ROAD GEOMETRY AND DRIVERS SPEED CHOICE

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ABSTRACT: This paper discusses a recent research project that investigated the relationship between observed travel speed, road geometry and crashes using data collected on six nominally 20km sections of New Zealand State Highway.

The speed data collected was matched onto the highway geometry profile (radius and crossfall) in order to investigate the relationship between road geometry and drivers speed choices at the 488 curves covered by the study, and the impact this relationship has on crash risk.

The research confirmed that driver's speed choices are more strongly related to curve radius than curve design speed, and that the approach speed environment also has a significant impact on speed choice. While these findings support the approach to horizontal curves on rural roads, relationships derived from this research predict higher negotiation speeds that those currently used in Transit New Zealand's State Highway Geometric Design Manual.

While the relationship between speed choice and crashes was less than conclusive, due to the relatively small number of crashes, indications are that the crash rate on a particular curve is a function of the difference between the negotiation speed and the design speed.

1 INTRODUCTION

The majority of rural road crashes in New Zealand are of two major types, 1) loss-of-control and head-on on bends (45%) and 2) loss-of-control and head-on on-straights (19%). Speed has been explicitly identified as a contributory factor in 37% of the curve related and 11% of on-straight loss-of control and head-on injury crashes. Based on the assumption that, at worst only a very few drivers would consciously adopt a cornering speed that is likely to result in them losing control of their vehicle the question is asked:

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

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, and makes the following comments:

- *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.*
- *Consistent roadway design should ensure that most drivers would be able to operate safely at their desired speed along the entire alignment.*

The issue of driver expectations and alignment consistency are intertwined. A driver who travels a smooth flowing horizontal alignment will not expect a tight low speed curve and their speed choices will reflect that expectation. Whereas a driver on a tortuous alignment with numerous tight low speed curves is more likely to expect further low speed curves.

To date there, have been two New Zealand based research studies that generally support the above propositions.

Jackett (1992) investigated the relationship between curve crashes (head-on/loss of control on curve) and the speed reduction prior to entering the curve. The study found a strong positive relationship between crash risk (crashes per 1,000,000 vehicles entering a curve) and the difference between the approach speed and the ball bank derived, curve advisory speed. However, the approach speed was subjectively assessed and is understood to have focussed on the immediate approach to the curve.

Subsequently Koorey and Tate (1997) sought to develop a highway network screening tool that could be used in desktop studies of highway alignments. To overcome the subjective nature of Jackett’s approach speed assessment, and the resources cost of ball bank advisory speed assessments, Koorey and Tate relied on a synthetic speed metric the AS_{RGDAS}, which had been used successfully in New Zealand by Wanty et al (1995).

Developed by Rawlinson (1983), AS_{RGDAS} is an estimate of 85th percentile curve negotiation speed derived from the radius and crossfall data, collected using the ARRB Road Geometry Instrumented Vehicle, as shown in Equation 1.

Equation 1

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

where AS_{RGDAS} = RGDAS Advisory Speed (km/h)

X = % Crossfall (sign relative to curvature)

H = Absolute Curvature (rad/km) = (1000/Radius in metres)

Using this relationship Koorey and Tate investigated the safety impact of differences between the advisory speed (AS_{RGDAS}) on a particular 200m road segment and the mean advisory speed (AS_{RGDAS}) over the preceding kilometre. The study used data from the entire State Highway network, and found a strong relationship between curve related crash rates, and the drop in AS_{RGDAS} at a curve.

While these two pieces of research support the general concept discussed by Wooldridge et al (2003), they focus on the degree of consistency between a particular geometric element and the preceding alignment. While relationships are useful to those seeking to identify high risk curves, the only safety improvement solution offered by these relationships, are geometric improvements to increase highway consistency. These studies do not really address the important questions:

- *What influences drivers speed choice on a particular curve?*
- *What will be the likely impact of differences between a driver's expectation of a safe travel speed and the "safe negotiation speed"*?

If these two questions can be answered, it will then be possible to better consider the benefits of other treatments, aimed at modifying drivers' expectations and importantly drivers speed choices.

2 APPROACH

To seek to answer these two questions, Beca and MWH collected data on drivers speed choices along 6 sections of State Highway and related this to the road geometry and crash occurrence. State Highways were selected as the necessary road geometry data is collected annually for these roads. Each section was nominally 20km in length.

Groups of 12, predominantly young male drivers, drove each highway 4 times, in each direction, using an instrumented vehicle; a Mitsubishi Galant. The instrumentation provided a speed profile with data collected at 1 Hz. These time based measures were subsequently converted to distance based measures and a speed profile was developed to report the speed every 10m along the route.

The speed profile data was combined with spot speed data (for all free car drivers) collected using traffic classifiers at 26 locations. From this combined data 85th percentile speed profiles were developed along each road section, in each direction, reporting speeds every 10m.

The speed data and reported crashes were then matched onto the highway geometry, also reported at 10m intervals, in order to investigate the relationship between road geometry and drivers speed choices at the 488 curves covered by the study, and the impact this relationship has on crash risk.

2.1 Site Selection

Potential study sites were identified using a "sliding strip" GIS procedure, that moved a 20km analysis strip along the selected State Highway in 1km increments. The procedure, reported the number of rural (open road speed limit) injury crashes, together 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 or night-time crashes were excluded from consideration, in order to limit the potential for skid resistance or delineation issues to confound the analysis.

Boundaries were also placed on the volume of traffic using the highway, in an attempt to balance issues of crash rate (crashes/unit of travel), crash density (crashes/kilometre of length), and the practicality of measuring free speeds on higher volume roads. Also, the results of a preliminary analysis suggested that the majority of curve related crashes occur on highways with intermediate volumes. The final selection criteria for potential survey locations are set out in Table 1.

Criteria	*Lower Bound*	*Upper Bound*
Proportion of Wet Crashes	*25%*	*45%*
Proportion of Night-Time Crashes	*25%*	*45%*
Traffic Volume (veh/day)	*3,000*	*10,000*

Table 1 Selection criteria for potential study locations

Having identified 100 potential survey locations, the final selection was based on ensuring a reasonable geographic coverage (with at least two surveys in the South Island and some in Northland, as requested by a project supporter), practical issues associated with undertaking 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 2, together with brief details of the section length, traffic volume, and reported crashes for the period 2001 to 2005 inclusive.

Location		*AADT*	*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*	*10430*	*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	*South Blenheim*	*3250*	*21.0*	*18*	*21*	*22*	*25*
6	*SH 75*	*2850*	*25.5*	*8*	*22*	*10*	*26*
Total			*131.6*	*98*	*143*	*157*	*262*

Table 2 Sites used in this study

2.2 Speed Profiles

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 those situations where the subject 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, the criteria resulted in relatively small data losses from particular runs, generally less than 15%. However, there were some cases where data loss was extreme. In these cases the particular run was compared to the others made by the same driver and where necessary part or all of the particular drive was deleted.

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 vehicles speeds was measured using traffic classifiers installed at a number of sites. Typically between three and five classifiers were installed on each survey section.

The data from each classifier was 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 greater than 6 second headways. With the exception of the sections from 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 directionally split.

A comparison of 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, is shown in Figure 1.

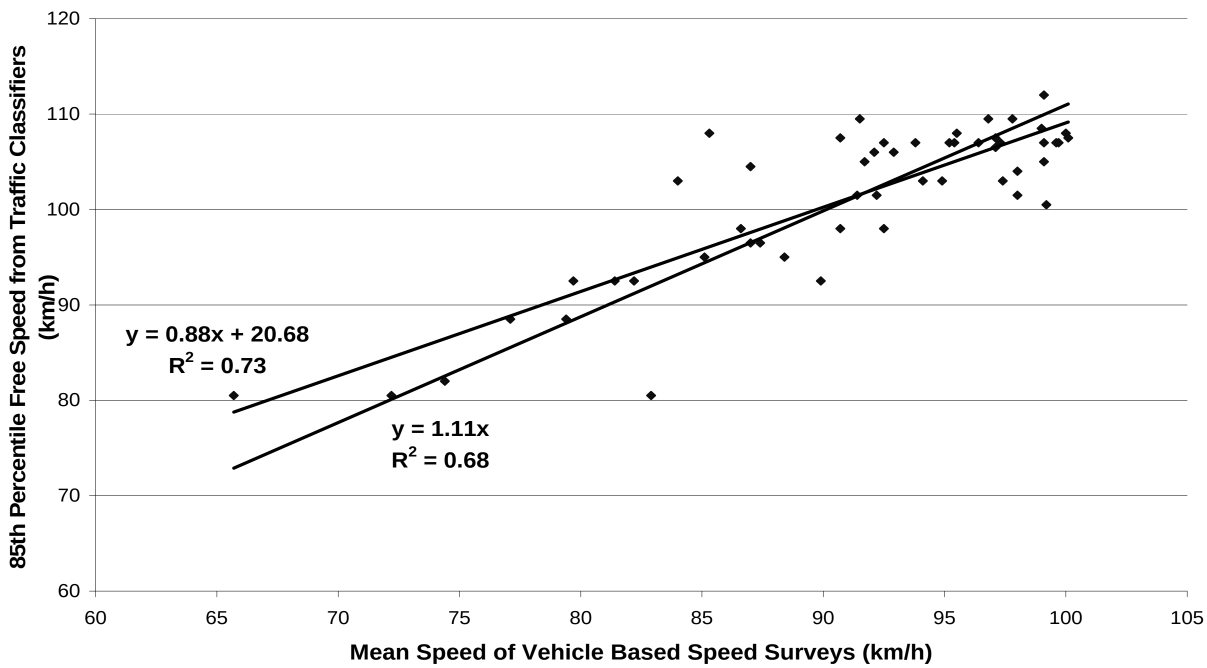


Figure 1 Relationship between mean speed of vehicle surveys and the 85th percentile speed from traffic classifiers

The relationship between the two sets of speed data is significant, both when the model includes a constant ($F_{1,50}$ =132, p<0.001) and when the relationship is forced though the origin ($F_{1,51}$ =24166, p<0.001). The resulting models account for approximately 70% of the variation between the data sources. However, further investigation found significant differences were associated with the data collected at locations 1 and 5.

A better model, Equation 2 ($F_{3,48}$=84.128, $p<0.001$, $R^2 = 0.84$), explains all but 16% of the variability between the two data sets by identifying the local effects at these two locations 1 and 5.

Equation 2

$$S_{85} = 12.428 + 0.968\ V_{mean} + 5.946L_1 - 2.966L_5$$

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 or Location 5 else 0

The overall effect of adjusting for locations 1 and 5 is to alter the constant shift between the mean speed for the sample and the 85th percentile speed.

This change in constant does have some face validity and the Land Transport New Zealand speed surveys (Ministry of Transport, 2005) report that 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, Location 5, are lower than elsewhere.

Its is also possible that the 12 young drivers used in the Northland surveys preferred to travel faster than those used in other areas, while the group used in the 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) appears robust, and on that basis the mean speed profiles for the sample drivers were adjusted.

Rather than applying a single uniform adjustment for each direction of each survey site, separate adjustment factors were calculated for each classifier and the resulting adjustment was interpolated between successive classifier sites and extrapolated beyond these.

2.3 Road Geometry Data

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 was then processed to identify the extent of each curve along the highway.

Curves were defined as those locations where the absolute value of radius dropped below 800m 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 10m data did at time create “phantom” curves in situations where the 10 m radius data increased and then decreased, e.g. 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 (500m to 800m) in the same direction. Although the convention adopted was to code these as separate curves, in retrospect it may have been better to code this as a single curve and flag the” broken-back” nature.

2.4 Crash Data

Data on reported crashes along the study sections was obtained from the New Zealand Crash Analysis System (CAS) for the period 2001 to 2005. Data for two sets of crash types (shown in Table 3), were extracted from CAS; the curve related crashes that are of obvious interest to the study, and a further set that included all loss of control and head-on crashes. This latter set was extracted, because in many cases where a loss of control crash occurs on a straight road, the problem may well have stemmed from attempting to take a preceding curve at an inappropriate speed. For each crash set, two datasets were produced, injury crashes only, and all reported crashes.

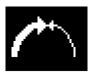
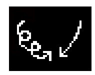
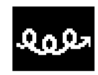
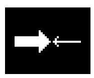
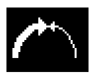
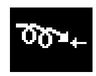
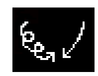
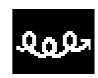
Crash Set	Crash Movements					
Curve related crashes	BB 	BC 	BD 	BF 	DA 	DB 
All loss of control and head-on crashes	BA 	BB 	BC 	BD 	BE 	BF 
	CA 	CB 	CC 		DA 	DB 

Table 3 Definition of crash sets

The crashes were matched to the highway geometry data based on the distance along the highway that the crash occurred, the location of adjacent curves, the direction of travel of the principle vehicle, 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 allocated to the;
    - nearest adjacent curve within 100m (upstream or downstream),
    - curve immediately upstream of the reported location if it was specifically identified as a curve related crash,
    - in the case of a loss of control crash (not on a curve) to the curve immediately upstream provided the distance to that curve was less than 500 m, or
    - the crash was dropped from the analysis.

3 RESULTS

3.1 Speed Environment

The analysis of speed environment identified that the strongest and most consistent relationships linking operating speed metrics to road geometry descriptors are those based on:

- Bendiness (*B*), and the
- Rawlinson Advisory Speed (*AS*).

Bendiness, is defined here as the sum of the absolute value of highway deviations, expressed in degrees per kilometre. As bendiness increases, the average 85th percentile operating speed over a section of road decreases. The relationship is non-linear and over the range for which data were collected (*B*<900 deg/km), a quadratic expression provided the best fit model.

When formulating the model in terms of Rawlinson's Advisory Speed (*AS*), a power model ($Y=cAS^b$) performed best.

In each case the strongest relationship between the assessed 85^{th} percentile speed and the predictor variable occurred when the assessment was based on the road geometry over the preceding 1000m. The Bendiness and Rawlinson's Advisory Speed models accounting for all but 11% and 12% respectively of the variation in the independent variable (85^{th} percentile speed), as shown in Table 4.

Dependant Variable (Y)	Independent Variable (X)	Model Form	a	b	c	R^2	F (df)
V_{1000}	B_{1000}	$Y=aX^2+bX+c$	0.000075	-0.124	110.425	0.89	1992 (474)
V_{1000}	As_{1000}	$Y=cX^b$	1.8347	0.873		0.88	3597 (475)
V_{500}	B_{500}	$Y=aX^2+bX+c$	0.000066	-0.118	109.565	0.86	1475 (482)
V_{500}	AS_{500}	$Y=cX^b$	2.1019	0.843		0.86	3101 (483)

Table 4 Models relating speed environment (85th percentile speed $V_{distance}$) to road geometry

Table 4 also includes a further pair of models based on the road geometry over 500m. Although the models based on the 500m sections did not perform as well as those based on 1000m the difference is relatively small.

3.2 Curve Negotiation Speed

The relationship between the 85th percentile curve negotiation speed and a number of geometric parameters was investigated. The predictor variables investigated included;

- Curve design speed,
- The Ralwinson's Advisory speed,
- Curve Radius, and
- Deflection angle with and without a secondary term, length of curve.

The relationships based on deflection angle performed poorly There is also a very poor relationship between curve design speed, as defined in State Highway Geometric Design Manual (Draft) (Transit NZ 2003), and drivers speed choices (see Figure 2 left). A better relationship existed between drivers speed choice and the Advisory Speed predicted by the Rawlinson equation (see Figure 2, right).

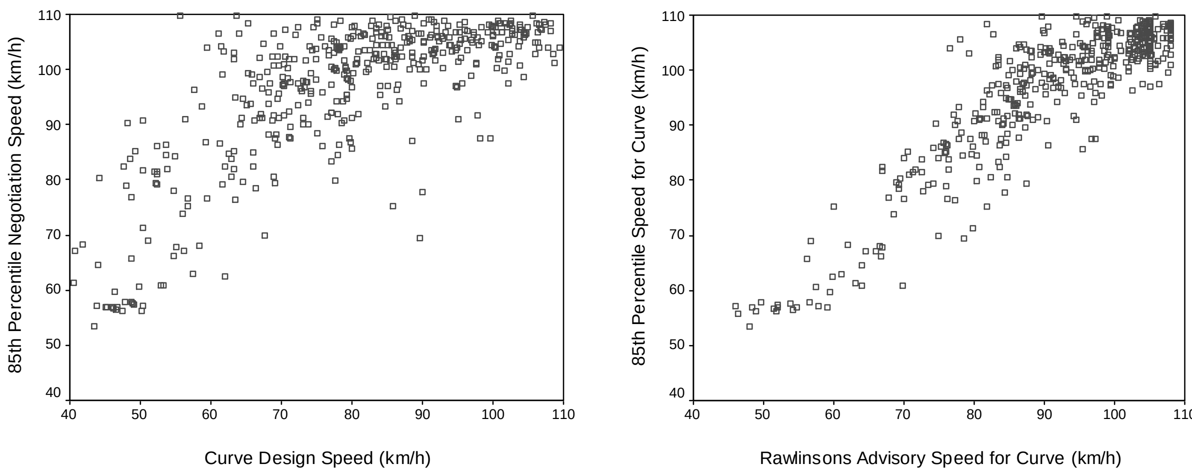


Figure 2 The relationship between curve design speed (left), Rawlinson's Advisory Speed (right), 85th percentile negotiation speed

The radius of a curve (minimum value assessed over 30m), is the single greatest determinant of passenger car drivers' expected negotiation speed through a curve. The resulting simple model (Equation 3) can be considered a good fit (see Figure 3), as it accounts for approximately 85% of the variation in the 85%ile negotiation speed. The model parameters and level of significance are shown in Table 5.

Equation 3

$$V_c = e^{(4.7142 - 26.736/R)}$$

Where

V_c = the (average) 85th percentile speed around the curve (km/h)

R = the minimum radius of the curve (m)

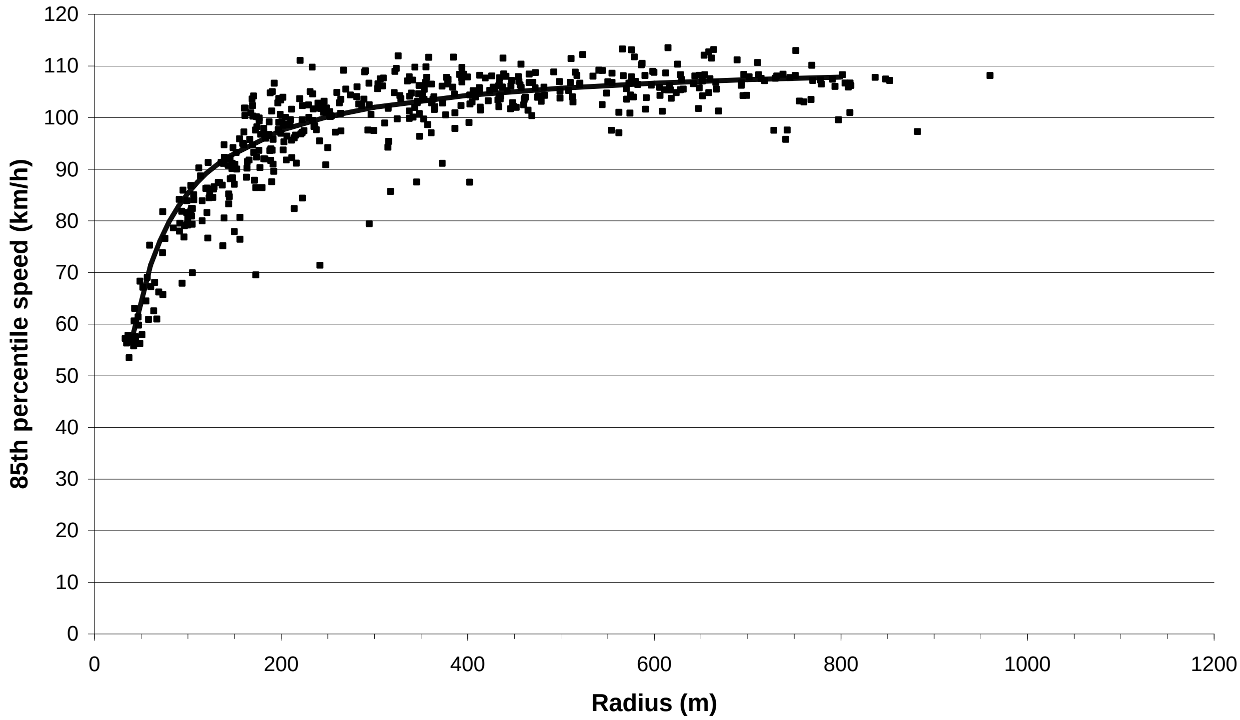


Figure 3 Relationship between curve radius and 85th percentile negotiation speed

Adjusted R^2	df regression (residual)	F	Model Parameters				
			Terms	Coefficients	Std. Error	t	Sig.
0.853	1 (483)	2801.4	(Constant)	4.7142	0.0036	1299	.000
			Coefficient B	-26.736	0.5017	-55.64	.000

Table 5 Model parameters for the simple model relating radius and curve negotiation speed

Investigation of the residuals from the above simple model found they were highly correlated with the speed environment. As a result a more powerful model could be developed by adding a term representing the speed environment, V_{500} (Equation 4). This more complex model accounts for all but 10% of the variation in the independent variable (Table 6).

Interestingly, it is the speed environment of the preceding 500m, not the preceding 1000m (see 0 above), that provides the best predictor of curve negotiation speed. The resulting model can be applied using an estimate of the speed environment (V_{500}) based on either Bendiness (B_{500}) or Rawlinson's Advisory Speed (AS_{500}), depending on what data is available.

Equation 4

$$V_c = -24.967 + 0.397V_{500} + 0.741e^{(4.7142 - 26.736/R)}$$

Where

V_c = the average 85th percentile speed around the curve (km/h)

V_{500} = the average 85th percentile speed over the previous 500m (km/h)

R = the minimum radius of the curve (m)

And

$V_{500} = 0.000066(B_{500})^2 - 0.1179\, B_{500} + 109.565$ for $8 < B_{500} < 900$ OR

$V_{500} = 2.1019(AS_{500})^{0.8432}$

Adjusted R^2	Deg.free. regression (residual)	F	Model Parameters				
			Terms	Coefficients	Std. Error	t	Sig.
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

Table 6 Parameters for a model relating speed environment, radius and curve speed

The resulting model (Figure 4) is similar to that currently used in the State Highway Geometric Design Manual (Draft), Section 2 Figure 2.5 (Transit 2003), shown in figure 5. However, a comparison of the three models, the two models of this study and that used by Transit New Zealand, reveals:

1. The model developed in this study, predicts lower 85th percentile negotiation speeds than Transit New Zealand's geometric design advice, when the approach speed environment is greater than 100km/h.
2. When the approach speed environment is 100 km/h the three models are essentially the same.
3. For approach speed environments less than 100km/h the models developed here, predict higher 85th percentile negotiation speeds than Transit New Zealand's geometric design advice, and the difference between the two increases as the approach speed environment decreases.

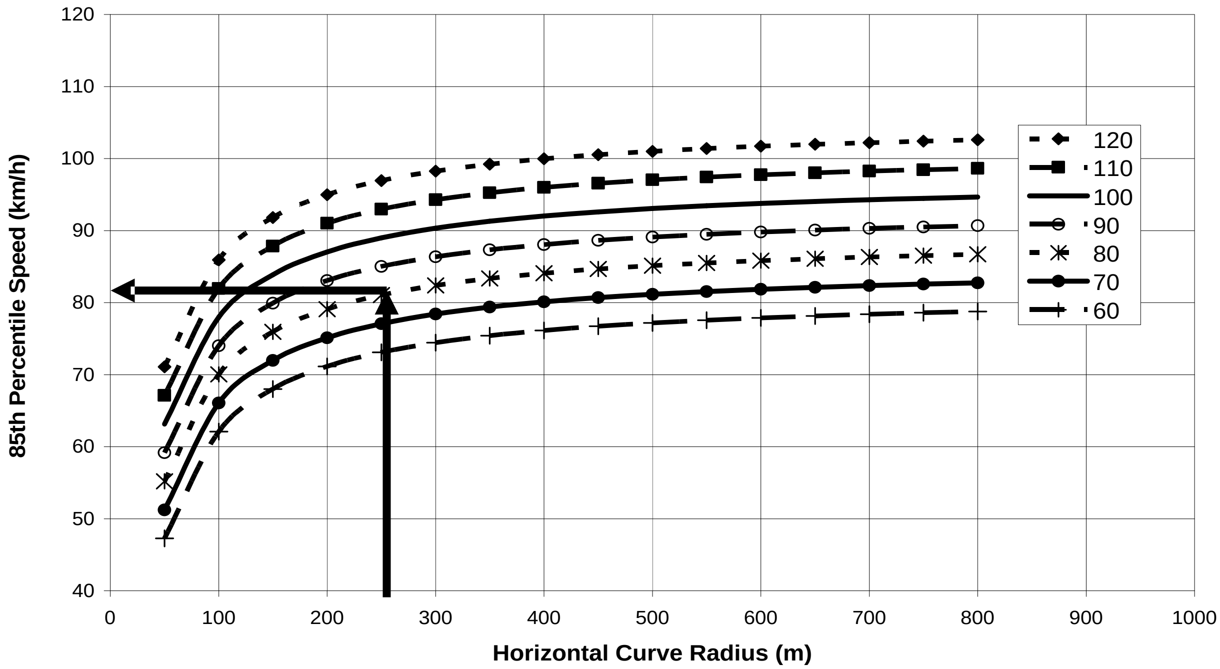


Figure 4 Revised relationship between environment curve radii and 85th percentile speed

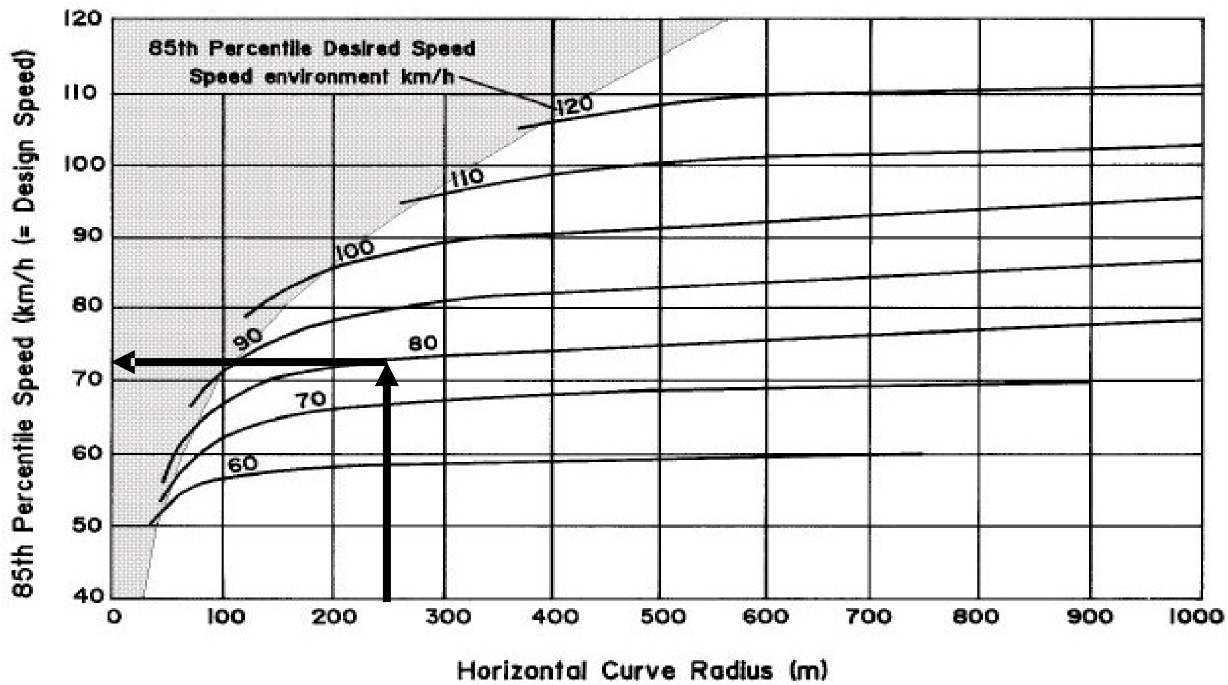


Figure 5 Relationship between speed environment curve radii and 85th percentile speed (State Highway Geometric Design Manual (Draft), Section 2 Figure 2.5, April 2003).

3.3 Crash Prediction

The impact of inappropriate speed choice, on crash rate, expressed in terms of both vehicles entering the curve and crashes per 100 million vehicle kilometres of travel through the curves was investigated. In each case the latter provided superior results, presumably because this takes into account the length of the curve.

The degree to which drivers speed choices are inappropriate was defined by the difference between the negotiation speed and the design speed around each curve, which was calculated in accordance with the State highway Geometric Design Manual (Draft). The speed difference was then rounded to the nearest 5 km/h and the crashes and exposure data for all curves in a particular 5km/h speed drop band were aggregated.

Using this aggregate data it was possible to develop crash prediction relationships based on the difference between the safe curve speed and the mean curve negotiation speed adopted by the sample of drivers (see Figure 6). However, when non-injury crashes were included the relationship deteriorated dramatically, possible reflecting differences in reporting rates that are known to occur.

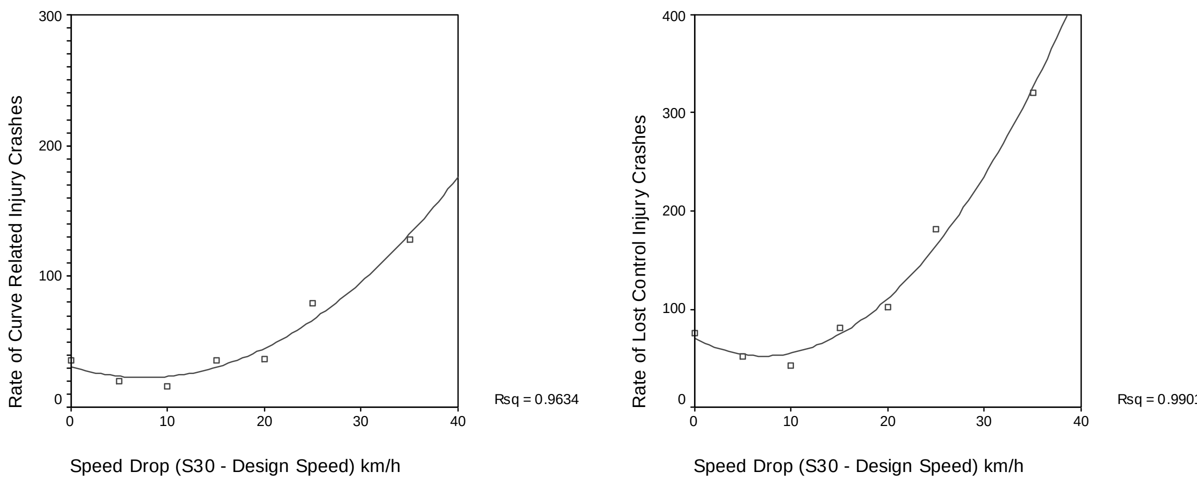


Figure 6 The relationship between the rate of reported curve related injury crashes (left), rate of reported lost control injury crashes (right) and the difference between the negotiation speed of sample drives (S30) and curve design speed.

These results were clearly encouraging, and the bounded quadratic equations that fit Figure **6**, appear intuitively correct, in that once the difference between drivers negotiation speed and design speed exceeds 15 to 20 km/h crash rates rise dramatically. However, attempts to construct similar relationships between the assessed 85^{th} percentile negotiation speed, were less successful. Although statistically significant models could be generated, these models typically accounted for less than 60% of the variation in the independent variable (crash rate).

Given that it is generally the highest percentile speeds that result in crashes, better models may result from using the 90^{th} or 95^{th} percentile speeds, more sophisticated modelling or a larger sample size.

4 Conclusions

Given the speed prediction models generally produce significant results, the concept of factoring up speed profile data collected for a sample of drivers, using the results of a limited number of more detailed speed classifier surveys has merit. It may however, not be suitable for establishing speed choice crash relationships.

The road speed environment, the expected the 85th percentile speed of free light vehicles (cars), can be predicted from road geometry data using either:

highway Bendiness (sum of absolute degrees of deviation per kilometre), and

the mean speed predicted using Rawlinson's Advisory Speed model which is based radii and crossfall.

While the models based on Bendiness are generally stronger the difference is only small. However, neither a linear relationship, which suggests that should the Advisory Speed approach continue to be used to predict speed environment, it should be re-formulated.

Drivers curve negotiation speed choices are most strongly related to the radius of the curve. There is a very poor relationship between the speed choice and design speed of a curve, as defined in the State Highway Geometric Design Manual (Draft) 2003, and the 85th percentile negotiation speed.

A model of the 85th percentile curve negotiation speed has been developed. Based on curve radius and the speed environment of the preceding 500m, the model accounts for all but 10% of the variability in drivers speed choices.

While this model is in keeping with the speed environment philosophy of the State Highway Geometric Design Manual, the model produced here predicts higher negotiation speed choices for curves in speed environments less than 100km/h. The difference between the results of this new model and that underlying the State Highway Geometric Design Manual (Draft) 2003, increases as the speed environment drops further below 100 km/h.

There appears to be some indication that a curve related injury crash rates can be predicted on the basis of the difference between drivers curve negotiation speed choices and the "safe" or rather the design speed of a curve. However, further modelling using larger samples, higher percentile speeds and more advanced techniques will be required.

5 AKNOWLEGEMENTS

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