736
	Minimum three-point mean 85th percentile speed ($minV_{30}$)[a]	0.917	5164	<0.001	4.7100	-28.495
	Minimum 85th percentile speed within curve ($minV_{10}$)[b]	0.918	5220	<0.001	4.7098	-28.605

Notes to Table 4.7:

a This is the minimum value of S_{30} or V_{30} within the length of the curve, where S_{30} and V_{30} are the mean speeds measured over three consecutive readings taken at 10 m intervals.

b This is the minimum value of S_{10} or V_{10} within the length of the curve, where S_{10} and V_{10} is the mean speed measured over 10 m.

4.2.4 Overall curve speed model

Given that this phase of the study intended to produce a model for predicting the expected 85th percentile curve negotiation speed, the most powerful predictive model, which predicts the mean 85th percentile speed over the entire curve (V_c) based on the minimum radius within the curve, has been selected.

The residuals of the fitted model were subsequently investigated. Correlations between the residual values and measures of the approach speed environment were identified, and a series of linear regression analyses were undertaken to identify the best model for predicting the mean 85th percentile speed adopted by drivers negotiating a particular curve.

The resulting model included terms representing the curve radius and the approach speed environment:

$$Vc = -24.967 + 0.397V_{500} + 0.741e^{(4.7142 - 26.736/R)} \quad \text{[Equation 5]}$$

Where:

- V_c = the (average) 85th percentile speed around the curve (km/h),
- V_{500} = the average 85th percentile speed over the previous 500 m (km/h),
- R = the (minimum) radius of the curve (m).

And:

$$V_{500} = 0.000066(B_{500})^2 - 0.1179\,B_{500} + 109.565 \text{ for } 8 < B_{500} < 900 \quad \text{[Equation 6]}$$

Or:

$$V_{500} = 2.1019(AS_{500})^{0.8432} \quad \text{[Equation 7]}$$

The summary statistics for this model and a simplified model which only involved the radius of the curve under consideration are given in Table 4.8.

Table 4.8 Summary statistics of curve speed prediction model.

Model	Adjusted R^2	df regression (residual)	F	Model parameters				
				Terms	Coefficients	Std. error	*t*	Sig.
1	0.853	1 (483)	2801.4	(Constant)	-17.665	1.985	-8.901	.000
				$e^{(4.7142 - 26.736/R)}$	1.066	.020	52.929	.000
2	0.904	2 (482)	2279.4	(Constant)	-24.967	1.665	-14.996	.000
				$e^{(4.7142 - 26.736/R)}$	.741	.026	28.537	.000
				V_{500}	.397	.025	16.103	.000

Using this model, safety analysts and designers can compute the likely 85th percentile curve negotiation speed for passenger cars. This value can be compared to the design speed of the curve. The expected rate of curve-related injury crashes can be calculated based on the relationship outlined in Chapter 4.1.

While the model form is similar to that used by Transit New Zealand (Transit New Zealand 2003) when designing rural road alignments, a comparison of Figure 4.11 and Figure 4.12 suggests the new model presented here covers a far narrower band of predicted speeds.

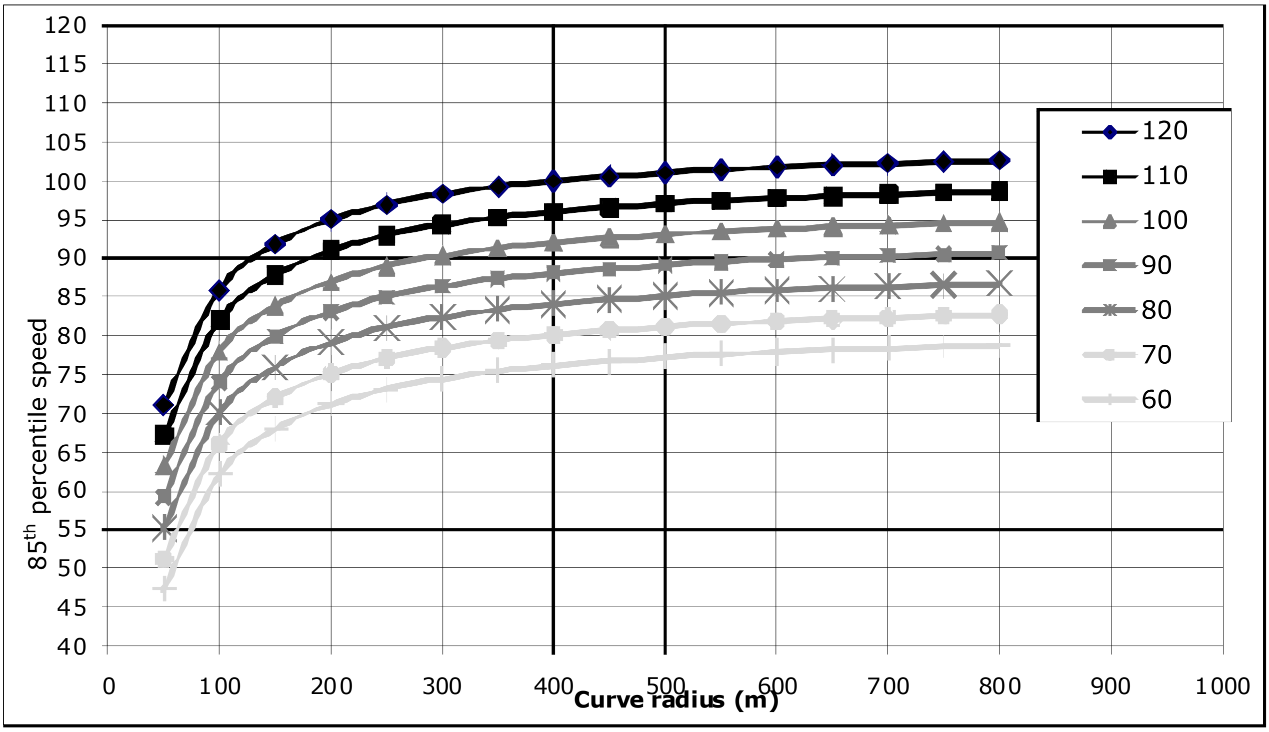


Figure 4.11 Relationship between 85^{th} percentile speed and curve radius developed by this model.

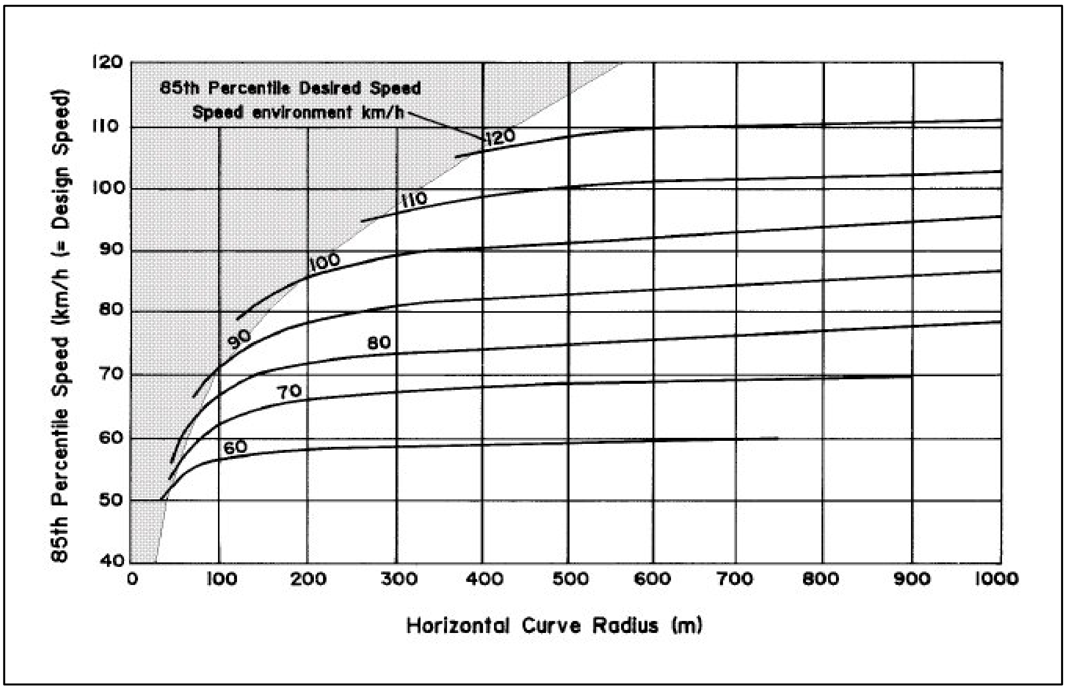


Figure 4.12 Transit New Zealand curve speed model (Transit New Zealand 2003).

These differences show that when travelling in speed environments below 100 km/h, drivers are seeking to negotiate curves at higher speeds than are assumed in the design code. This is of concern and should be investigated further, and the approach to design amended accordingly.

5. Assessing improvement options

In this chapter, we look at how the results of this research may be applied to identify improvements and benefits for two of the highway sections considered in the study. Unfortunately, the inability to identify a robust relationship between the crash rates and the speed differential (the difference between the 85th percentile negotiation speed and the design speed) has precluded such an analysis.

However, given the high likelihood that a robust relationship could be defined with a larger crash dataset, the alternative is to describe how this could be analysed. We will illustrate this process using an example based on the crash relationships derived by using the speeds of sample drivers.

1. **Determine the curve negotiation speed:** The curve negotiation speed approaching from either direction may be either measured or estimated. The actual 85th percentile speed of free vehicles (those not constrained by other traffic) may be measured by using a laser speed gun or suitable traffic classifier. Alternatively, it can be estimated from highway geometry data including the radius of the curve under consideration and the bendiness of the approaching 500 m of highway using Equations 5, 6 and 7.
2. **Determine the safe speed:** Using the curve geometry data (radius and crossfall) and the approach speed environment, determine the curve design speed using Equation 4.
3. **Determine the speed differential:** Calculate the speed differential, the difference between the curve negotiation speed (Step 1) and the safe speed (Step 2).
4. **Determine the expected crashes:** Calculate the traffic exposure as the length of the curve in kilometres times the annual average daily traffic divided in half (assuming a 50/50 directional split). Use the crash rate equation and speed differential to calculate the expected number of crashes.
5. **Determine the benefits of an improvement:** Repeat Steps 3 and 4 based on the expected change in safe speed or negotiating speed.

Our example is based on State Highway (SH) 75 (Location 6), for which we have identified a total of 46 curves. The 'safety' of each curve has been assessed based on the speed differential, the difference between the minimum value of the mean speed over 30 m from the subject drivers (S_{30}) and the assessed design speed. In Table 5.1 (decreasing route position) and Table 5.2 (increasing route position), the curves have been ranked in terms of the current speed differential (Diff).

Table 5.1 SH75 (Location 6) curves requiring improvements (decreasing direction).

RS[a]	Start	End	Radius (m)	Design speed (km/h)	Subject speed (km/h)	Speed differential (km/h)	VKT[b] in curve	Crash Type 1[c]	Crash Type 2[d]	Rank
14	1160	1210	435	74	94	19.5	0.0014	0.0294	0.0769	10
14	1520	1620	99	49	72	23.7	0.0028	0.1065	0.2726	3
14	3490	3580	197	74	87	13.5	0.0025	0.0130	0.0369	18
14	3710	3840	189	69	79	9.9	0.0037	0.0029	0.0104	29
14	3880	4100	104	48	70	22.1	0.0062	0.1895	0.4882	5
14	4520	4620	210	68	89	21.1	0.0028	0.0756	0.1955	8
14	4880	5050	128	61	75	13.4	0.0048	0.0235	0.0668	19
14	5440	5570	148	69	79	10.2	0.0037	0.0038	0.0128	26
14	5790	5920	121	54	74	20.3	0.0037	0.0867	0.2254	9
14	6030	6120	121	52	69	17.0	0.0025	0.0326	0.0871	11
14	6220	6410	100	44	66	21.8	0.0054	0.1585	0.4087	6
14	7370	7540	264	78	93	15.3	0.0048	0.0411	0.1122	14
24	390	650	100	52	66	13.5	0.0064	0.0332	0.0940	17
24	3620	3800	171	59	81	22.7	0.0045	0.1481	0.3806	4
24	4230	4330	197	73	87	13.7	0.0025	0.0136	0.0384	16
24	5000	5150	166	70	80	9.3	0.0037	0.0016	0.0065	31
24	5430	5580	143	50	78	28.0	0.0037	0.2250	0.5686	2
24	6420	6450	541	87	100	12.6	0.0007	0.0027	0.0079	21
24	8760	8870	191	68	83	14.7	0.0027	0.0199	0.0550	15
24	9260	9530	150	66	76	9.8	0.0067	0.0049	0.0177	30
35	1150	1320	200	70	86	15.6	0.0042	0.0399	0.1082	13
35	2380	2640	94	54	67	13.3	0.0064	0.0310	0.0882	20
35	2670	2770	215	73	85	11.8	0.0025	0.0064	0.0194	23
35	2870	2950	210	67	88	21.4	0.0020	0.0548	0.1416	7
35	3050	3130	202	66	83	16.9	0.0020	0.0249	0.0665	12
35	3430	3530	325	78	89	11.4	0.0025	0.0053	0.0163	24
35	3580	4040	329	82	92	10.0	0.0114	0.0093	0.0328	28
35	4400	4440	573	61	97	36.1	0.0010	0.1176	0.2931	1
35	5150	5320	214	73	85	11.9	0.0042	0.0114	0.0342	22
35	6420	6570	220	82	93	11.4	0.0037	0.0077	0.0239	25
35	7020	7210	106	59	69	10.0	0.0047	0.0041	0.0142	27
							ANNUAL TOTAL	1.5249	4.0007	–

Notes to Table 5.1:
a RS = route station
b VKT = vehicle-kilometres of travel along a given curve.
c Crash Type 1 is the annual number of reported injury crashes involving loss of control or head-on movements on curves (crash types BB, BC, BD, BF, DA and DB – see Appendix D for the full list of CAS definitions).
d Crash Type 2 is the annual number of reported injury crashes involving loss of control or head-on movements. It includes all Type 1 crashes and crash types BA, BE, CA, CB and CC.

The predicted annual injury crash reduction has been based on the assumption that measures undertaken to treat these sites will result in a zero speed differential and it assumes no increase in traffic volume. If all of the curves identified in Tables 5.1 and 5.2 were treated, we could expect a reduction of 3.6 reported Type 1 injury crashes (those involving loss of control and head-on crashes occurring on curves), or 9.4 Type 2 injury crashes (all loss of control and head-on crashes) each year for this nominally 20 km section of highway.

Table 5.2 SH75 (Location 6) curves requiring improvements (increasing direction).

RS[a]	Start	End	Radius (m)	Design speed (km/h)	Subject speed (km/h)	Speed differential (km/h)	VKT[b] in curve	Crash Type 1[c]	Crash Type 2[d]	Rank
14	1200	1250	476	79	94	15.6	0.0014	0.0131	0.0355	17
14	1560	1650	96	48	67	19.2	0.0025	0.0502	0.1315	11
14	3520	3630	225	66	87	21.0	0.0031	0.0814	0.2108	8
14	3750	3880	192	56	77	20.5	0.0037	0.0886	0.2302	9
14	3920	4150	99	52	70	17.7	0.0065	0.0972	0.2577	13
14	4560	4650	206	58	86	28.4	0.0025	0.1603	0.4046	1
14	4920	5080	124	49	72	23.0	0.0045	0.1565	0.4016	6
14	5480	5610	139	67	79	12.0	0.0037	0.0103	0.0307	23
14	5820	5960	128	52	75	23.0	0.0040	0.1370	0.3515	5
14	6270	6440	96	49	65	16.1	0.0048	0.0510	0.1375	16
14	7420	7570	241	83	91	8.2	0.0042	0.0003	0.0019	28
24	410	700	104	52	66	13.8	0.0072	0.0404	0.1137	20
24	2160	2490	234	74	89	14.6	0.0082	0.0589	0.1627	19
24	3660	3840	174	71	80	8.7	0.0045	0.0007	0.0038	27
24	4260	4360	192	76	85	9.2	0.0025	0.0009	0.0038	26
24	5840	5970	186	67	86	18.6	0.0032	0.0576	0.1516	12
24	6440	6480	598	78	100	21.3	0.0010	0.0272	0.0704	7
24	7590	7660	341	71	98	27.2	0.0017	0.0977	0.2472	3
24	7780	7890	355	84	97	12.8	0.0027	0.0108	0.0312	22
24	8780	8900	188	65	82	17.0	0.0030	0.0386	0.1030	14
24	0	9530	164	64	79	14.8	0.0070	0.0531	0.1461	18
35	1200	1360	211	74	85	10.4	0.0040	0.0046	0.0153	25
35	1710	2030	148	67	81	13.8	0.0080	0.0446	0.1253	21
35	3620	4080	315	63	91	28.0	0.0115	0.6997	1.7676	2
35	4430	4460	554	61	87	26.5	0.0007	0.0390	0.0988	4
35	4530	4550	742	68	88	19.3	0.0005	0.0100	0.0262	10
35	4600	5050	252	79	90	10.5	0.0112	0.0140	0.0461	24
35	7060	7230	103	59	76	16.3	0.0042	0.0467	0.1257	15
							ANNUAL TOTAL	1.5249	4.0007	–

Notes to Table 5.2:

a RS = route station

b VKT = vehicle-kilometres of travel along a given curve.

c Crash Type 1 is the annual number of reported injury crashes involving loss of control or head-on movements on curves (crash types BB, BC, BD, BF, DA and DB – see Appendix D for the full list of CAS definitions).

d Crash Type 2 is the annual number of reported injury crashes involving loss of control or head-on movements. It includes all Type 1 crashes and crash types BA, BE, CA, CB and CC.

The big question is how to improve drivers' speed choices in order to achieve the necessary reduction in speed differential.

6. Conclusions

6.1 Summary

This study has investigated the relationship between road geometry, observed travel speed and crashes, using data collected on six sections of State Highway.
The data included:

- the speed profiles for a sample of young, predominately male drivers;
- the road geometry data (radius of curvature and pavement crossfall) collected at 10 m intervals as part of the annual pavement friction monitoring (SCRIM); and
- crash data

The final dataset contained 488 curves where a total of 89 curve-related injury crashes and 128 non-injury curve-related crashes had been recorded.

The data were used to explore the relationship between road geometry and the speed choices made by the sample drivers. Based on 'calibration' data from a series of traffic speed classifiers, these investigations have been extended to consider the expected 85th percentile speed choice of the wider population.

The speed at which drivers chose to negotiate a particular curve is more strongly related to the radius of the curve than to the design speed. However, the impact of radius on negotiation speed does not generally begin to have an effect until curve radii fall below 300 m.

The best model for predicting the negotiation speed of a particular curve is based on curve radius and a term representing the approach speed environment measured over the preceding 500 m.

The resulting model for predicting 85th percentile speed curve negotiation speed accounts for 85% of the variation in the dependent:

$$V_c = -24.967 + 0.397V_{500} + 0.741e^{(4.7142 - 26.736/R)} \qquad \text{[Equation 5]}$$

Where:

- V_c = the (average) 85th percentile speed around the curve (km/h),
- V_{500} = the average 85th percentile speed over the previous 500 m (km/h),
- R = the (minimum) radius of the curve (m).

Two models were identified as being suitable for predicting the approach speed environment. The first was based on B_{500}, the bendiness ratio (degrees/km) over the preceding 500 m:

$$V_{500} = 0.000066(B_{500})^2 - 0.1179\,B_{500} + 109.565 \text{ for } 8 < B_{500} < 900 \qquad \text{[Equation 6]}$$

The other was based on the mean advisory speed AS_{500}, as predicted by the equation previously developed by Rawlinson (1983):

$$V_{500} = 2.1019(AS_{500})^{0.8432} \qquad \text{[Equation 7]}$$

Where:

- AS_{500} is the mean of the of AS_{RGDAS} over 500 m.

$$AS_{RGDAS} = -\left(\frac{107.95}{H}\right) + \sqrt{\left(\frac{107.95}{H}\right)^2 + \left[\frac{127{,}000}{H}\right]\left[0.3 + \frac{X}{100}\right]} \qquad \text{[Equation 1]}$$

Where:

- AS_{RGDAS} = min RGDAS advisory speed, 106 (km/h),
- X = % crossfall (sign relative to curvature),
- H = absolute curvature (rad/km) = (1000 m/R).

A comparison of the 85th percentile negotiation speeds predicted by this model and the relationship currently used in design of rural roads suggests that for speed environments less than 100 km/h, drivers are, in practice, seeking to negotiate curves at higher speeds than are currently assumed in design.

A highly significant positive correlation exists between curve-related crash rates (crashes per 100 million vehicle-kilometres through curves), and the difference between the negotiation speed and the design speed. While the relatively small crash dataset precluded the development of robust crash rate prediction models, the approach used here shows that refinement of the methodology could be expected to provide a useful procedure for highway network screening and crash prediction.

6.2 Key findings and recommendations

6.2.1 Key findings

- Drivers' speed choices can be investigated using the approach developed in this research, i.e. by monitoring the performance of a sample of drivers and relating their performance to that of the population using data from a number of traffic classifiers. The approach adopted here provides a very rich dataset that allows detailed consideration of a number of alternative variable definitions.
- Drivers' speed choices can be predicted from highway geometry, using a number of alternative measures of highway geometry. However, the best relationship is based on the 85th percentile speed and highway bendiness (absolute angular deviation measured in degrees/kilometre), measured over 1000 m.
- Drivers' speed choice when negotiating a particular curve is a function of the curve radius and the approach speed, where the approach speed is established over the preceding 500 m, and may be predicted based on the bendiness of the preceding 500 m.

6.2.2 Recommendations

- The relationship between crash risk and the speed differential (the difference between negotiation speed and design speed) should be investigated further with a view to developing an accident prediction model that may be used in network screening and safety analysis.
- Design guidance regarding the relationship between speed environment, curve radius and 85th percentile speed should be reviewed, as this research suggests that the current guidance underestimates drivers' speed choices.
- Crash coding definitions need to be given greater consideration in future studies. In particular, coding definitions should specify whether BE, CA, DA, CB and CC crashes actually occurred on curves.

7. References

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APPENDIX A Variable definitions

Table A1: Definitions and measures associated with the variables used for the analysis in this study.

Measure	Variable	Description
Traffic exposure	traf	Traffic volume at each curve was taken using the estimated AADT of the 2003 RAMM database as the volume that applied at the mid-point of the five-year crash history
	veh	The number of vehicles entering the curve: = (traff/2) *365days*5 years
	vkt	The vehicle-kilometres of travel on that curve: = curve length (km)*veh
Crashes	Set1_i	The number of reported curve-related crashes resulting in injury associated with the curve (2001–2005 inclusive)
	Set2_i	The number of reported loss of control crashes resulting in injury associated with the curve (2001–2005 inclusive)
	Set1_n	The number of reported curve-related crashes associated with the curve (2001–2005 inclusive)
	Set2_n	The number of all reported loss of control crashes associated with the curve (2001–2005 inclusive)
Curve geometry	R R_{10} R_{30} R_C	The absolute radius (m) of the curve path: for a particular 10 m reading, averaged over three consecutive readings and reported against the mid-point of that sequence, averaged over the entire curve
	X X_{10} X_{30}	The pavement crossfall (m/m) recorded by the HSD: for a particular 10m reading of the HSD, averaged over three consecutive readings and reported against the mid-point of the sequence
	D	The design speed of the curve calculated using Equation 3, based on the minimum value of R_{30}
	B B_{500} B_{1000}	The deflection angle of the curve in absolute degrees of horizontal deviation per kilometre measured over: 500 metres, 1000 metres
Curve speed	S S_{10} S_{30} S_C	The mean speed recorded by a sample of young drivers: for a particular 10 m interval, averaged over three consecutive readings and reported against the mid-point, averaged over the entire curve
	V V_{10} V_{30} V_C	The estimated 85th percentile speed (calculated using Equation 2): for a particular 10 m interval, averaged over three consecutive readings and reported against the mid-point, averaged over the entire curve
Speed environment	V V_{500} V_{1000} V_{2000} V_{3000}	The estimated 85th percentile speed (calculated using Equation 2) averaged over the: 500 m approaching the curve, 1000 m approaching the curve, 2000 m approaching the curve, 3000 m approaching the curve
	AS AS_{500} AS_{1000} AS_{2000} AS_{3000}	The advisory speed AS_{RGDAS} speed (calculated using Equation 1) averaged over the: 500 m approaching the curve, 1000 m approaching the curve, 2000 m approaching the curve, 3000 m approaching the curve
Radius	R R_{500} R_{1000} R_{2000} R_{3000}	The average radius of the highway where straights are defined as being all sections of R_{10} >800 m and are assigned a default radius of 1000 m: 500 m approaching the curve, 1000 m approaching the curve, 2000 m approaching the curve, 3000 m approaching the curve

APPENDIX B Scatter plots for crash rates

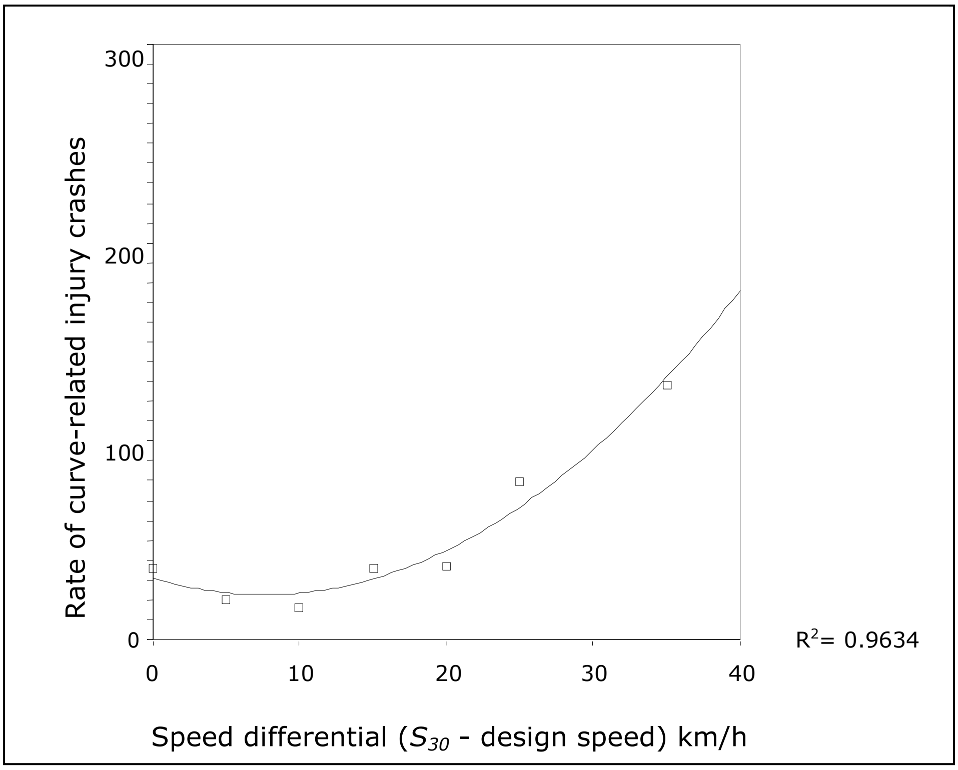

Figure B1 Rate of curve-related injury crashes v. speed differential.

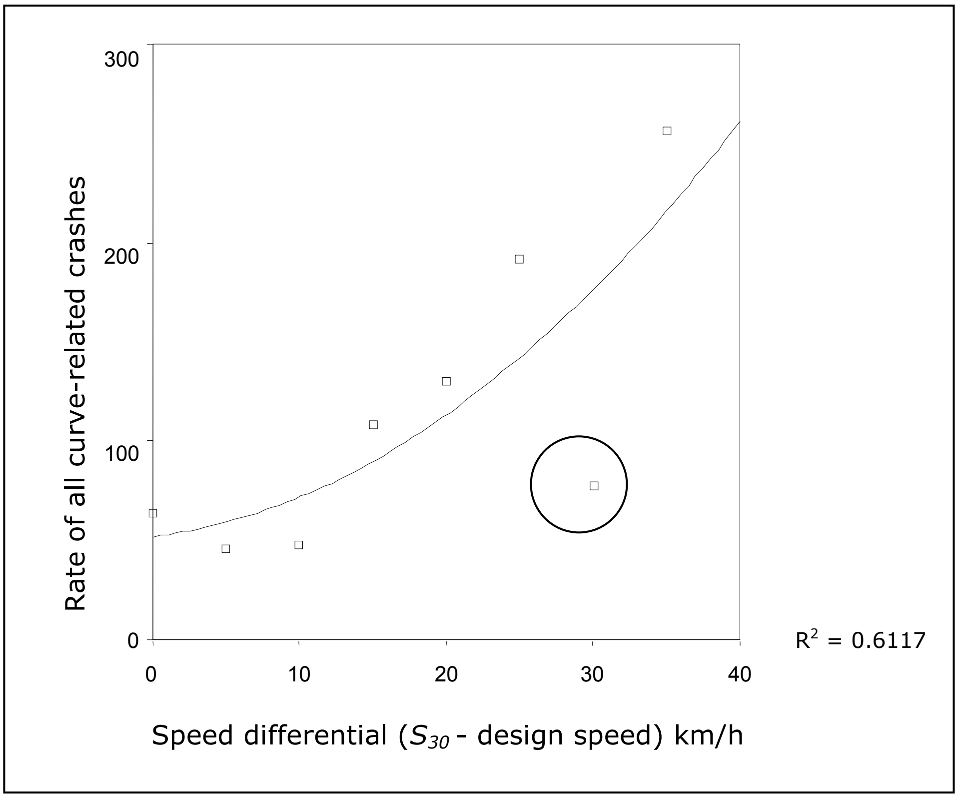

Figure B2 Rate of all curve-related crashes v. speed differential (outlier included).

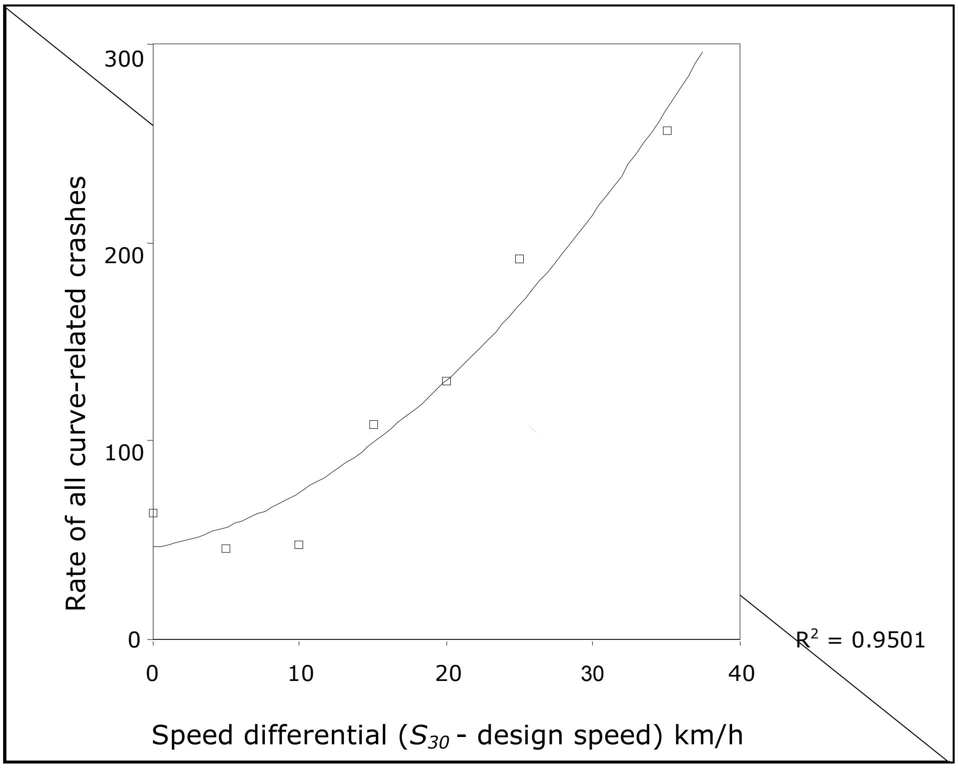

Figure B3 Rate of all curve-related crashes v. speed differential (outlier removed).

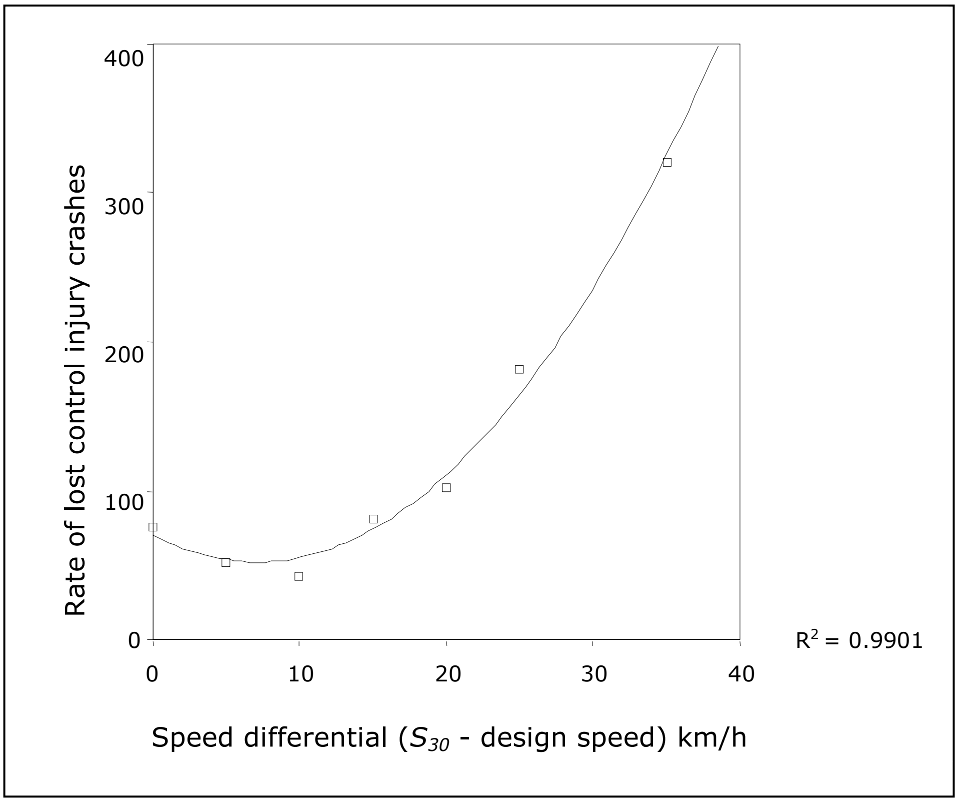

Figure B4 Rate of 'loss of control' injury crashes v. speed differential.

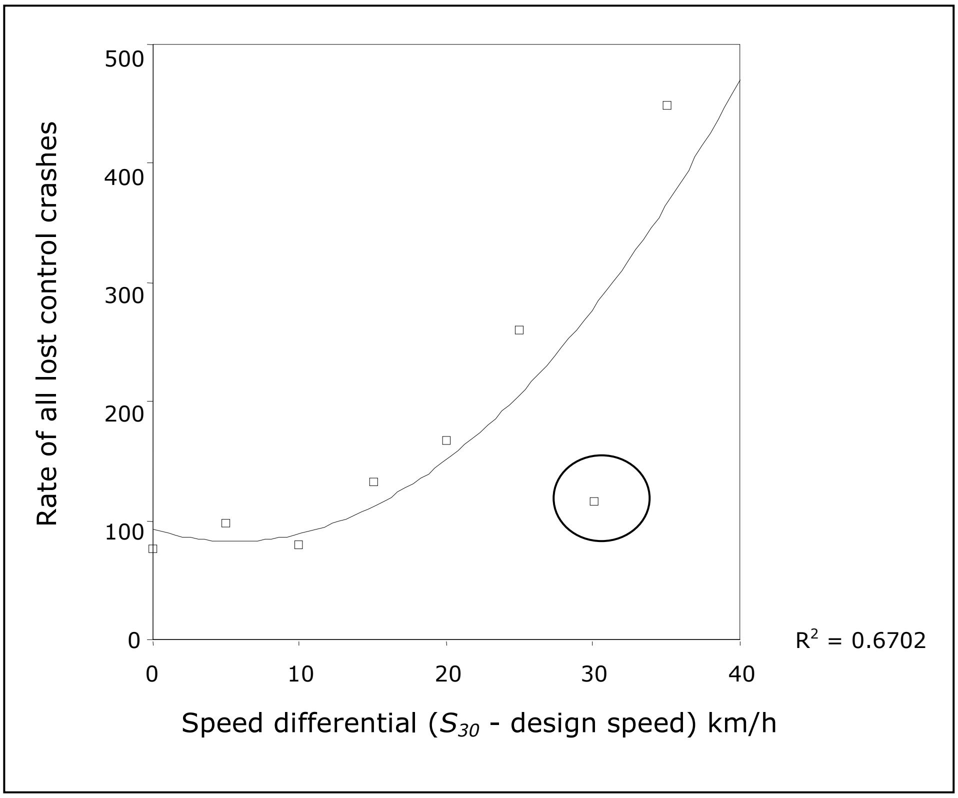

Figure B5 Rate of all 'loss of control' crashes v. speed differential (outlier included).

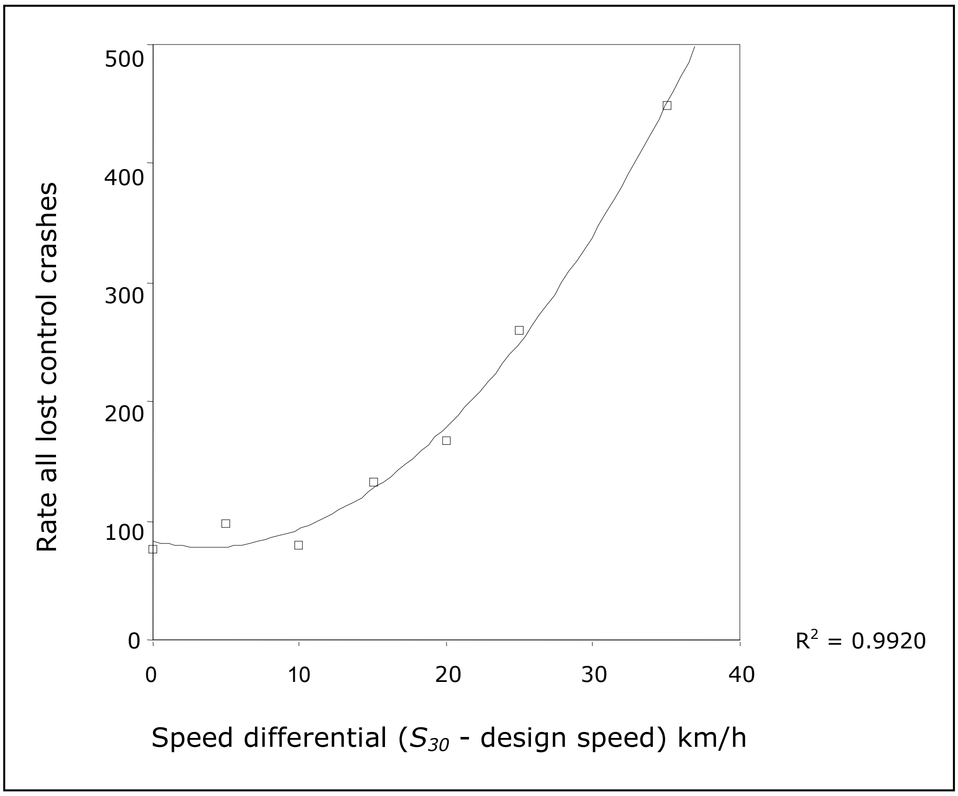

Figure B6 Rate of all 'loss of control' crashes v. speed differential (outlier removed).

APPENDIX C Scatter plots for curve negotiation speed

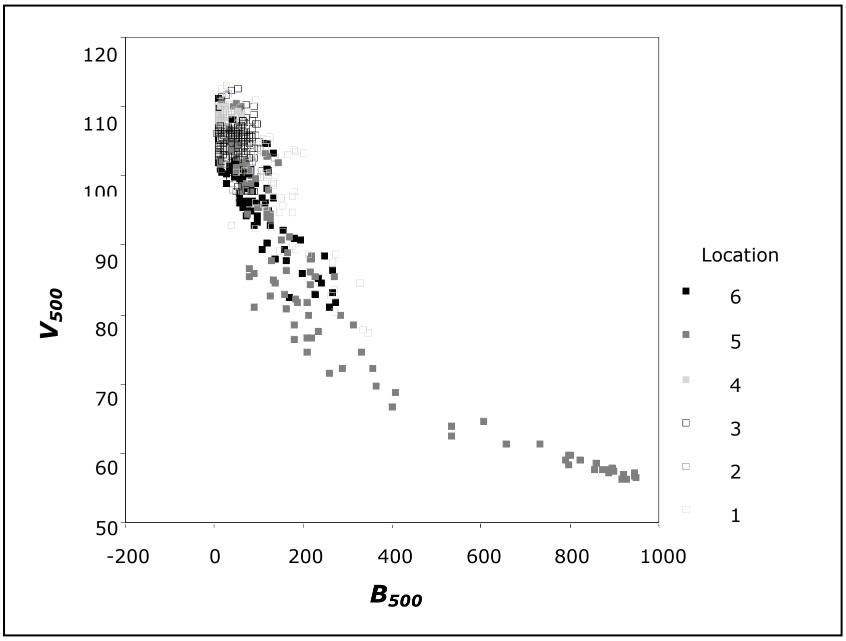

Figure C1 Relationship between bendiness and 85th percentile speed, measured over 500 m.

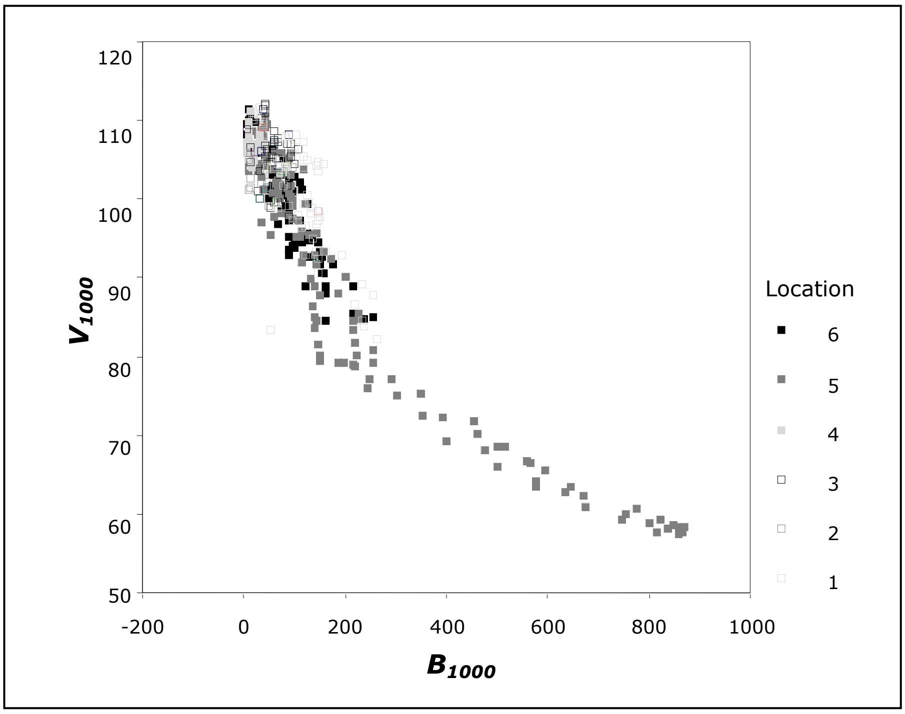

Figure C2 Relationship between bendiness and 85th percentile speed, measured over 1000 m.

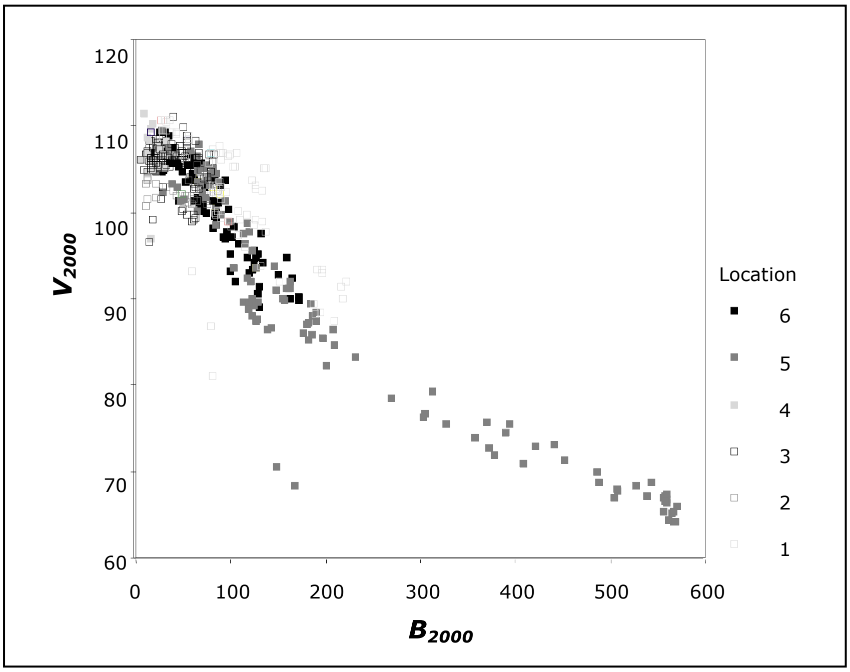

Figure C3 Relationship between 85th percentile speed and bendiness, measured over 2000 m.

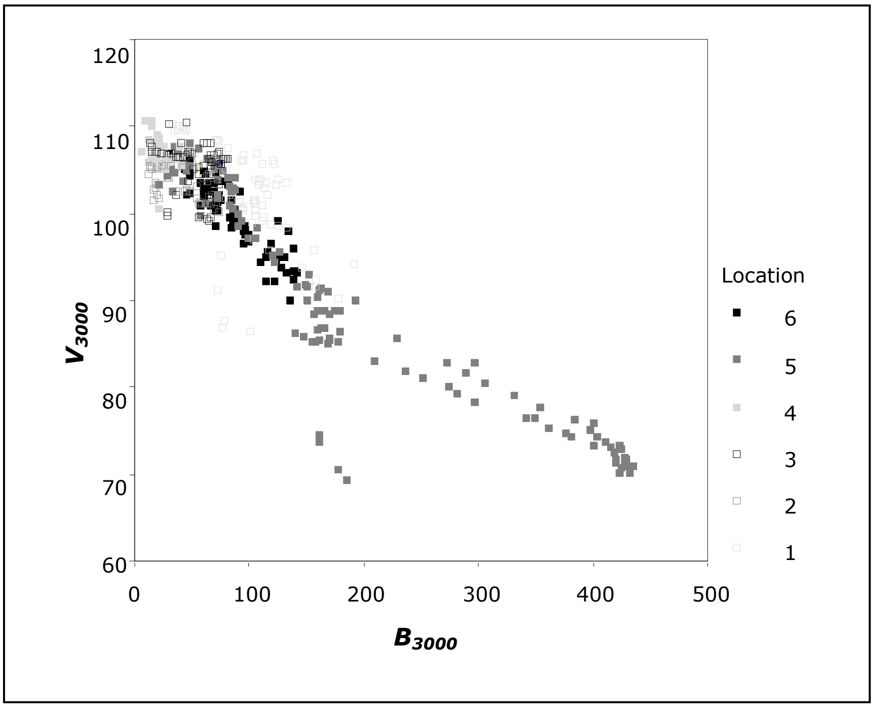

Figure C4 Relationship between 85th percentile speed and bendiness, measured over 3000 m.

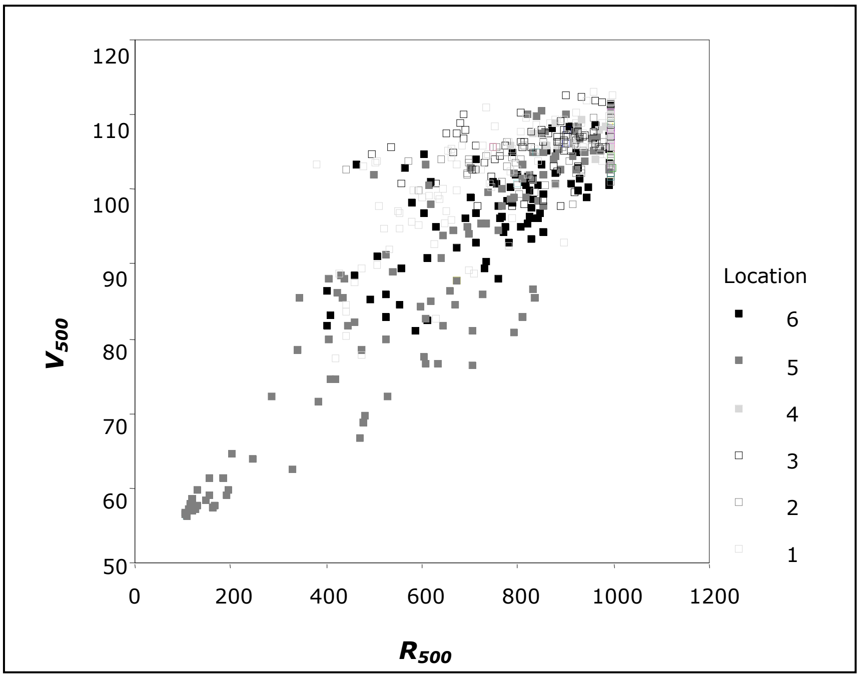

Figure C5 Relationship between 85th percentile speed and average highway radius measured over 500 m.

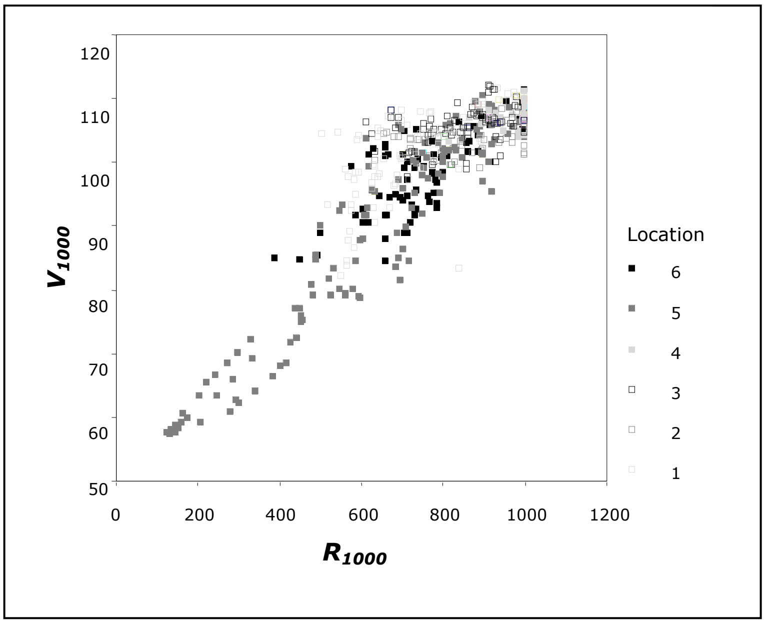

Figure C6 Relationship between 85th percentile and average highway radius measured over 1000 m.

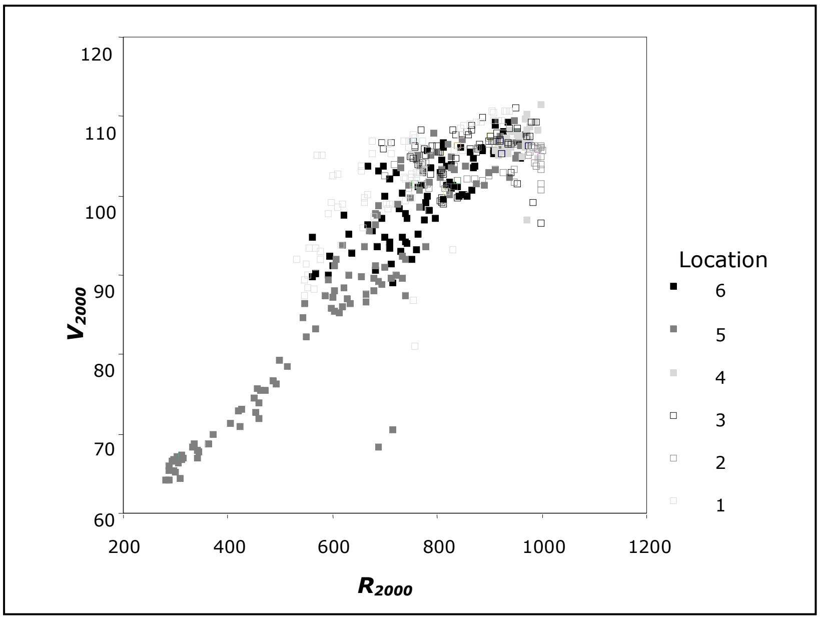

Figure C7 Relationship between 85th percentile speed and average highway radius measured over 2000 m.

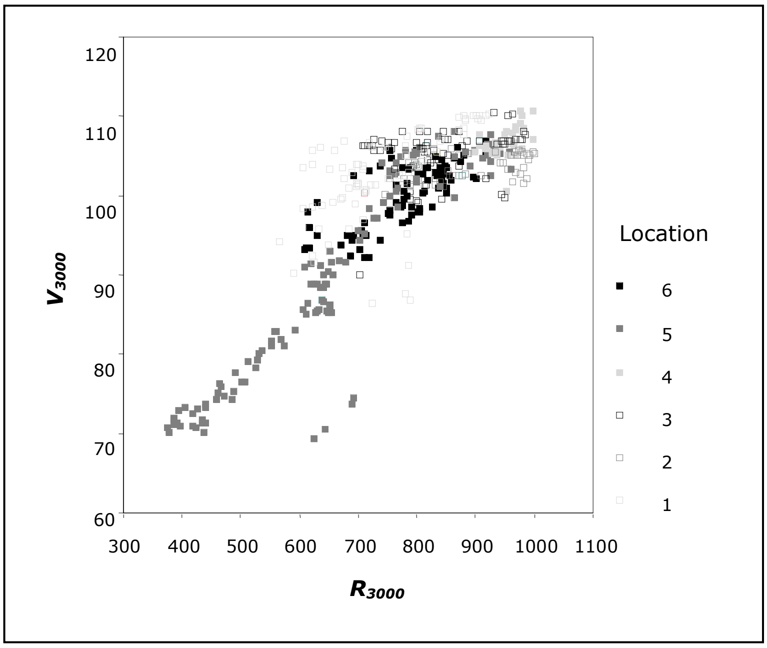

Figure C8 Relationship between 85th percentile and average highway radius measured over 3000 m.

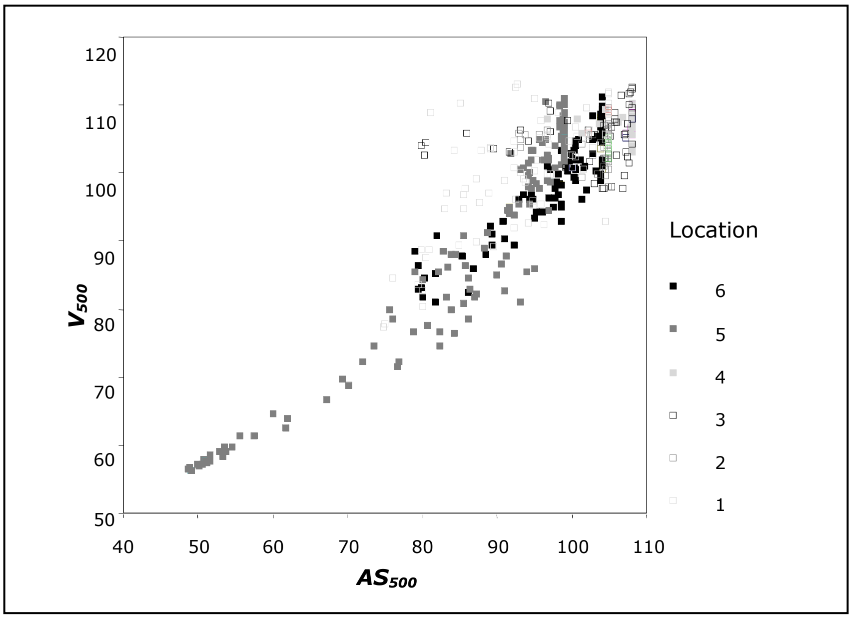

Figure C9 Relationship between 85th percentile speed and advisory speed measured over 500 m.

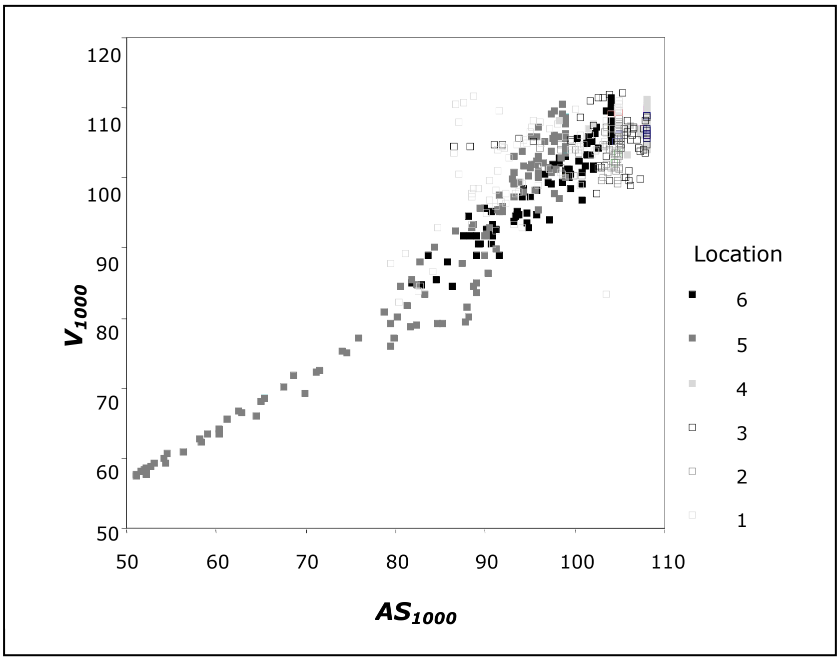

Figure C10 Relationship between 85th percentile speed and advisory speed measured over 1000 m.

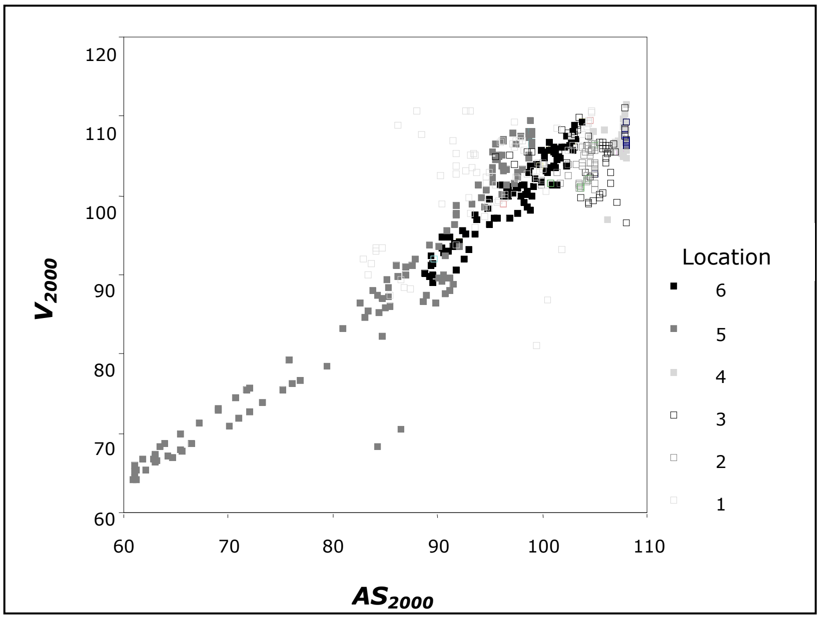

Figure C11 Relationship between 85th percentile speed and advisory speed measured over 2000 m.

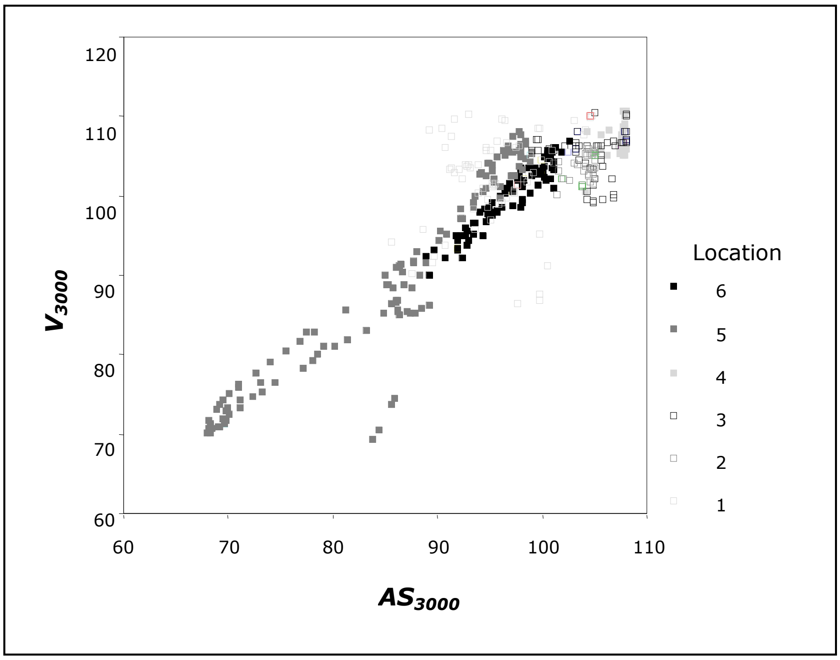

Figure C12 Relationship between 85th percentile speed and advisory speed measured over 3000 m.

Appendix D CAS categories

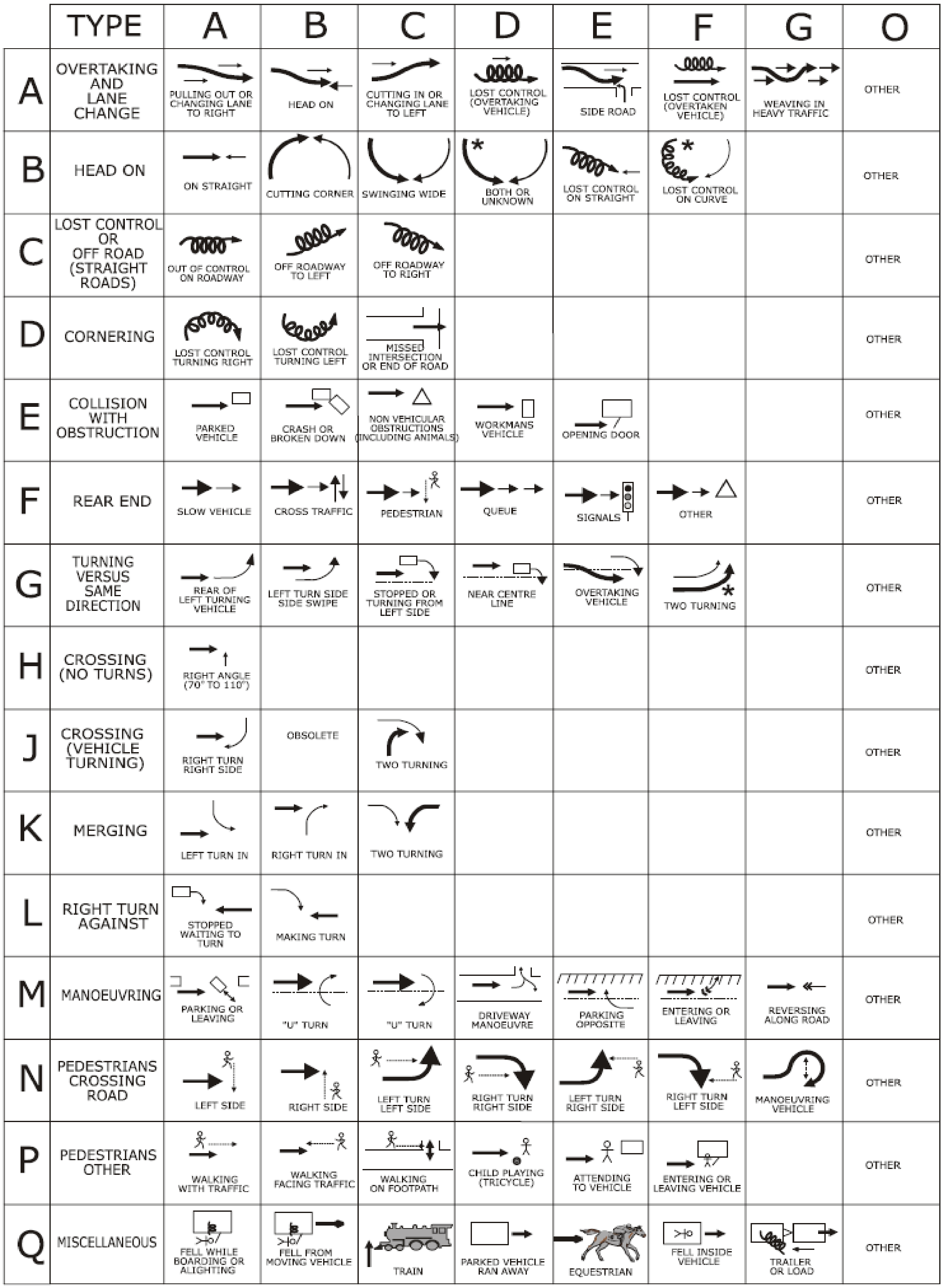

Figure D1 The CAS coding list used to label the crash types investigated in this study.

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