The Safety Risks of Out-of-Context Curves: Three Decades of Rural Curve Research in New Zealand

Joseph Corbett-Davies
Senior Transportation Planner
Abley
Christchurch, New Zealand
Email: joe.corbettdavies@abley.com

Dr Shane Turner
Technical Director
Abley
Christchurch, New Zealand
Email: shane.turner@abley.com

Dr Glen Koorey
Director and Principal Transportation Engineer
ViaStrada
Christchurch, New Zealand
Email: glen@viastrada.nz

Dr Fergus Tate
Technical Director
WSP New Zealand
Wellington, New Zealand
Email: fergus.tate@wsp.com

Steve Abley
Chief Executive
Abley
Christchurch, New Zealand
Email: steve.abley@abley.com

Word Count: 5278 words + 1 table (250 words per table) = 5528 words (max 7500)

Submitted 31 July 2025
Revised 1 December 2025

ABSTRACT

The rural road network of New Zealand contains many horizontal curves that are inconsistent with their surrounding environment. These "out-of-context" curves – where the safe negotiation speed is significantly lower than the prevailing approach speed – are associated with higher crash risk than in-context curves of otherwise similar geometry. Over the past three decades, New Zealand researchers and transport agencies have developed a robust body of work to understand and address this issue, although it remains under-explored internationally. This paper reviews the evolution of rural curve safety research in New Zealand, including the development of high-resolution road geometry datasets, operating speed models, and crash prediction models. It also highlights how these insights have informed national project evaluation guidance and safety prioritization frameworks, and some recent adaptation of this research to international contexts, including the United States. In particular, it was found that traditional crash prediction models such as those in IHSDM and the *Highway Safety Manual* can underestimate the observed numbers of crashes around out-of-context curves by at least 30%, and potentially up to 60%. The recent application of New Zealand curve context modeling to US rural roads through the *SafeCurves* software tool addresses this limitation. This review aims to demonstrate the value of incorporating curve context into safety analysis and prioritization, and encourage broader application of these methods to reduce crash risk on rural roads worldwide.

Keywords: Curve, Curves, Safety, Risk, Crash Prediction Model, New Zealand, Road Safety, Horizontal, Context, Rural, Network**,** Spatial**,** Safety Performance Functions, SPF, Operating Speed

INTRODUCTION

Although a comparatively developed country with an extensive road network, New Zealand (NZ) has both a low population density and relatively rugged terrain. As a result, roading expenditure has been limited and the country continues to rely largely on two-lane roads of varying standard to link the major urban areas.

Many of these roads have evolved from historical trails, rather than being purpose-designed for modern vehicles. Consequently, they often contain many substandard curves out of character with the surrounding environment. Both the motoring public and roading authorities have identified these as significant concerns that need to be identified, managed and, ultimately, remedied. As a result, considerable effort by researchers and government agencies has gone into identifying the nature of these problems and assessing the effectiveness of potential treatments. These efforts have included extensive analytical work since the 1990s, aided by high quality road geometry and crash datasets.

International reviews of the literature on rural highway safety have often overlooked the significant body of work resulting from this longstanding analysis of rural roads in New Zealand. In particular, the safety effects identified from relative changes in travel speed through curves has often not been picked up in horizontal curve safety research elsewhere, with a focus largely on just the absolute curvature.

The purpose of this paper is to provide a succinct overview of operational and research activities related to the safety of curves on rural highways in NZ over the past three decades, and outline how this research can be applied to improve rural road safety. In particular, this review is focused on:

- The collection and availability of road geometry, crash, and other road inventory data,
- Development of curve operating speed models,
- Crash prediction models for rural curves, including the effects of curve geometry and context,
- The application of safety research in project evaluation guidance and safety prioritization.

Brief details of these initiatives are given below, as well as some resulting insights; readers should refer to the full publications listed for further information.

THE NEW ZEALAND RURAL ROAD NETWORK

New Zealand has a population of just over five million people. A significant proportion of the population resides in urban centers such as Auckland, Wellington, and Christchurch, while vast areas of the country remain sparsely populated. This geographic dispersion necessitates an extensive rural road network to connect remote communities, support primary industries like agriculture and forestry, and enable access to tourism destinations and essential services.

The rural road network includes both state highways (approx. 10,700 km) and local roads (approx. 65,000 km). The New Zealand Transport Agency Waka Kotahi (NZTA) oversees the state highway (SH) system, while local government manage local roads. These roads often traverse challenging terrain, including mountainous regions and coastal areas, and are typically characterized by two-lane configurations—one lane in each direction—with narrow shoulders and limited passing opportunities. Rather than full asphalt paving, rural roads in New Zealand often use chip seal (a cheaper and less durable form of surface treatment using bitumen and aggregate), especially on lower-volume roads. Road widths are typically narrow (sometimes less than 6 meters, or 20 feet, wide), and many rural roads lack centerlines or edge markings. Curves, steep grades, and one-lane bridges are common, particularly in more remote areas. As of the early 2020s, nearly all of the rural SH network is sealed, but around half of rural local roads remain unsealed.

Traffic volumes vary significantly across the rural network. Major undivided rural highways may carry over 10,000 vehicles per day, especially near urban centers or tourist routes, while lesser regional state highways often average no more than 5,000 vehicles per day. Non-SH local roads often have even lower traffic volumes, with many local rural roads seeing fewer than 500 vehicles per day. These low volumes, combined with the rugged geography and variable weather conditions, present ongoing challenges for maintenance and safety.

COLLECTION OF ROAD AND CRASH DATA

Since 1992, New Zealand's state highway (SH) network has been regularly surveyed to collect data on horizontal curvature, gradient and cross-fall at 10-meter intervals. In early 1992, the entire SH network was surveyed in both directions by an instrumented RGDAS (Road Geometry Data Acquisition System) (*1*) vehicle recording:

- relative position along highway;
- (longitudinal) gradient and vertical curvature
- crossfall or superelevation;
- horizontal curvature;
- survey vehicle speed (km/h); and
- comments or features, such as road works, intersection or bridge locations.

Since 1997 NZTA have repeated the exercise as part of their annual data collection program, which has included surface roughness and skid resistance measurements using a specialist SCRIM (Sideways-force Coefficient Routine Investigation Machine) vehicle. Since 2000, the dataset has also been augmented with spatial information in the form of centerline coordinates. The availability of road geometry data, and later surface condition information, on NZ's SH network enabled a range of previously infeasible studies. Integration with existing road inventory data, containing additional data such as traffic volumes and seal widths, provided relatively complete coverage of key variables of interest on the network.

Koorey (*2*) describes in more detail a number of other novel applications in highway research and operations that this valuable data source has enabled; some of these are described elsewhere in this paper. Koorey derived measures for "speed environment" (average speeds over the surrounding 1 km) and "local speed" (average speeds over a particular 100m) to determine road sections where local speeds were significantly below the speed environment, indicating potential curves with safety issues. Measurement of crossfall against radius and local speed also helped to identify curves with radii below design standards or with adverse cambers. Furthermore , by identifying the start and end locations of curves and matching these against existing recorded curve advisory speed signs, a desktop assessment could identify the locations where no advisory speed sign was present or the advisory speeds were incorrect..

New Zealand has a centralized crash reporting system: the Crash Analysis System (CAS) (*3*). This system is operated by NZTA and uses inputs from NZ Police crash reporting, including all reported crashes on both local roads and state highways. CAS includes variables describing location, vehicles/road users involved, injury severity, surface conditions, light levels, and movement codes denoting the nature of the crash.

Most authorities responsible for managing road networks in New Zealand, including NZTA, use a standardized asset management system called RAMM (*4*) that contains estimated traffic volumes, surface construction and dimension information, and some pavement condition data for all roads. Traffic volume data is generally complete and readily available for use by transportation professionals and researchers to inform analysis or prediction of safety outcomes.

OPERATING SPEED AND SPEED ENVIRONMENT MODELING

Development of operating speed models is an ongoing focus of NZ road safety research, both to inform curve speed selection and as an input to other crash modeling.

An early model of curve speeds developed by Rawlinson (*5*) was designed to be applied to the newly-collected RGDAS geometric data for the SH network. The model estimated 85th percentile curve negotiation speeds according to:

$$AS = -\left(\frac{107.95}{H}\right) + \sqrt{\left(\frac{107.95}{H}\right)^2 + \left(\frac{127{,}000}{H}\right)\left(0.3 + \frac{X}{100}\right)} \qquad (1)$$

Where:

- AS is the RGDAS curve advisory speed in km/h,
- X is the road segment crossfall (%)
- H is the absolute curvature of the road segment (rad/km)

It should be noted that the RGDAS curve advisory speed is *not* the same as those typically posted on curve advisory speed signs. Instead, it represents the expected negotiation speed for each road segment. Koorey (*2*) applied a similar approach using the standard design speed calculation from Austroads (*6*) and a side-friction derivation from Rawlinson (*5*) to estimate an advisory speed at each 10-m road segment (with upper limit restrictions to account for maximum free speeds and gradients), then applying rolling averages to infer other speed measures.

Tate & Turner (*7*, *8*) developed curve speed models from surveyed speed profiles over six sections of rural highway around New Zealand. The starting point for this work was the Rawlinson model of 85th percentile curve advisory speed shown above. An instrumented vehicle was used to collect speed profile data at 10 m intervals, which was used to fit alternative models relating curve radius and other road geometry to negotiation speed. Additional speed measurements of all traffic from fixed sites were used to calibrate the mean speeds from the instrumented vehicle sample against the overall 85th percentile speeds on the highway section.

The preferred model by Tate and Turner (*8*) predicted curve speed as a function of minimum curve radius and the approach speed environment, defined as the average 85th percentile speed over the previous 500 m of road, according to:

$$V_C = -24.967 + 0.397V_{500} + 0.741e^{\left(4.7142-\frac{26.736}{R}\right)} \quad (2)$$

Where:

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

The approach speed environment V_{500} was in turn modeled using two alternative methods, to allow for different data availability: as a function of "bendiness" (cumulative curve deflection per unit road length), or as a function of the average advisory speed:

$$V_{500} = 6.6 \times 10^{-5} - 0.1179B_{500} + 109.565 \quad \text{for } 8 < B_{500} < 900 \quad (3)$$

Or:

$$V_{500} = 2.1019\,(AS_{500})^{0.8432} \quad (4)$$

Where:

- B_{500} is the average bendiness over the preceding 500 m (deg/km),
- AS_{500} is the average calculated advisory speed (according to Equation (1)) over the previous 500 m (km/h)

The predicted curve speeds by curve radius and speed environment are shown in **Figure 1**.

The operating speed models presented here have seen widespread use in crash prediction modeling and other safety research, as discussed in the following sections.

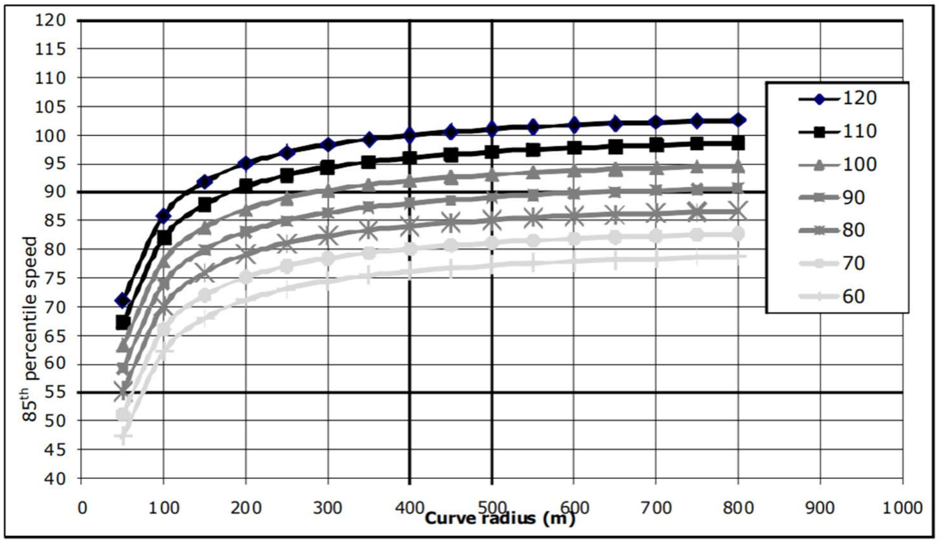

Figure 1 Estimated curve 85th percentile speed (in km/h) vs curve radius, for different approach 85th percentile speed environments (shown in legend, km/h). From Turner and Tate (*8*).

EFFECT OF CURVE CONTEXT ON RURAL CURVES

Crash analyses in New Zealand have often examined *curve context* as a key explanatory variable. A curve is considered "out of context" if its safe traversal speed is significantly lower than the prevailing approach speed. Some of the earlier research highlighting the safety effects of out-of-context curves is found in New Zealand analyses, conducted in light of the high rate of loss-of-control crashes on the rural network.

Research internationally has often focused on the roles of curve radius and length, and sometimes the presence of spiral transitions, in determining likely crash rates. For example, Lamm et al (*9*), in summarizing various German studies investigating the relationship between various road design parameters and crash rates on two-lane rural roads, found that some of the factors related to higher crash rates were smaller horizontal curve radii, the lack of spiral transition curves for small radius curves, and higher "Curvature Change Rates" (defined as the rate of angular deflection per length of curve). Similarly, Cairney & McGann (*10*) examined nine lengths of highway in Australia and related geometric attributes such as curvature, pavement width and gradient against recorded crash rates, and noted increasing crash rates with increased horizontal curvature.

The effect of curve context has less commonly been explored in international work, although some examples exist. Elvik found an association between curve crash risk and spatial factors, for example the presence or radii of adjacent curves in close proximity (*11*) or isolated curves with long straight approaches (*12*). AASHTO's *Highway Safety Manual* (*13*) notes that, based on some exploratory work by Hauer (*14*), when a long tangent is followed by a "sharp" curve, the number of crashes on the horizontal curve appears to increase. The crash effect appeared to be related to the length of the tangent in advance of the curve; however, the magnitude of the crash effect was not certain.

The remainder of this section outlines NZ analyses of the effect of curve context on rural curve crash risk. Much of the initial work in this area used univariate models, although these were later incorporated into more detailed multivariate crash prediction models in order to improve the applicability of the models and reduce omitted variables bias.

Univariate analyses

Even before the widespread availability of geometric data for the state highway network, early analysis work highlighted the impact of curve geometry and context on crash rates.

In 1988, Matthew and Barnes (*15*) manually constructed a database of (horizontal) geometric information for all curves on two-lane sections of SH 1, the primary highway that runs the length of New Zealand. They conducted univariate analyses of curve crash rates against geometric variables such as curve radius, curve direction, and tangent length prior to curve, although these were not combined in a formal prediction model. The authors found an increasing relationship between tangent length preceding a curve and crash rate.

In 1992, Jackett (*16*) used data from 990 rural SH curves to analyze the relationship between estimated 85th percentile approach speed and curve speed (as determined using a ball-bank indicator). The analysis found a relationship between the proportional speed decrease required to negotiate the curve and the rate of crashes coded as curve-related in CAS, as shown in **Figure 2**, according to the following model:

$$y = 0.0396\, e^{2.5674x} \quad (5)$$

Where:

- y is the curve-related crash rate per 10^6 vehicles negotiating the curve, and
- x is the percentage speed reduction between approach and curve speeds in km/h.

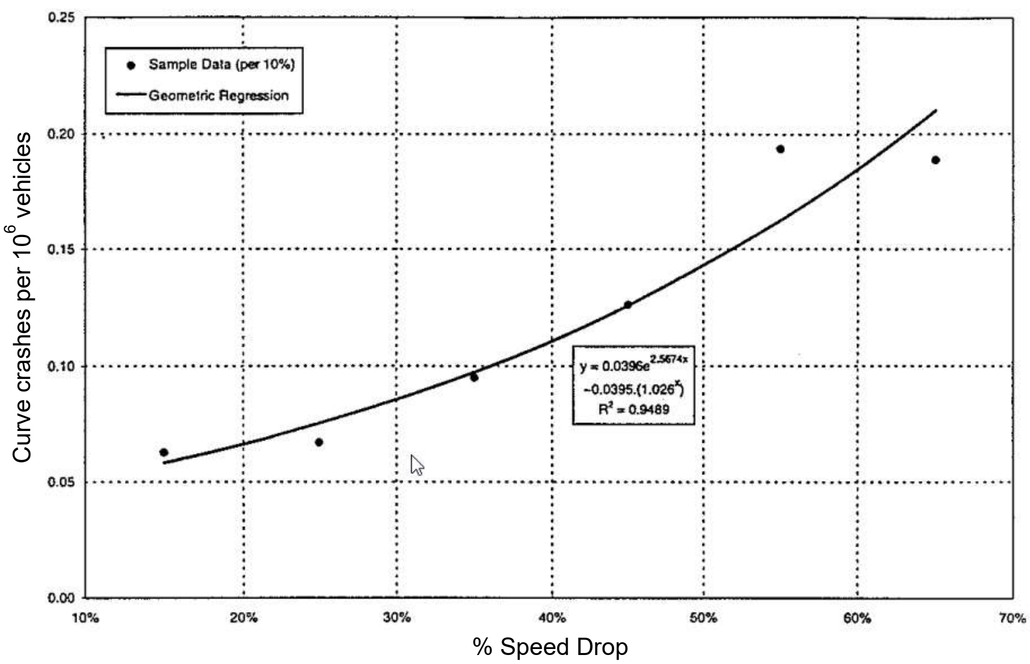

Figure 2 Curve-related crash rate (per 10^6 vehicles, over entire curve length) for 990 rural state highway curves as a function of curve speed reduction (from Jackett (*16*))

Koorey & Tate (*17*) used geometry data for the full sealed SH network to develop speed measures for assessment of curve safety, particularly in relation to speeds in advance of the curve. They updated Jackett's 1992 model of crash rate as a function of the relative speed reduction between the approach and curve speeds, although their analysis considers crashes at each 200-m road segment, rather than at each curve, as in the Jackett study. Approach and curve speeds were estimated based on advisory speeds computed from curve segment radius and nominal friction factors, capped at maximum observed 85th percentile free-flow speeds from national speed surveys. The authors note issues with aligning crash and road geometry data at the time, with 40% of the crash data unable to be matched to route position due to the lack of a common location reporting standard. The preferred model is shown in **Figure 3** and uses the following geometric form:

$$y = 1.599 \times (1.025)^{x} \quad (6)$$

Where:

- y is the curve-related crash rate per 10^8 vehicles negotiating the 200-m segment,

- x is the absolute speed reduction between approach and curve speeds in km/h, and

The approach speed is defined as the average calculated RGDAS advisory speed over the preceding 1000 m of road, and the curve speed is the minimum RGDAS advisory speed over the 200-m segments that make up the curve. This model was applied to project evaluation guidance to estimate the reduction in crash rate resulting from curve improvements to increase curve design speed (and hence decrease the speed reduction between approach and curve speeds).

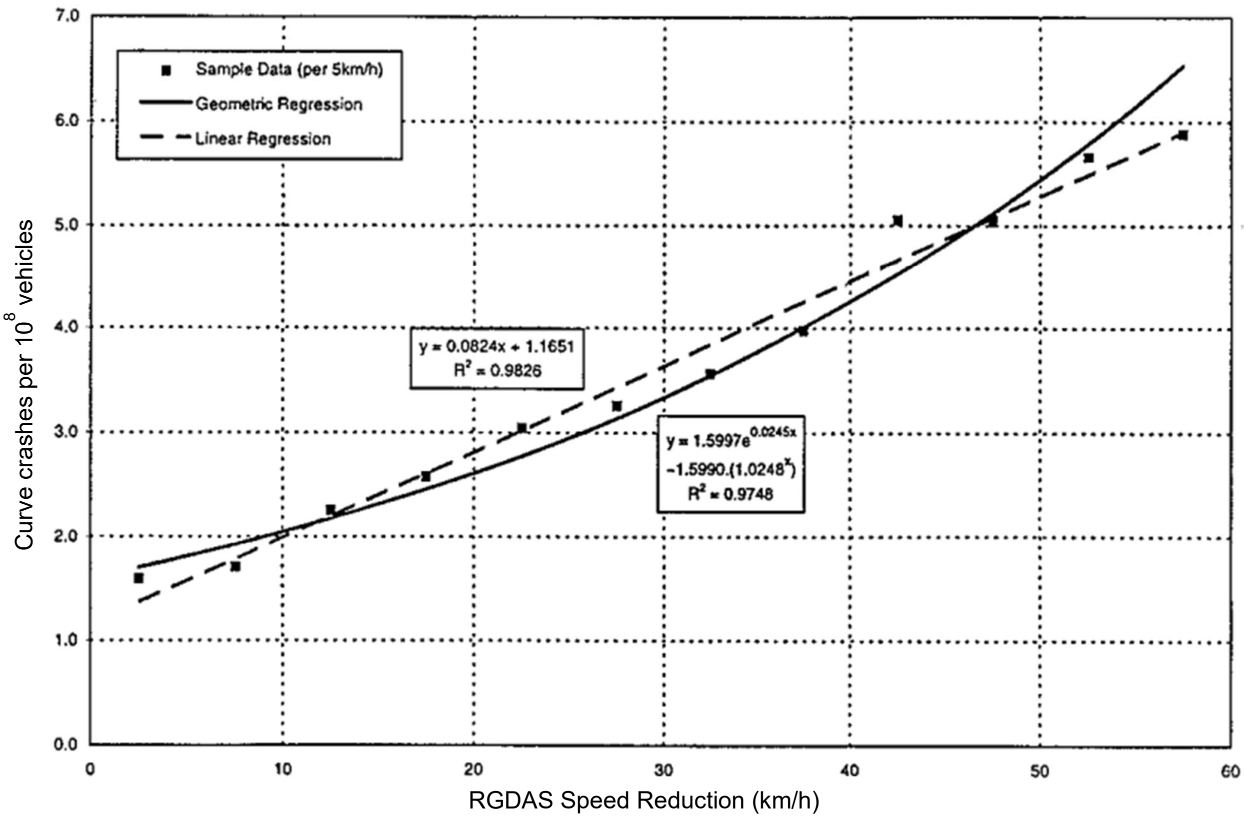

Figure 3 Curve-related crash rate (per 10^8 vehicles per 200-m segment) vs speed reduction (km/h) from approach to minimum curve speed (from Koorey and Tate (*17*))

The current edition of the New Zealand crash prediction guidance, the *Crash Estimation Compendium* (*18*), contains a model adapted from Jackett (*16*) for isolated rural curves with speed limit above 80 km/h, which uses the percentage reduction between approach (estimated 85^{th} percentile speed) and curve speeds as a key predictor. The relationship between approach speed, curve design speed and crash rates is shown in **Figure 4**, and has the equation:

$$y = 3.38e^{2.0S} \quad (7)$$

Where:

- y is predicted crash rate (reported injuries per 100 million vehicles, in one direction)
- $S = 1 - \frac{\text{Curve design speed}}{\text{Approach speed}}$ is the relative speed differential.

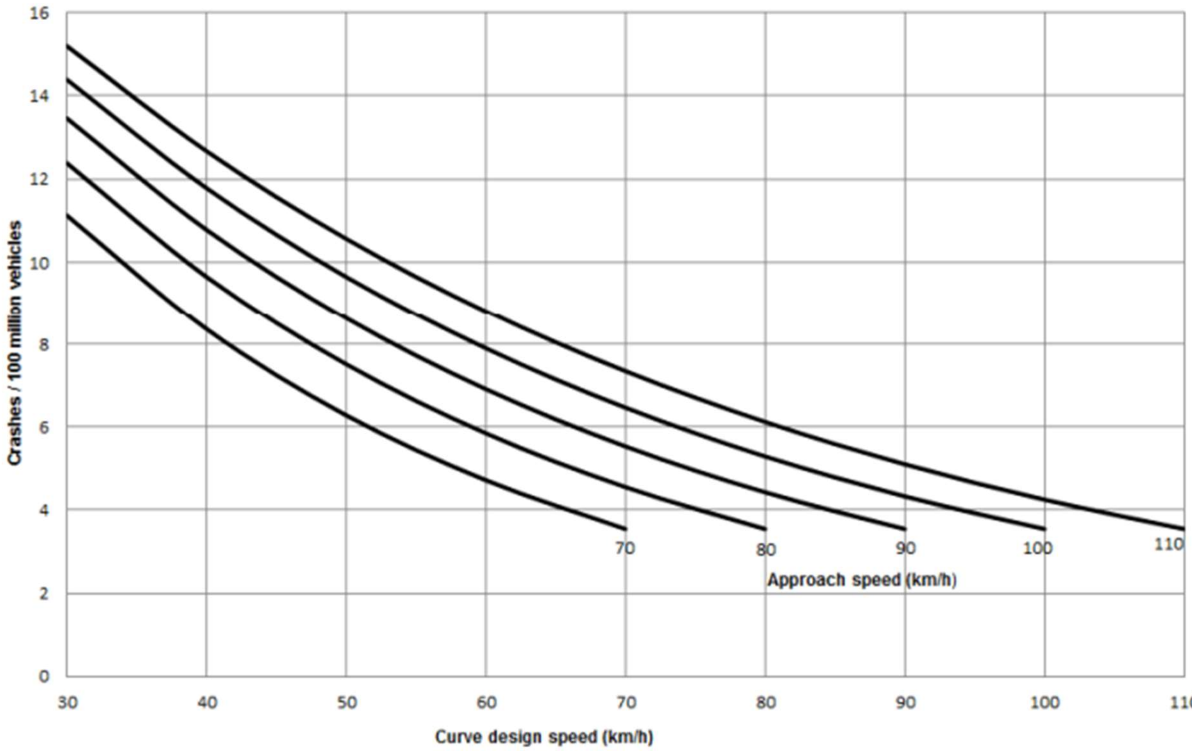

Figure 4 Curve crash rate (injury crashes per 100 million vehicles traversing the curve) vs estimated curve approach and design speeds (from (*18*)**)**

As part of Turner and Tate's 2009 study of operating speed models discussed earlier, the authors also related surveyed speed profiles from sampled drivers to the five-year observed crash history on the 488 individual curves in the dataset (*8*). The crash rate model that best fitted the observed data was a quadratic in the speed differential between observed negotiation speed (influenced by curve approach speeds) and design speed. Negotiation speed is defined as the minimum of mean surveyed speeds over a 30-m curve section. The design speed is calculated from the NZ State Highway Geometric Design Manual (*19*). The model is shown in **TABLE 1** and **Figure 5**.

TABLE 1 Quadratic models relating crash rate and speed differential (from Turner and Tate (*8*))

Dependent variable (per 100 million vehicle-km)	Coefficients			R^2
	$(V_{min} - V_{design})^2$ [(km/h)^2]	$V_{min} - V_{design}$ [km/h]	Constant	
Curve injury crashes	0.1461	-2.2205	30.9842	0.963
All curve crashes	0.1407	1.3915	46.3244	0.950
All lost control injury crashes	0.3517	-4.9947	69.9197	0.990
All lost control crashes	0.3785	-2.7560	82.8552	0.992

Note: ***Speed differential between design speed V_{design} and the lowest mean observed negotiation speed across a 30-meter window V_{min}***

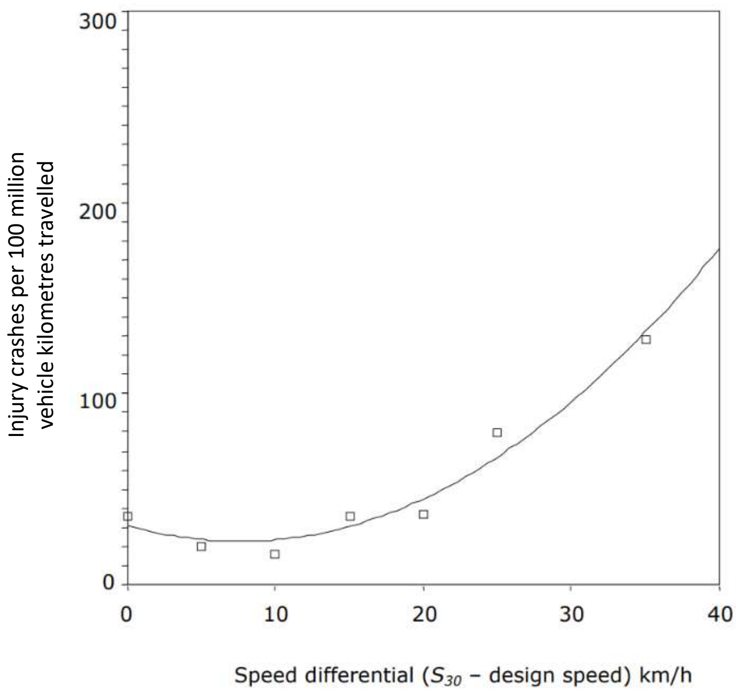

Figure 5 Curve crash rate (injury crashes per 100 million vehicle kilometers traveled) vs differential between observed and design speeds (from Turner and Tate (*8*))

Crash prediction models

Crash prediction models (also known as Safety Performance Functions, SPFs) are a key tool in identifying high-risk curves on a network in order to prioritize safety treatments, and can also be used alongside crash modification factors (CMFs) to estimate the impact of safety interventions on crash rates. Because crash prediction models can incorporate all significant predictive variables that are available, they reduce the impact of confounding between variables; for example, roads carrying higher traffic volumes typically being built to a higher standard.

In 1997, Cenek et al. (*20*) undertook the first major statistical study using the NZ road geometry dataset described above. The authors fitted a Poisson generalized linear model to predict injury crashes for each 200-meter segment of rural undivided two-lane state highway. Crash risk was modeled as proportional to vehicle distance travelled, with additional quadratic terms for average curvature, difference between maximum and minimum curvature, and an additional logarithmic AADT term to capture non-proportional effects of traffic volume on risk. While approach and curve advisory speeds (calculated from curve radii) were associated with higher crash risk in univariate analyses, they were not included in the preferred model.

In 2004, Cenek and Davies (*21*) undertook crash prediction modeling using combined geometry and surface condition datasets for the SH network for the period 1997 to 2002. They developed Poisson regression models to predict per-segment crashes including variables for traffic volume, gradient, curvature, surface friction and roughness, although they did not include curve context.

Turner et al. (*22*, *23*) developed unified crash prediction models for rural roads as part of a large NZTA study from 2006-2012, including new collection of data on roadside point hazards, shoulder width, road access density and roadside environment. Terms for calculated approach speed (RGDAS) were included in models of curved segment and driveway-related crashes, providing some consideration of curve context.

In a 2011 paper, Cenek et al. (*24*) developed a crash prediction model for rural curves with a radius less than 500 meters, with the aim of prioritizing road resurfacing to maximize safety benefit. Crash data from non-intersection curves from 1997 to 2002 was used to fit the model. In this work, curve speeds were estimated using a geometry-based curve advisory speed formula, developed earlier by Turner and Tate (*7*). Approach speeds were estimated as the average curve speed in the preceding 500 meters of road, if preceding curves exist, otherwise a nominal value was used. Despite the use of an approximate approach speed model, the authors found that the difference between estimated approach and curve negotiation speeds was a significant predictor of crash risk on the NZ rural highway network, capturing the effect of out-of-context curves.

An update of this model in 2012 by Cenek et al. (*25*) used crash data from 2000-2009. Coefficients for the updated model, including those for the difference between approach and curve speeds, showed good agreement with earlier work.

Other operating speed models have also been employed to more accurately estimate prevailing operating speeds and, consequently, curve context. Abeysekera et al. (*26*) estimated explicitly whether a curve is out of context with the surrounding road environment, and therefore expected to produce higher crash risk. An Austroads operating speed model (*27*) was used to infer typical vehicle speeds on a subset of the New Zealand rural road network. Curves were considered “out-of-context” if likely operating speeds exceeded published design speed criteria based on curve radius, shown by the “undesirable” and “unacceptable” regions in **Figure 6**. Out-of-context curves were found to have significantly higher crash rates than in-context curves.

Over the past 30 years, repeated NZ studies have identified curve context as an important factor determining crash risk, aided by mature operating speed models and geometry datasets for the NZ road network.

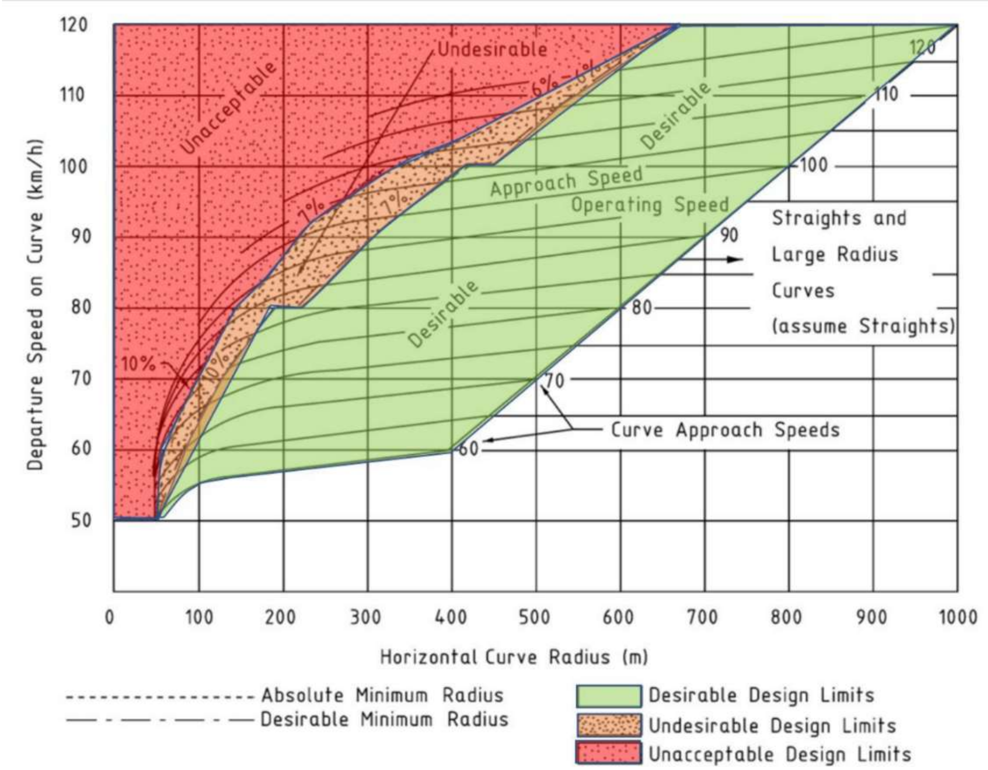

Figure 6 Austroads curve radius design limits (from (*6*))

EXTENSION OF U.S. CRASH MODELS TO INCLUDE CURVE CONTEXT

Koorey (*28*) investigated whether the safety performance used in the FHWA's Interactive Highway Safety Design Model (IHSDM) could be calibrated for NZ highways. First developed in 1993, IHSDM is a suite of software tools for assessing the safety and operational impacts of geometric design decisions within highway projects (*29*). While IHSDM has been discontinued by the FHWA since this work, IHSDM's two-lane rural crash prediction model have been subsequently incorporated into AASHTO's *Highway Safety Manual* (HSM) (*13*). Harwood *et al* (*30*) developed this crash prediction model; the relevant CMF for horizontal curves only has inputs for length and radius of curve and whether a spiral transition is present or not.

Koorey tested how well the HSM model estimated expected crashes for a section of winding state highway in the South Island of New Zealand, featuring several out-of-context curves and two narrow bridges. He found that, without applying the crash history of the road, the model under-predicted actual crash numbers there by about 30%. By contrast, when the HSM model was applied to the subsequent realignment of this highway (featuring no sub-standard sections), the estimated crash numbers virtually matched the observed ones.

In reviewing the merits of IHSDM, Koorey (*28*) recommended further research be undertaken to incorporate the effect of inconsistent adjacent road elements and narrow bridges into its crash prediction model. McMullen & Mendis (*31*) investigated these effects and found that, by incorporating the decrease in speed and absolute speed for each road section element, modeled crashes had strong correlation ($r^2>0.95$) with observed crash numbers. The resulting crash prediction model was:

$$N = (\text{Base Crash Rate})\left(2.43e^{0.059D}\right)(-0.019V_2+1.99) \quad (8)$$

Where:

- N is predicted number of crashes
- V_2 is the speed of road element in mph

- V_1 is the road element entry speed in mph
- D is the decrease in Speed (V_1-V_2) in mph

McMullen & Mendis found that, prior to applying this correction to the IHSDM model, the base crash rate typically underestimated the observed crash numbers of inconsistent road elements by 30-60%.

APPLICATION OF CURVE SAFETY RESEARCH

The numerous studies described in the sections above lend themselves to various applications where they have been used in New Zealand (and beyond) to improve the safety of existing sub-optimal rural roads.

Project Evaluation

Much of the research presented in this paper has been initiated and/or supported by NZTA (or its predecessor organizations) in an effort to improve and standardize the design and evaluation of transport projects.

New Zealand has used some form of cost-benefit appraisal of major national roading projects since the early 1980s (*32*), which has included assessments of the social cost of death and serious injuries due to road crashes. Over this time the preferred approaches and corresponding guidance from government has evolved in line with road safety research. The introduction of the first national guidance in 1986 and a 1988 requirement for cost-benefit analyses of national roading projects further hastened the development of appropriate crash prediction tools, either via new research or application of existing findings.

The *Project Evaluation Manual* (PEM) was released in 1991 by Transit NZ (an early predecessor of NZTA) and included basic procedures to estimate crash risk (and its associated social costs), based on the previous work of Jackett (*16*), subsequently updated by Koorey and Tate (*17*).

The PEM was superseded by the *Economic Evaluation Manual* (EEM) (*33*) in 2006, which also included procedures to calculate the social costs of death and injury associated with road crashes. The EEM – and its present-day evolution, the *Monetised Benefits and Costs Manual* (MBCM) (*34*) – contain a number of accepted procedures to estimate crash risk, based on availability of crash history, expected changes to the site/corridor, and suitability of crash prediction models. Where historical crash data allows, the manual recommends an empirical Bayes approach, which combines predicted risk and observed crash data.

The *Crash Estimation Compendium* (CEC) (*18*) was introduced in 2018 as a companion to the EEM, containing crash prediction models for rural and urban environments, intersection and midblock crash types, and for vehicular, pedestrian and cyclist road users. The CEC compiled models from previous national studies such as those of Cenek et al. (*25*), Turner et al. (*23*), and Jackett (*16*). It also includes an extensive set of crash modification/reduction factors, largely from Australian and other international sources, supplemented with New Zealand research where available, that can be used to estimate the likely change in crashes due to a proposed safety treatment or other infrastructure change. Of particular relevance to this review, the CEC contains Equation (7) above, a univariate model of crash risk as a function of speed change for isolated rural curves.

Taken together, the CEC and other published guidance allow practitioners to appropriately estimate the safety performance (and associated economic benefits and costs) of a wide variety of road types and potential safety countermeasures, including those related to curve context.

Safety Prioritization of High-Risk Curves in New Zealand and USA

New Zealand curve safety research has also been successfully applied to optimize the prioritization of safety treatments. A key application has been to determine the consistency of curve advisory speed signage, both in terms of location and posted speed, to better warn drivers when curves are out of context. The research has also been used in the assessment of *crash migration:* occurring where infrastructure improvements will increase the approach speeds to downstream curves, potentially altering curve context and crash risk. The degree to which curves are out of context has been used as a proactive prioritization metric for curve improvements such enhanced delineation, the application of curve widening and/or the installation of roadside barriers on higher risk curves. The research has also been widely applied through the establishment of a skid resistance management policy for the NZ SH network.

NZTA's T10 skid resistance specification (*35*), first introduced in 1997, prioritized road segments for surface improvement using a risk-based approach that aimed to equalize predicted crash risk, such that higher levels of surface treatment are applied to higher-risk segments, particularly small-radius curves. This contrasted with a prior approach that applied minimum skid resistance values determined only by operating speed and ad-hoc identification of areas with higher friction demand. An analysis of this specification by Cook et al (*36*) estimated that by 2008, the T10 standard resulted in a 15% to 25% reduction in wet weather curve crashes, as measured by the difference between trends for curve crashes in wet and dry conditions. Under the economic appraisal procedures of the time, the introduction of this standard was estimated to have resulted in economic benefits 13 to 35 times greater than its economic costs. This specification was further strengthened in 2011 by the addition of curve context as a prioritization metric, based on the work of Cenek et al. (*24*) and Brodie (*37*).

NZ curve safety research has seldom been applied internationally, particularly as it relates to curve context. However, crash prediction models incorporating curve context have been recently developed as part of the *Abley SafeCurves* software (*38*, *39*), which adapts the approach of Abeysekera et al. (*26*) to the United States context. An operating speed model and derived curve geometry are used to estimate context at every curve in a desired network, classifying these curves as Class 1 (most out of context), Class 2, and Class 3 (least out of context). Consistent with Abeysekera et al., these classifications are equivalent to "unacceptable", "undesirable", and "acceptable" curve geometries from Austroads geometric design guidance (**Figure 6**, above). These classifications are used as inputs to a crash prediction model that predicts risk based on curve context and other geometric characteristics. Corridors are prioritized for potential safety treatment according to the risk of out-of-context curve crashes (*40*). The model is fitted to crash data from Arkansas and California, with an example of corridor priority predictions and curve context classification shown in **Figure 7**. In Arkansas, the highest-priority 25% of the network by length accounts for over two-thirds of out-of-context curve crash risk, consistent with empirical data on the distribution of crash risk and highlighting the value of targeted safety improvements.

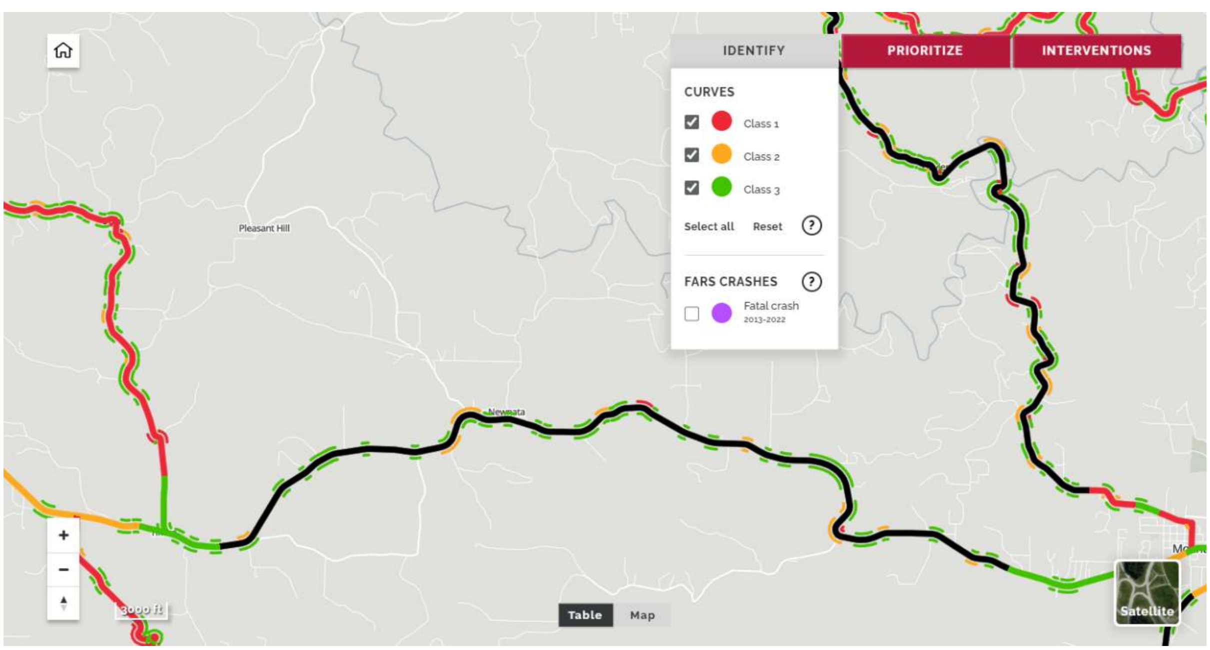

Figure 7 *SafeCurves* curve context and corridor priority detail (State Route 66 near Mountain View, Arkansas)

CONCLUSIONS AND FUTURE DIRECTIONS

Understanding the relative crash risk of curves on rural two-lane roads is a critical factor in helping to address the safety problems present at many sub-standard curves around the world. Many of the relevant attributes of road curves have been investigated to develop a clearer picture of the most pertinent contributors to higher crash risk, including curve radius, length and spiral geometry. However, historically there has often been a gap in recognizing the role that curve context (relative to the surrounding road environment) plays in crash risk.

Considerable New Zealand research over several decades has recognized this issue, particularly regarding the relative change in travel speeds when entering a curve. It is evident from this work that greater drops in travel speed approaching curves typically result in greater crash risks, and several crash prediction models and crash modification factors have been developed to capture this effect. Furthermore, the application of these models to the NZ State Highway network has enabled optimized deployment of safety treatments, resulting in significant safety benefits, including a 15-25% reduction in wet weather crashes (*36*). By contrast, traditional crash prediction models such as those in the *Highway Safety Manual* have been found to underestimate the observed numbers of crashes around out-of-context curves by at least 30%, and potentially up to 60%.

While some more recent work has begun to apply these insights to modeling in other jurisdictions, it is hoped that this review can further encourage the application of these models and factors by other practitioners (or similar research undertaken elsewhere) to produce more robust estimates of crash likelihood on rural curves. New Zealand's experience indicates that improved analysis of rural curve risk can produce large real-world reductions in deaths and serious injuries.

The United States has an extensive rural road network characterized by high crash rates, indicating a need for effective targeting of safety improvements. Further consideration of curve context when estimating safety performance, as introduced by the *SafeCurves* software tool, is recommended. The scale of the US network and its richer data availability should also enable refinement or re-estimation of the New Zealand curve context safety models. This could include confirmation of appropriate functional forms and assessment of the relative importance of curve context compared to other factors, such as traffic volumes and operating speeds. Refinement of associated operating speed models and geometry datasets would also strengthen this promising research direction.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: J. Corbett-Davies, S. Turner, F. Tate, G. Koorey, S. Abley; draft manuscript preparation: J. Corbett-Davies, S. Turner, F. Tate, G. Koorey, S. Abley. All authors reviewed the results and approved the final version of the manuscript. A language model (Microsoft Copilot) was used to generate an initial draft of the abstract.

REFERENCES

1. Wanty, D. Application of Road Geometry Data Acquisition System (RDGAS). in *Seventh World Conference on Transport Research*, Sydney, Australia, 1995.
2. Koorey, G.F. The Use of Road Geometry Data for Highway Applications. in *3rd International Symposium on Highway Geometric Design*, Chicago, United States, 2005.
3. New Zealand Transport Agency. Crash Analysis System (CAS). *New Zealand Transport Agency*, https://cas.nzta.govt.nz/. Accessed July 24, 2025.
4. Transfund NZ. RAMM Road Condition Rating and Roughness Manual. Transfund NZ, Wellington, New Zealand, 1997.
5. Rawlinson, W.R. The ARRB Road Geometry Instrumented Vehicle - General Description. ARRB, Vermont South, Victoria, Australia, 1983.
6. Austroads. Guide to Road Design - Part 3: Geometric Design. Austroads, Sydney, Australia, 2021. https://austroads.gov.au/safety-and-design/road-design/guide-to-road-design.
7. Turner, S., and F. Tate. Road Geometry and Drivers Speed Choice. in *IPENZ Transportation Group Conference*, Tauranga, New Zealand, 2007.
8. Turner, S., and F. Tate. Relationship between Road Geometry, Observed Travel Speed and Rural Accidents. New Zealand Transport Agency, Research Report 371, 2009.
9. Lamm, R., A. Beck, and K. Zumkeller. Analysis and Evaluation of Interrelationships between Traffic Safety and Highway Geometric Design on Two-Lane Rural Roads. in *Proceedings of the 2nd International Symposium on Highway Geometric Design*, Mainz, Germany, 2000.
10. Cairney, P., and A. McGann. Relationship Between Crash Risk and Geometric Characteristics of Rural Highways. Austroads, Austroads Publication AP-R162/00, 2001.
11. Elvik, R. The more (sharp) curves, the lower the risk. *Accident Analysis & Prevention*, Vol. 133, 2019. DOI: https://doi.org/10.1016/j.aap.2019.105322.
12. Donnell, E., R. J. Porter, L. H.I. Li, S. C. Himes, and J. Wood. Reducing Roadway Departure Crashes at Horizontal Curve Sections on Two-lane Rural Highways. Federal Highway Administration, Washington, DC, 2019.
13. American Association of State Highway Transportation Officials (AASHTO). *Highway Safety Manual.*, 1st ed. Washington, DC; United States, 2010. https://www.highwaysafetymanual.org/.
14. Hauer, E. Safety of Horizontal Curves. Draft IHSDM literature review 2000.
15. Matthews, L., and J. Barnes. Relation between road environment and curve accidents. in *Australian Road Research Board (ARRB) Conference, 14th, 1988*, Canberra, Australia, 1988.
16. Jackett, M. J. On which curves to accidents occur? A policy for locating advisory speed signs. in *IPENZ Annual Conference*, 1992.
17. Koorey, G.F., and F.N. Tate. Review of Accident Analysis Procedures for Project Evaluation Manual. Transfund New Zealand, 1997.
18. New Zealand Transport Agency. Crash Estimation Compendium, Second Edition, Version 3. *Monetised Benefits and Costs Manual*, 2018. https://www.nzta.govt.nz/assets/resources/monetised-benefits-and-costs-manual/crash-risk-factors-guidelines-compendium.pdf. Accessed July 28, 2025.
19. Transit New Zealand. State Highway Geometric Design Manual. Transit New Zealand, Wellington, 2003.
20. Cenek, P.D., R.B. Davies, M.W. McLarin, G. Griffith-Jones, and N.J. Locke. Road Environment and Traffic Crashes. Transfund New Zealand, 1997.
21. Cenek, P.D., and R.B. Davies. Crash Risk Relationships for Improved Safety Management of Roads. in *Towards Sustainable Land Transport Conference*, Wellington, New Zealand, 2004.

22. Turner, S., R. Singh, and F. Tate. Next generation of rural roads crash prediction models - pilot study. New Zealand Transport Agency, Research Report 437, 2011.
23. Turner, S., R. Singh, and G. Nates. The next generation of rural road crash prediction models: final report. New Zealand Transport Agency, Research Report 509, 2012.
24. Cenek, P., C. A. Brodie, R. B. Davies, and F. N. Tate. A prioritisation scheme for the safety management of curves. in *3rd International Surface Friction Conference*, Gold Coast, Australia, 2011.
25. Cenek, P., R. Henderson, and R. Davies. Modelling crash risk on the New Zealand state highway network. New Zealand Transport Agency, Research Report 477, 2012.
26. Abeysekera, R., C. Brodie, P. Durdin, R. Gardener, D. Harris, and C. O'Neil. Vehicle Speed and Risk Modeling of Horizontal Curves at a Network Level. in *Transportation Research Board 97th Annual Meeting*, Washington DC, United States, 2018.
27. Austroads. Guide to Road Design Part 3: Geometric Design. Austroads, Sydney, Australia, 2009.
28. Koorey, G. F. Incoporating Safety Into Rural Highway Design. Department of Civil & Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand, PhD Thesis 2009.
29. Federal Highways Administration. Interactive Highway Safety Design Model (IHSDM). *Federal Highways Administration*, 2005. https://highways.dot.gov/safety/data-analysis-tools/rsdp/rsdp-tools/interactive-highway-safety-design-model-ihsdm. Accessed July 19, 2025.
30. Harwood, D.W., F.M. Council, E. Hauer, W.E. Hughes, and A. Vogt. Prediction of the Expected Safety Performance of Rural Two-Lane Highways. Office of Safety Research and Development, (US) Federal Highway Administration, Washington, DC; United States, Report No. FHWA-RD-99-207, 2000.
31. McMullen, A., and K. Mendis. Improvements to the Interactive Highway Safety Design Model. Dept of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand, Final Year Project 2014.
32. Douglas, N., A. Lawrence, I. Wallis, and D. Wignall. A Review of Transport Project Appraisal in New Zealand. ITS Leeds University, 2013. https://www.researchgate.net/publication/316788936_A_Review_of_Transport_Appraisal_in_New_Zealand.
33. Land Transport New Zealand. *Economic Evaluation Manual, Vol. 1*, 1st edition, Ed. Wellington, New Zealand.
34. New Zealand Transport Agency. Monetised Benefits and Costs Manual v.1.7.3. *New Zealand Transport Agency* , 2025. https://www.nzta.govt.nz/resources/monetised-benefits-and-costs-manual/. Accessed July 18, 2025.
35. New Zealand Transport Agency. T10 Specification for state highway skid resistance management. *New Zealand Transport Agency*, 2013. https://nzta.govt.nz/resources/skid-resistance-investigation-treatment-selection/. Accessed July 28, 2025.
36. Cook, D., D. Whitehead, and J. Towler. An Evaluation of the Economics of New Zealand's Skid Resistance Policy. in *3rd International Surface Friction Conference*, Gold Coast, Australia, 2011.
37. Brodie, C. Risk Ranking of Curves on New Zealand State Highways for Skid Resistance Monitoring and Treatment. Transit New Zealand, 2016. https://saferroadsconference.com/wp-content/uploads/2016/05/Colin-Brodie-Risk-Ranking-of-Curves-NZ-SH.pdf.
38. Abley. SafeCurves. *Abley*, https://abley.com/safecurves. Accessed July 25, 2025.
39. Abley. SafeCurves: Identify - White Paper. *Abley*, 2023. https://abley.com/safecurves-identify. Accessed July 25, 2025.
40. Corbett-Davies, J., C. Tredinnick, S. Turner, P. Durdin, and S. Abley. Prioritizing Safety Treatment of Rural Corridors Using Curve Context. in *Transportation Research Board 104th Annual Meeting*, Washington DC, United States, 2025.