Peer-reviewed papers

From research to practice – development of a rural mass curve treatment program

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Abstract

Rural road curves provide one of the most challenging features to be negotiated by drivers on high speed rural roads. As a result, many drivers make errors resulting in run-off-road and head-on casualty crashes. It has been estimated that such curve crashes on curves account for 18% of all serious casualty crashes on rural roads in Victoria. In order to address this problem VicRoads funded ARRB to investigate and develop a rural mass curve treatment program.

This paper presents overseas and local research background leading to the development of an engineering model for categorising curves according to their crash risk. The risk model prioritised curves to the right, with greater approach speed, change in speed, narrower pavement and a steeper downhill grade. The paper then describes how this research was used to propose an economically viable $100 million road safety funding program using standardised delineation treatment packages applicable to each curve along a route. Such an approach is expected to provide a consistent level of curve delineation and warning, and thus, condition drivers to better respond to the crash risk of the curves ahead. The program is proposed to be applied on selected rural routes with a history of run-off-road and head-on casualty crashes. It is expected the program will save 28 lives and 315 serious injuries over the treatment life.

Introduction

The task of driving on a curve represents a major increase in the risk of driver error, loss of control and a crash event. This is caused by the centrifugal force due to vehicle's inertia which needs to be constantly countered by side friction and corrective action of the driver. Failure to adjust speed and correct vehicle's direction results in a run-off-road event which is sometimes over-corrected. In some cases, such over-correction events result in head-on crashes with opposing traffic.

In the five-year period of 2009 to 2013, run-off-road and head-on crash types accounted for 38% of all serious casualty crashes (i.e. fatal and serious injury) in Victoria, equally proportioned between urban and rural roads. On the rural roads, 32% of these crashes occurred on curves. Figure 1 shows the breakdown of serious casualty crashes on the Victorian road network by crash type (ROR stands for run-off-road, and HO for head-on).

Overall, run-off-road and head-on crashes on curves accounted for 18% of all serious casualty crashes, and 21% of all fatal crashes, on rural roads in Victoria. For these reasons, reducing the risk of these crash types on rural roads was seen as a strategic direction in reducing serious casualties. There was a keen interest by TAC and VicRoads (The Victorian State Road Authority; future program's developer and administrator) to treat curves in a systematic way across the rural road network using low-cost treatments. It was recognised that strict crash history-based approaches would result in inconsistent application of treatments along rural routes, as most curves have no recent casualty crash history. A risk-based approach was preferred in order to deliver a mass treatment of rural curves.

This paper describes how international research evidence was used to develop an engineering risk model for categorising rural road curves according to their risk of run-off-road and head-on crashes. Each curve along a given route was assigned a low-cost delineation treatment package consistent with its risk category, based on the risk score. Such an approach is expected to provide a consistent level of curve delineation and warning, and thus, condition drivers to better respond to the crash risk of the curves ahead. Using additional road network data, the model was used to prepare a successful business case for a rural curve mass treatment program. The paper then describes development of program guidelines and a curve risk categorising practitioner tool. The tool will be used in preparation of candidate projects for a TAC-funded mass curve treatment program implemented by VicRoads.

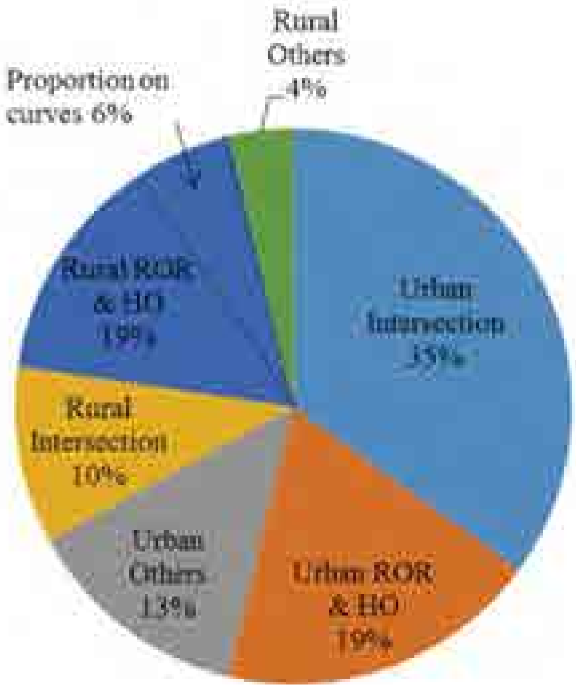


Figure 1. Serious casualty crashes in Victoria (2009 – 2013)

Literature

Herrstedt and Greibe [4] proposed one of the earlier approaches to ranking curves according to risk. This theoretical approach proposed that the change in speed at a curve (difference between approach and design speeds) was the main driver of crash risk. Large change in kinetic energy was proposed to relate to crash severity. They proposed a chart which recognised both the magnitude of speed change and the approach speed. The key innovation of their approach was assignment of five curve risk categories as shown in Figure 2. Each risk category was to be assigned a standardised low-cost delineation treatment package. Herrstedt and Greibe [4] proposed that treatments should be consistent, unambiguous, understandable and easily recognisable. This approach would create driver association between the surprise element (inconsistency), required braking, mental workload and the observed delineation level. It was required that all curves were to be treated along a route to create repetition of the experience.

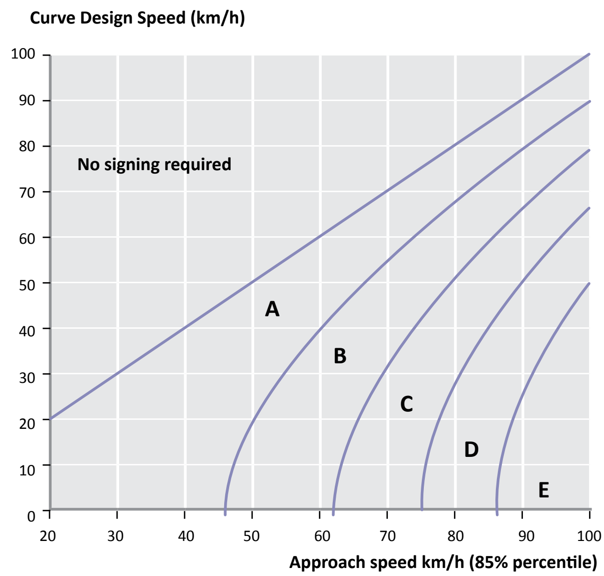


Figure 2. Curve risk categories. Source: Herrstedt and Greibe [4]

The risk categories ranged from low (A) to very high (E). Kirk, Hills and Baguley [7] developed this approach further by designing proposed treatment packages as shown in Figure 3.

Cardoso [2] developed this approach further in Portugal to address the serious problem of curve crashes on rural roads (approx. 31% of all casualty crashes in rural areas). The basic theoretical model was replaced by empirically-developed models for estimating average approach tangent speed, and average speed through the middle part of a curve. These complex equations used factors such as average bendiness (° per km) and average level change (m/km) in the 500m segment preceding the curve, the previous curve radius, pavement width, tangent and curve lengths, and presence/lack of sealed shoulders. These models were in essence similar to operating speed models used in Australia and New Zealand.

The calculated curve and tangent speeds were used in Cardoso's crash prediction models estimating crash rates for curve and approach tangent segments, and the ratio of these (VRAC). Cardoso proposed then that the curve inconsistency factor (FH) should be based on the product of VRAC and the ratio of approach tangent and curve kinetic energies (Equation 1). A higher value indicated a greater inconsistency of the curve with the preceding tangent.

$$FH = VRAC \times \frac{E_c^{tangent}}{E_c^{curve}} \qquad (1)$$

where

FH = inconsistency factor

$VRAC$ = ratio of the injury crash rates on curve and tangent

$E_c^{tangent}$ = kinetic energy at the approach speed (J)

E_c^{curve} = kinetic energy at the speed on the curve (J)

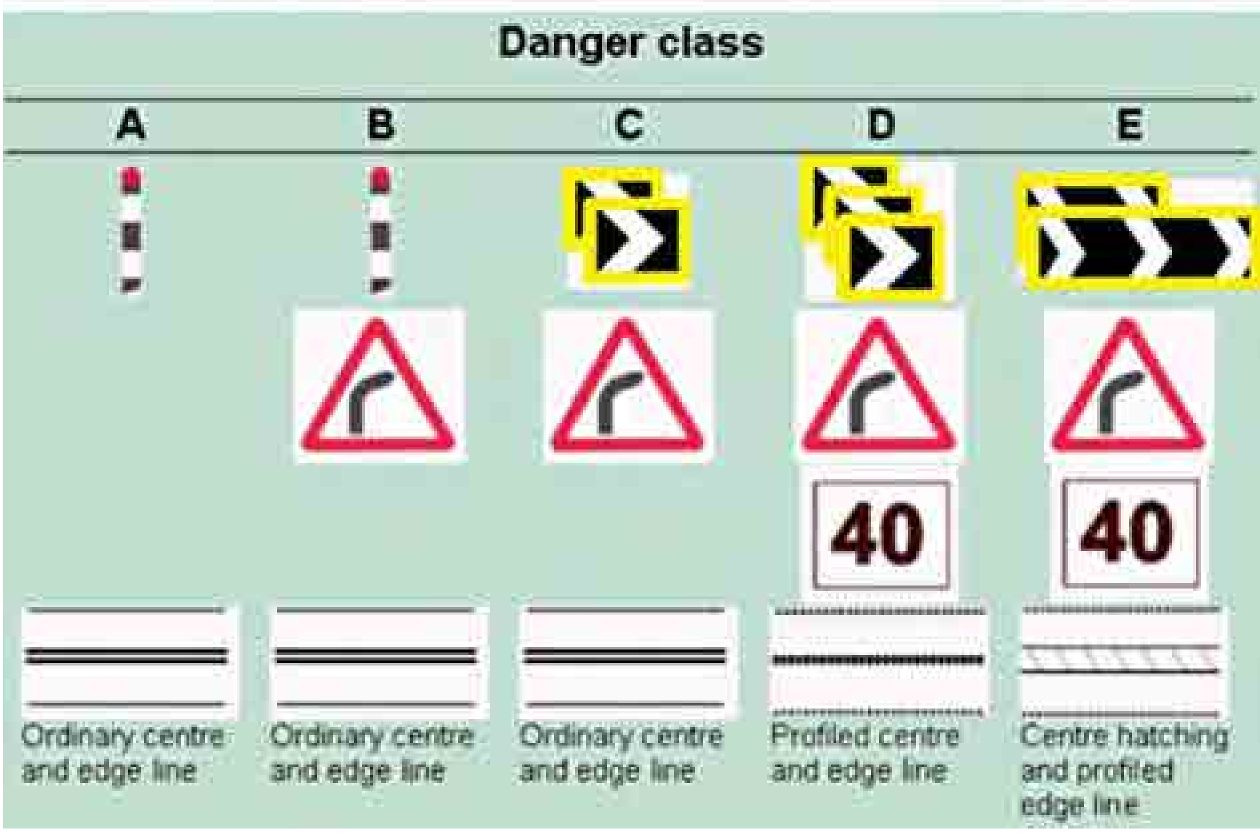


Figure 3. Low-cost treatments for different curve risk categories. Source: Kirk, Hills and Baguley [7]

The major advantage of Cardoso [2] and Herrstedt and Greibe [4] models is that they recognised that both the approach speed and speed change are relevant in the crash risk on curves.

Cardoso developed five curve risk categories based on the inconsistency factor (FH), speed reduction threshold (< or ≥ 5 km/h), deceleration threshold (< or ≥ 2 m/s^2), and presence/absence of sealed shoulders. It appears that approach tangent speed and change in speed were included in the risk categorisation process multiple times. It is not clear why this was seen as appropriate.

As with previous work by Kirk, Hills & Baguley [7], Cardoso [2] proposed five standard treatment packages increasing in delineation and warning sign components as the risk category increased.

Only preliminary, single-year before/after evaluation of the effectiveness of this approach could be identified [3]. The approach, combined with other treatments such as speed limit reduction pavement and drainage treatments, resulted in reported 'risk reduction' of 18% and fatality reduction of 46%. Gomez noted that evaluation could not be completed due to crash data collection difficulties.

Development of the curve risk model

VicRoads sought to develop a curve risk ranking approach with the view to assess all curves on B and C rural routes in Victoria. The B and C routes are the lower order state-controlled rural roads. They carry lower traffic volumes and are typically of a lower design standard than rural highways (A routes). Geometric design inconsistencies were more common, especially on C routes, although isolated curve improvements have been carried out in recent years in response to crash history at individual curves. This added to route-level inconsistency in how the individual risk level of each curve was communicated to a driver. There was a need to develop a curve-specific risk model, and to use it to estimate inputs into a business case for a curve mass treatment road safety program.

Work of Cardoso [2] influenced the approach, although it was agreed that it was overly complex and based on the attributes of the Portuguese road network which may not translate well to Victoria. There was insufficient data available in Victoria to develop similar models. Also, there was a concern that complex models would require inputs requiring costly and time-consuming data collection by practitioners. Such limitations would impede success of a future road safety program. It was agreed to focus on developing an engineering model similar to that proposed by Cardoso [2], but better suited to rapid deployment by VicRoads regional offices.

The critical step in the process was to use research evidence for the key risk factors in curve crashes. These were obtained from reviewing recently published Austroads projects on rural road safety. The initial list of targeted casualty crash risk factors considered were:

- radius of curvature
- curve direction
- clear zone, roadside hazard density, type of hazards
- the overall alignment standard expressed as curves per kilometre
- superelevation
- curve transition – presence, quality
- sealed pavement width
- lane width
- sealed shoulder width
- unsealed shoulder width
- grade
- approach speed
- change in speed at the curve
- AADT.

The quality of the available research evidence for some risk factors was weak (e.g. superelevation). Other factors were well researched, but their influence on crash risk was low (e.g. hazard density). Other risk factors were correlated with each other (e.g. pavement width, sealed shoulder width, lane width and clear zone). After careful consideration, the project team reached consensus to select the following risk factors for the model: curve direction, approach speed and change in speed, sealed pavement width and grade. Traffic flow, AADT, was not included as it describes exposure to risk, rather than the risk itself. It was important to create a model which described the individual driver's risk of curve crash.

The relative risk for curve direction was derived from new analysis of Victorian rural curve data sourced from a recent Austroads project [6]. Table 1 shows that curves leading to the right were relatively more likely to have a run-off-road casualty crash than curves leading to the left. The risks related to differences in crash rates with the risk value of 1.00 being the average crash rate for all curves.

Table 1. Relative run-off-road casualty crash risk on curves of given their direction

Curve direction	Relative risk
Left	0.79
Right	1.21

Cardoso [2] developed crash prediction models to calculate crash rate given approach tangent speed and speed change at the curve. Two variants were developed: in presence of paved and unpaved shoulders. Given that a similar variable, the sealed pavement width, was already included in the model, Cardoso's results were interpolated to account for both shoulder scenarios. The relationship between the relative curve crash risk, average approach speed and average change in speed at the curve is presented as a matrix in Table 2.

Table 2. Relative curve casualty crash risks based on approach speed and speed reduction

	Average speed on the approach tangent (km/h)					
Average change in speed (km/h)	**60**	**70**	**80**	**90**	**100**	**105**
1	1.00	1.16	1.33	1.49	1.66	1.74
10	2.12	2.48	2.83	3.19	3.54	3.72
20	2.67	3.11	3.56	4.00	4.45	4.67
30	3.05	3.56	4.07	4.57	5.08	5.34
40	3.35	3.91	4.47	5.03	5.59	5.87
50		4.21	4.81	5.41	6.01	6.31
60			5.14	5.75	6.38	6.70
70				6.04	6.72	7.05
80					7.02	7.37
90						7.66

Source: adapted from Cardoso [2]

The analysis of this design feature relating to Victorian rural undivided road data and run-off-road casualty crashes was reported in Jurewicz and Pyta [6]. The relationship is shown in Table 3.

Table 3. Relative run-off-road casualty crash risks for various sealed pavement widths

Pavement width (m)	Relative crash risk
< 6	2.70
6–7	1.69
7–8	1.57
8–9	1.13
9–10	1.00

Source: Jurewicz and Pyta [6]

Similarly, Jurewicz and Pyta provided the relative risk values for the effect of road grade, based on run-off-road casualty crashes and on the same sample of Victorian rural undivided roads.

Table 4. Relative run-off-road casualty risks of positive and negative grades

Grade (%)	Run-off-road relative crash risk
> 6	2.60
4 to 6	1.80
2 to 4	1.40
0 to 2	1.00
0 to -2	1.20
-2 to -4	2.00
-4 to -6	3.40
< -6	5.60

Source: Jurewicz and Pyta [6]

At first a simple multiplicative model was created and applied to all curves of radius less than 600 m on a 400 km sample of rural Victorian B and C roads (200 km of each type). (Jurewicz and Pyta [6] showed that risk of a run-off-road casualty crash was not significantly elevated for curves with radius greater than 600 m). Using an assumption that risk score should have a normal distribution, the model was iteratively refined by adjusting its form and weighting factors. It was expected that the majority of curves across the network should have low to moderate risk score, a significant minority should be moderate and a small minority be of high risk. The final form of the model was as shown in Equation 2.

$$\text{Curve risk score} = RR_{dir}[(0.6 \times RR_{\Delta approach\ speed} \times RR_{pavement\ width}) + (0.4 \times RR_{grade})] \quad (2)$$

where:

RR_{dir} = relative risk of the curve direction (right, left)
$RR_{\Delta approach\ speed}$ = relative risk of the change in approach speed, including its original value
$RR_{pavement\ width}$ = relative risk of the pavement width
RR_{grade} = relative risk of the road grade

The application of the model produced the following distributions of the risk scores shown in Figures 4 and 5.

Figure 4. Curve risk scores for C roads

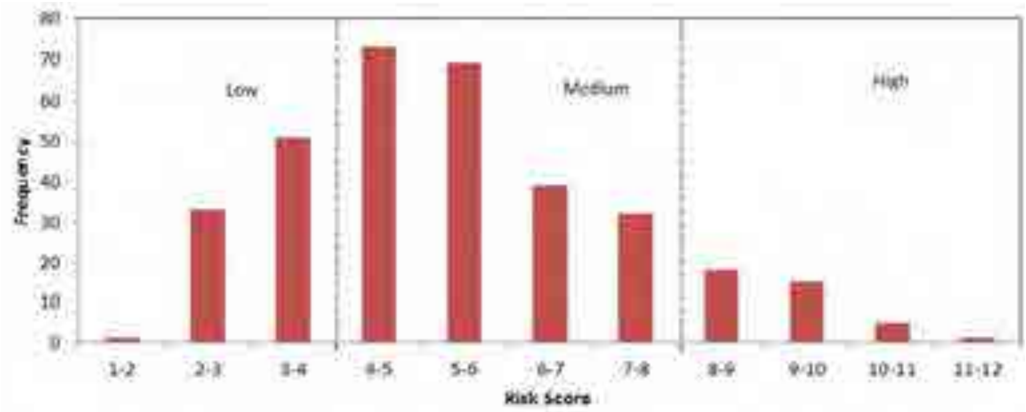
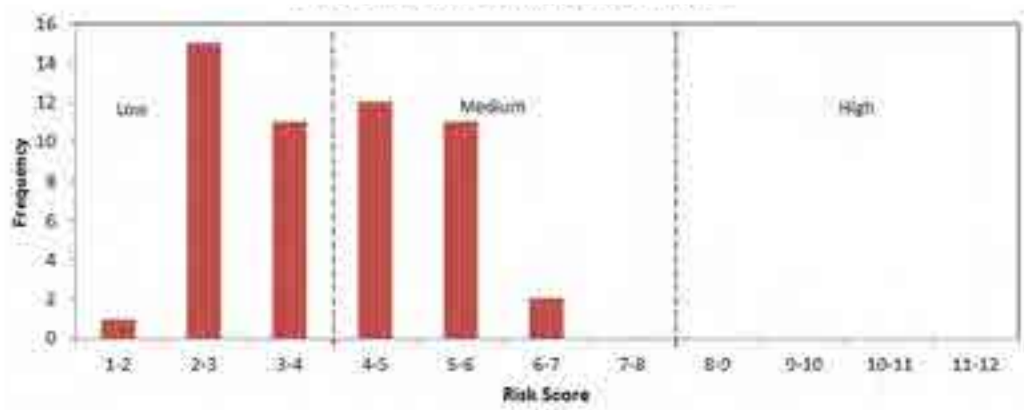


Figure 5. Curve risk scores for B roads



Risk rating of curves on B and C roads confirmed the assumption, although B roads had significantly fewer curves given the same length, and the curves were of lower risk. This confirmed the overall higher design standard of B roads.

To simplify the European approach, only three risk categories were created: low, medium and high, as shown in Figures 4, 5 and 6. Visual sense-checking was applied to a selection of scored curves to confirm the model and risk categories produced results credible to drivers, i.e. high-risk curves were significantly more inconsistent with the approach tangent, than low-risk curves.

Figure 6. High, medium and low-risk category curves

This division into three risk categories allowed the introduction of a consistent treatment package for each category. The treatments were sourced from the VicRoads signs and linemarking guidelines and vetted by VicRoads engineers. The treatments were generally somewhat more generous than the guidelines. Many were made dependant on site conditions, mainly the pavement width along the route.

Low-risk curves received minimal treatment consistent with the approach tangent. Medium-risk category received the same plus additional warning devices. High-risk curves were to be equipped with same as medium plus Chevron Alignment Markers (CAMs) and advisory speed signs.

Additionally, the worst of the high-risk curves will be also eligible for additional treatments such as hazard removal, pavement widening and safety barrier installation. This level of treatment could only be recommended by regional engineers on case-by-case basis, following site inspections, where additional risk factors were present that were not accounted for by the model (e.g. a high roadside drop-off, an intersection, or high number of serious casualty crashes). However, the need to achieve a competitive BCR for each route will place constraints on the type and the extent of these additional treatments.

Each treatment package had an associated crash reduction factor (CRF) estimated from the combination of treatment CRFs, as shown in Table 5.

Table 5. Proposed treatment packages for each curve risk category, with estimated CRFs

Curve type	Treatments	Combined CRF
Low risk	1) Guideposts 2) Edge line (only if pavement width allows) 3) Centreline (only if pavement width allows)	22%
Medium risk	4) RRPM (only if linemarking exists or is possible) 5) Audio-tactile (only if pavement width allows) 6) Curve warning signs for isolated or group of curves	51%
High risk	7) CAMs 8) Advisory speed signs 9) Pavement widening, hazard removal, safety barriers (site-conditional)	57%

As an economic modelling exercise, the correct treatment was hypothetically applied to each risk scored curve in the 400 km road sample. Where curve run-off-road and head-on casualty crashes were recorded in the previous five years, the relevant treatment CRF was applied (only some curves had past crashes). Thus crash savings could be calculated separately for B and C routes. Similarly, treatment costs were estimated using recent historical unit cost rates provided by VicRoads. This approach allowed approximation of risk category and treatment package distribution on B and C routes and of the expected program BCRs for each road category.

Rural mass curve treatment program development

The economic exercise was sufficiently encouraging to extend it into a network-level economic model of program benefits and costs. A proposal was developed and submitted for TAC consideration. TAC approved a $100 million sub-program under the $1 billion Safe System Roads Infrastructure Program (SSRIP) funded by the TAC, to address these prominent crash types on curves of B and C rural roads.

The program is to be applied on all B routes and on the worst performing 6% of C routes, which have 35% of curve run-off-road and head-on serious casualty crashes. The selection of candidate routes for consideration in this program is based on the historic number of serious casualty run-off-road and head-on crashes which occurred on curves of the whole route. This approach ensures only routes with the highest collective risks are included and the highest return from investment can be achieved (ranked by BCR and dollars per serious casualty saved). While only 6% of C routes are proposed to be treated, the high number of curves on this part network demands the greatest expenditure. Treatments in Table 5 will be applied according to risk rating of each curve on the selected routes and local engineering input.

The expected program-level crash reduction factor of 33% is expected, with 28 lives and 315 serious injuries saved over the 15-year life of the treatments. The program is expected to deliver a BCR of 3.7, or the cost of $116,618 per each serious casualty saved.

Program guidelines and curve risk rating tool

Program guidelines were developed to assist regional road safety engineers in preparation of candidate projects. VicRoads used its crash database to rank B and C routes based on curve run-off-road and head-on crash history per kilometre in the latest five-year period. Top routes were prioritised for further assessment by regional engineers in the first year of the program.

The risk model was converted into a practitioner tool in Microsoft Excel to enable rapid risk assessment of all curves along any selected route using Gipsi-Trac data as a source. (GipsiTrac provides a set of geometric road attributes with GPS coordinates at 10m intervals for the entire state road network. Calibrated digital video is also available enabling measurement of other attributes such as widths and lengths). Gipsi-Trac calculates instantaneous traffic speed which was used by the tool to estimate average approach and curve speeds. The speed profile along the road was calculated within the tool using acceleration rates

Curve No	Pavement Width (m)	Risk Score (Fwd)	Risk Score (Rev)	Ranking (Fwd)	Ranking (Rev)	User Defined Ranking (Fwd)	User Defined Ranking (Rev)	Comments
10	6.4	3.66	2.55	LOW	LOW			
11	6.4	1.81	2.44	LOW	LOW			
12	6.4	1.91	1.71	LOW	LOW			
13	6.4	1.81	3.10	LOW	LOW			
14	6.4	3.58	5.39	LOW	MEDIUM			
15	6.4	1.18	1.71	LOW	LOW			
16	6.4	4.45	2.83	MEDIUM	LOW			
17	6.4	5.29	4.98	MEDIUM	MEDIUM			

Figure 7. Aspects of the curve risk rating tool

for straights sourced from Austroads [1] and the speed limit as an upper limit. Gipsi-Trac also produces grade information which was used by the tool to calculate average grade through the curve. This allowed practitioners to focus on driving each route, checking the appropriateness of estimated approach and curve speeds, and measuring the sealed pavement width. Other data may also be entered into the spreadsheet by practitioners such as curve crash records, risk category override and any additional comments to justify it (e.g. additional risk factors). Figure 7 shows different aspects of the tool. For example, curves' different directional categorisation, depending on curve direction and grade. Also, the tool provides an easy mapping export option to Google Earth.

Once all curves on a given route are assessed, engineers estimate the cost of works, obtain relevant crash details from the database, and use the VicRoads tool for estimating the project BCR. All candidate projects in this program which are above the funding BCR threshold nominated by TAC are to be funded.

Discussion

A crash-predictive statistical model based on the target crash group and B and C road network data would be a preferred tool for risk-rating curves. The modelling process would identify the statistically significant factors and quantify their influence on crash risk. The reason why an engineering risk model was chosen instead was that there was insufficient data available to create a viable statistical model. Modelling multiple independent variables using zero-inflated road segment and crash data relies on very large data sets (most curves have no crash history). Crash modelling experience gained during recent Austroads projects using the low-volume Victorian rural road data suggested that a sample of several thousand kilometres or B and C curve segments would be required [6, 5]. Such data sets were simply not available in Victoria, given that curves constituted only 10% of the targeted network.

The engineering risk model based on literature findings offered a more efficient way of building a model. The subsequent sense-checking on-site provided further confidence that curve crash risk categories were assigned accurately. Addition of further flexibilities in the program guidelines (e.g. case-by-case assignment of safety barrier and shoulder treatments) provided further assurance that risk factors excluded from the model would be considered.

Still, the engineering model presents certain limitations. For example, the role of superelevation could not be accounted as evaluation of this risk factor was not well documented in published literature. This aspect should be investigated further, as pavement superelevation at curves is a common treatment for run-off-road crashes.

One limitation of the overall approach is that the model and the funding program recommend mainly delineation treatments. They do not seek to address en-masse other underlying causes of curve crashes that may require more substantive works, e.g. realignment, or pavement rehabilitation. Feedback from regional engineers during development of the funding program guidelines suggested that pavement regulation problems, potholes and poor skid resistance were increasing risk factors behind curve crashes. On some routes, recreational motorcycling was also a key driver of curve crash risk. These factors may need to be accounted for by regional engineers and fed back to VicRoads for consideration in future asset management budgets on B and C roads. Future risk models should consider inclusion of such factors where data permits it.

Conclusions

This paper showed how overseas and local research evidence was combined to develop an engineering crash risk assessment model for ranking of curves. A funding program and project development guidelines were developed to assign standardised delineation treatment packages according to each curve's risk category. Such an approach will provide a consistent level of curve delineation and warning along selected routes, and thus, condition drivers to better respond to the crash risk of the curves ahead.

The risk model was used to secure funding for a $100 million rural curve mass treatment program to be rolled out across Victorian B and C roads over ten years. A practitioner tool was developed to deliver rapid ranking of curves on prioritised routes. Estimated benefits included savings of 28 lives and 315 serious injuries over the life of the treatments.

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Estimating crashes attributable to low and high level speeding: Melbourne compared with Perth and urban Queensland

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Abstract

Relationships linking travel speeds with the risk of casualty crashes have been combined with on-road speed surveys to estimate the proportion of crashes associated with each speed range and potentially attributable to speeding at different levels. This paper used speeds recorded by mobile speed cameras operated covertly in Melbourne 60 km/h speed limit zones. A 1% sample of mobile camera sessions was used to provide estimates of the proportion of casualty crashes attributable to low and high level speeding, using analysis methods similar to those used previously to analyse large speed surveys in Perth and urban Queensland. The analysis compared the results from functions linking casualty crash risk with absolute speed or with the difference between travel speed and the mean speed (mean-centred speed). The effect of different caps on the magnitude of the risk at high speeds was also examined.

The study concluded that a low cap placed on the risk functions is not justified; however analysis using higher caps should make use of the 95% confidence limits on the risk estimate. A rescaled version of the mean-centred speed risk function, referenced to the risk at the speed limit, provides similar results to the risk function based on the absolute speed in 60 km/h limit zones. Rescaled mean-centred speed risk functions could be applied with some confidence to estimate the casualty crash risk, relative to that at the speed limit, at speeds in other urban and rural speed limit zones. From the empirical results, it was also concluded that the pattern of speeding and its contribution to casualty crashes in Melbourne 60 km/h limit zones was very different from that in 60 km/h zones in Perth and urban Queensland.