Effect of clear zone widths on run-off-road crash outcomes

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Abstract

Current guidelines on clear zone selection and roadside hazard management adopt the US approach based on the likelihood of roadside encroachment by drivers. This approach is based on the available research conducted in the 1960s and 70s. Over time, questions have been raised regarding the robustness and applicability of this research in Australasia in 2010 and in the Safe System context.

This paper presents a review of the fundamental research relating to selection of clear zones. Results of extensive rural highway statistical data modelling suggest that a significant proportion of run-off-road to the left casualty crashes occurs in clear zones exceeding 13 m. They also show that the risk of run-off-road to the left casualty crashes was 21% lower where clear zones exceeded 8 m when compared with clear zones in the 4 – 8 m range.

The paper discusses a possible approach to selection of clear zones based on managing crash outcomes, rather than on the likelihood of roadside encroachment which is the basis for the current practice. It is expected that this approach would encourage selection of clear zones wider than 8 m when the combination of other road features suggests higher than average casualty crash risk.

Keywords

Roadside, clear zone, run-off-road casualty crashes, road design, shoulders

Introduction

Since the early 1960s, the concept of a clear zone has been employed by road authorities in many countries. The design aim of providing a width of roadside free of hazards is to increase the probability of errant vehicles being brought under control before colliding with a fixed object. The recommended width of clear zone varies according to a number of factors, but a benchmark of 9 m on 100 km/h roads is widely considered to be sufficient for 85% of errant vehicles to stop safely or recover control without collision.

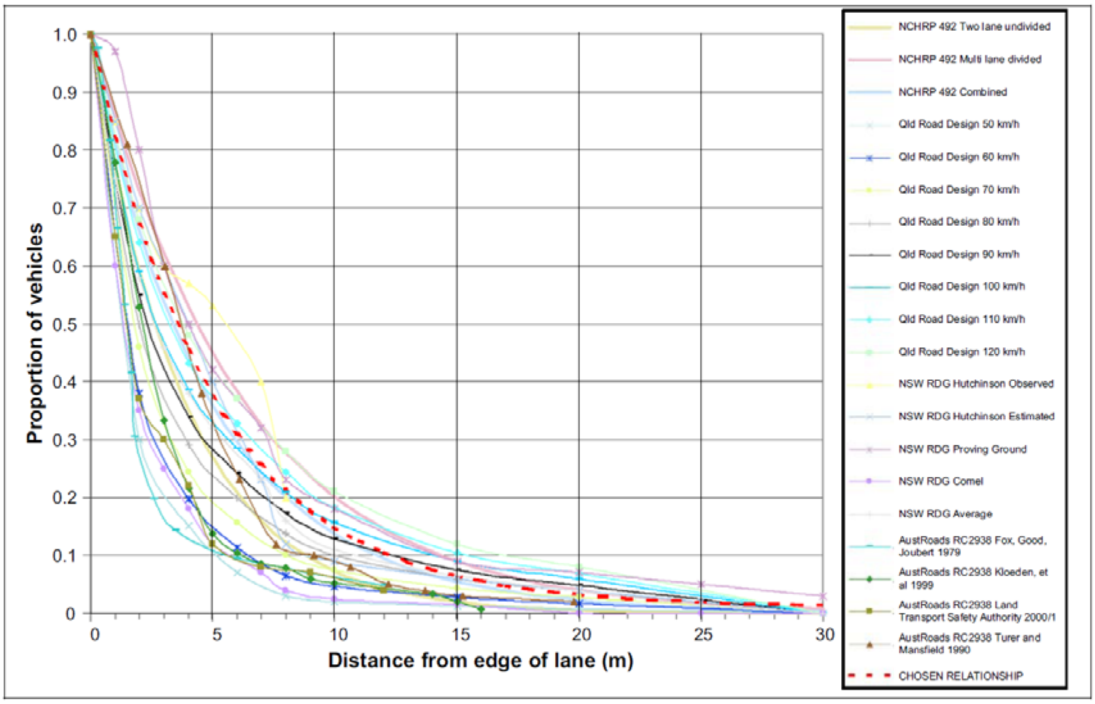
During a recent review of the Austroads roadside design guidelines [1] it became clear that the research basis for clear zone selection, while the best available at the time, raised many unanswered questions and needed to be revised. Firstly, the investigations on which the current standards are based were conducted more than 30 years ago. In that time, dynamic properties of vehicles have changed considerably; the most relevant to this discussion are changes in braking systems, tyres, and occupant protection. Secondly, the Australasian road authorities adopted the Safe System approach to road safety and design which seeks to minimise death and serious injury. Hence, a design model allowing a percentage of errant drivers to experience a crash event at impact speeds exceeding safe limits is not part of the Safe System vision.

An investigation was conducted into the effects of different clear zone widths and other road design parameters on crash outcomes, including deaths and serious injuries. In particular, run-off-road casualty crashes to the left were investigated as the crash type most affected by clear zone widths. Road and roadside design parameters were investigated in relation to clear zone width. This paper presents the results of these investigations and their potential application for improving roadside safety in the Safe System context. The findings are based on rural undivided road data, but may have a wider application for high speed roads. A full report on this investigation is part of a multi-year research into roadside safety funded by Austroads.

Literature

The existing Austroads design guidance on the selection of clear zones [1] draws heavily on the AASHTO [2] guide and Transportation Research Board [3]. For many years, selection of clear zones has been based on the probability of a vehicle leaving the road and encroaching into the roadside to a certain lateral distance from the traffic lane (depth), and on the likely severity outcome in case of a collision with a roadside hazard. The research carried out to estimate this probability was carried out between the mid 1960s and late 1970s in the US and Canada (e.g. Hutchinson and Kennedy [4], Cooper [5]). The probability of encroachment depth was based on measurements of roadside tyre tracks, both in medians and in verges. These studies suffered from similar problems. There was no way to differentiate between voluntary and errant roadside encroachments. Presence of hard shoulders confounded the collected data in the first 4 m and the regression relationships had to be extrapolated.

There have been various models developed from these and other similar studies over the years. Figure 1 presents a collection of these models as presented in Austroads [1]. According to some of these relationships, between 80% and 90% of the encroaching vehicles should stop or recover control within a 9 m clear zone in 100 km/h speed environments. This infers, that after adjusting for exposure (traffic volume, road length and time), the likelihood of a run-off-road casualty crash should be very low if a clear zone wider than 9 m was provided, given relatively straight roads with flat batters.



Source: Austroads [1] based on RTA [6]

Figure 1: Probability models for lateral depth of encroachment by an errant vehicle

Clear zone selection guidance has been based on these estimations, with various adjustments factored in for AADT, curve radius and side batter slope. The following questions arise regarding the accuracy of this approach:

- Did the methodology of measuring tyre marks capture only the relevant encroachments? Was there a proportion of vehicle encroachments (e.g. within the first few metres) which was intentional, hence reducing the calculated proportion of the deep encroachments?
- Given the age and origins of the research, is it still applicable to modern vehicle fleets in Australia and New Zealand?
- Is there a relationship between encroachment depth probability and run-off-road casualty crash probability?
- Assuming > 9 m clear zones are adequate to control the majority of the vehicle encroachment risk, what are the causal factors for the run-off-road casualty crashes occurring in the presence of very wide clear zones?

Some more recent studies demonstrated that the presence of wider clear zones was associated with reduced casualty crashes (e.g. Hildebrand, Lougheed and Hanson [7], Lee and Mannering [8], Zeeger, Hummer and Reinfurt [9]). These studies also showed that there was a significant residual likelihood of such crashes even in the presence of very wide clear zones, contrary to indications provided by the earlier models in Figure 1.

These doubts suggested that an investigation of run-off-road crash outcomes as a function of clear zone width was required in order to consider creation of a revised clear zone selection process. This would be an important input into future Austroads roadside design guidelines revisions.

Method

A database was developed which provided detailed information about clear zone widths, roadside hazards, shoulder conditions, lane widths, road curvature, grade and AADT on 2,900 km of undivided rural roads in Victoria. This was achieved by using geocoded referencing to extract relevant site attributes from the road asset, roadside feature, traffic flow and crash databases, and combine them in a database created for the study. Figure 2 shows schematically the different variables included in the database. Crash data included in the database contained all recorded casualty crashes over a 5-year period (2003-2007). Traffic volumes collected in the same period were adjusted to the year 2005 using the average annual growth factors for the rural network (provided by VicRoads).

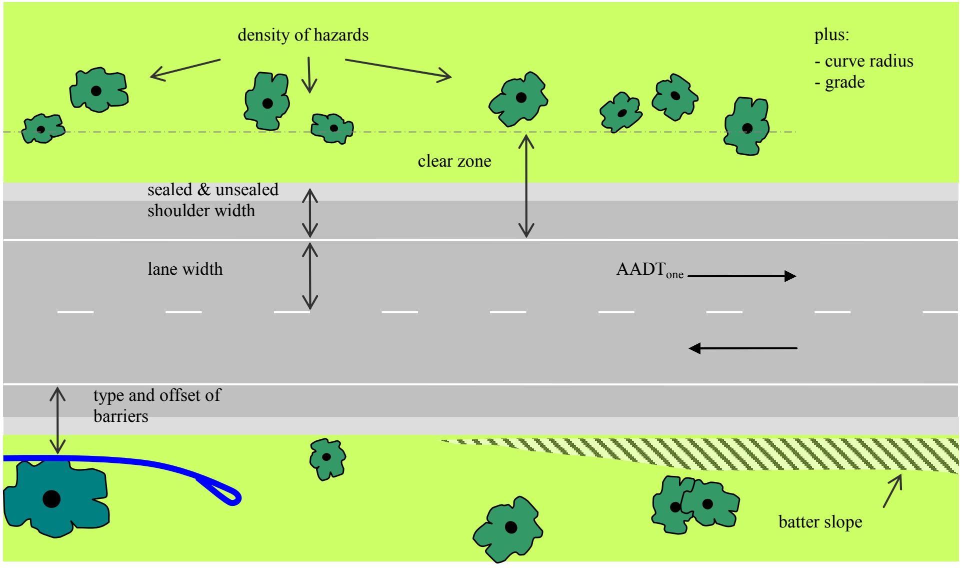


Figure 2: Road, roadside and traffic information collected for each road segment

Roads and all the associated information were split directionally (forward and reverse) and divided into 60 m segments. This segment length was selected to balance the level of crash mapping accuracy with the variability of the roadside environment, e.g. clear zone, batter slope or density of hazards. To test the choice of the 60 m segment length the key results were later checked using a sample of randomly selected 180 m homogenous road sections. The key results were almost identical suggesting there was no accuracy trade-off due to the shorter segment size. The data sample was narrowed down to roads with a 100 km/h speed limit as this was the most prevailing scenario on the rural road network. Additionally, a small proportion of segments which had safety barriers was excluded from the analysis – the safety performance at these locations differed from other road sections. Thus the sample available for analysis contained 57,925 one-way rural undivided road segments containing 217 run-off-road casualty crashes to the left.

First, an investigation of the road, roadside, traffic and crash data was undertaken to understand their nature and mutual correlations. The distribution of 60 m road segments by AADT indicated that the majority had traffic volumes of between 1,200 and 2,400 vpd, typical of the Victorian rural undivided road network. The majority of road segments (98.9%) experienced zero casualty crashes in 5 years. Only 1% experienced one crash and less than 0.1% experienced two or more casualty crashes. This showed that the crash data was zero-inflated, which suggested negative binomial regression as the preferred modelling technique.

The mean number of casualty crashes per road segment was very low (0.004 in 5 years), as expected for a one-way 60 m long section of a rural road. For the purposes of Poisson regression, the ratio of mean and variance should be one. When the ratio is less than one the data is described as underdispersed and when it is greater than one the data is described as over-dispersed. In both of these situations, a negative binomial regression is more appropriate than Poisson. The ratio of mean and variance was less than one for run-off-road to the left casualty crashes (0.85). This confirmed that a negative binomial model was preferable. The general model took the format presented in Equation 1.

$$\gamma = e^{(\beta_0 + \sum_i \beta_i Var_i + \varepsilon)} \qquad 1$$

where

γ = predicted casualty crashes in a 60 m road segment in one direction

β_0 = model intercept

$\sum_i \beta_i Var_i$ = vector of the model parameter estimates for the relevant variables

ε = error term not explained by the variables

Consistent relationships were expected between the potential model variables i.e. the road and roadside parameters measured in this study. Where the correlation between variables is high, there is nothing to be gained from including both, thus some parameters were excluded from the model up front. Section operating speed was left out due to its obvious correlation with curve radius (used in calculating this parameter). Batter slope, however, was left out as the data attribute collected for this variable lacked the cut/fill distinction thought to be essential for meaningful modelling.

Analysis of the correlations between the selected variables was performed to check for redundancy. Spearman's Rho was used in preference to Pearson's r due to the non-normal distribution of the variables and the non-linear relationships between them. Spearman's Rho converts measurements into ranks and then computes the level of correlation between the ranked variables. The closer the value of Rho is to ±1.00, the higher the degree of correlation between the two variables. When two variables are strongly correlated, one may be excluded from a model as a redundant variable.

There were generally weak correlations between most road and roadside design variables as shown in the Table 1. The exceptions were strong the negative relationships between traffic lane plus sealed shoulder width and the unsealed shoulder width (-0.596), and between clear zone width and hazard density (-0.570). The first correlation reflects the application of the road design cross-section standards. The second correlation was related to the intensive farming along many rural highways and the relative lack of trees in these environments. On the basis of these strong correlations, the hazard density and unsealed shoulder width variables were excluded from the model. Most of the other variables were weakly correlated with the one-way AADT. These correlations support the observation that higher volume roads tend to be upgraded and reconstructed over time. In this instance one-way AADT was included in the model, as it was considered to be a strong predictor variable.

Table 1: Matrix of correlations between independent variables (Spearman's Rho)

Left hand side features	Traffic lane + sealed shoulder width	Unsealed shoulder width	Density of hazards	Batter slope	Grade	Curve radius	Clear zone	AADT (one direction)
Traffic lane + sealed shoulder width	1.000							
Unsealed shoulder width	-0.596	1.000						
Density of hazards	-0.063	-0.016	1.000					
Batter slope	-0.040	-0.077	0.401	1.000				
Grade	0.002	-0.002	-0.006	-0.002	1.000			
Curve radius	0.085	0.088	-0.126	-0.269	0.003	1.000		
Clear zone	-0.051	0.254	-0.570	-0.441	-0.001	0.132	1.000	
AADT (one direction)	0.328	-0.168	-0.170	-0.273	0.000	0.164	0.059	1.000

To determine the best form of the model, variables were added to the base model one at the time (one-way AADT only). The model fit and predictive validity were compared using the Bayesian Information Criterion (BIC) and log-likelihood of the models. The BIC is a measure of how parsimonious the model is. A parsimonious model is one which explains the most variance in the dependent variable (casualty crashes) from the fewest predictors. The log-likelihood is a measure of goodness of fit. For both of these diagnostic criteria, a number closer to zero is desirable. The base model had a log-likelihood of -1835 and a BIC of 3694.

The Wald chi-square statistic was used to test the statistical significance of the overall model and each of the independent variables contained in it. The test indicates whether including an independent variable in the model makes a statistically significant difference to the crash predictions. Some independent variables were included in the model because they gave improved model fit and contributed to a parsimonious model even though they did not make a statistically significant difference. It is likely that the non-significant variables have a modifying relationship with other predictors in the model.

There was insufficient data to build a model for discrete variable values (i.e. clear zone of 1, 2, 3 m, etc.). Variable categories were created, based on value ranges instead to improve the statistical power of the model. These categories were defined by trial and error to obtain the best model fit and statistical significance of the key parameter estimates. The selection of variables and their categories was based on the best log likelihood and BIC values. The final model had a log-likelihood of -1794 and a BIC of 3690 which was better (lower) than the base model.

Results

The frequency distribution of run-off-road to the left casualty crashes was compared to the distribution of clear zone widths as shown in Figure 3. It is clear that a substantial proportion (42%) of the rural road network in the sample had clear zones in excess of 9 m. Still, 35% of run-off-road to the left casualty crashes, and similar proportion of the associated fatalities and serious injuries, occurred on segments with these wide clear zones.

The same data was adjusted for exposure, i.e. expressed as run-off-road to the left casualty crash rate per 100 million vehicle-kilometres. Figure 4 shows that the average crash rate in the first 0 – 4 m is higher than in the 4 – 8 m range, which is a little higher than in the > 8 m range. More importantly, it is clear that the likelihood of a run-off-road to the left crash does not approach zero at wide clear zones. This residual risk suggests that:

- the probability of deep roadside encroachment may be higher than suggested by Figure 1
- other roadside injury mechanisms are active when the path of an errant vehicle is free of roadside hazards.

Either or both of these statements may be true. The first statement could not be tested using the methodology employed for the project. The second statement was supported by further data analysis showing a decline in the proportion of the relevant crashes resulting in hitting objects and an increase in the proportion of rollovers as clear zones become wider. It appears that reduced object impact probability was offset by higher rollover probability in wider clear zones. Figure 5 presents this relationship.

Further analysis showed that the average cost of a run-off-road crash remained steady across the range of clear zone width, indicating that availability of run-out space free of hazards had no measurable effect on the severity outcomes of run-off-road casualty crashes.

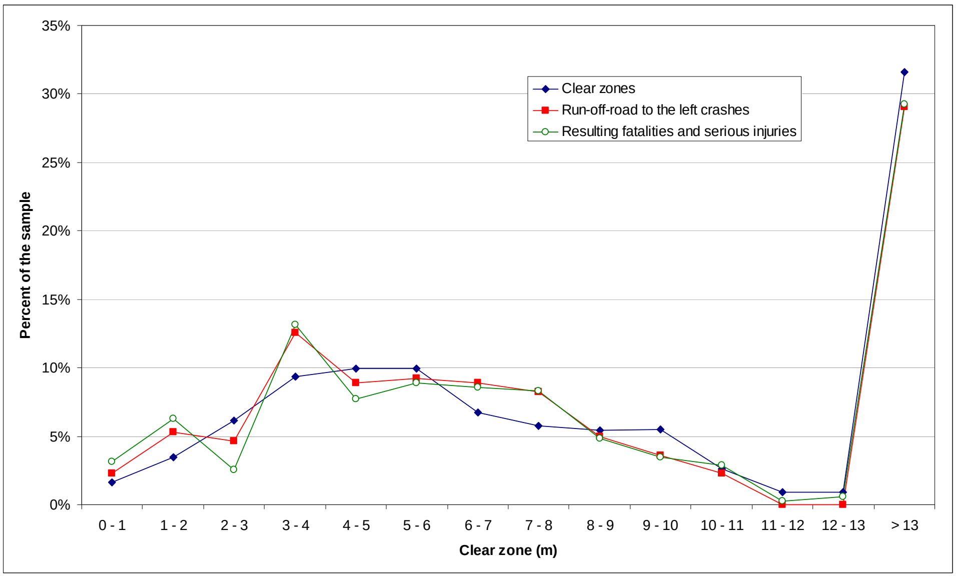


Figure 3: Distributions of clear zones, run-off-road to the left casualty crashes and the resulting fatalities and serious injuries

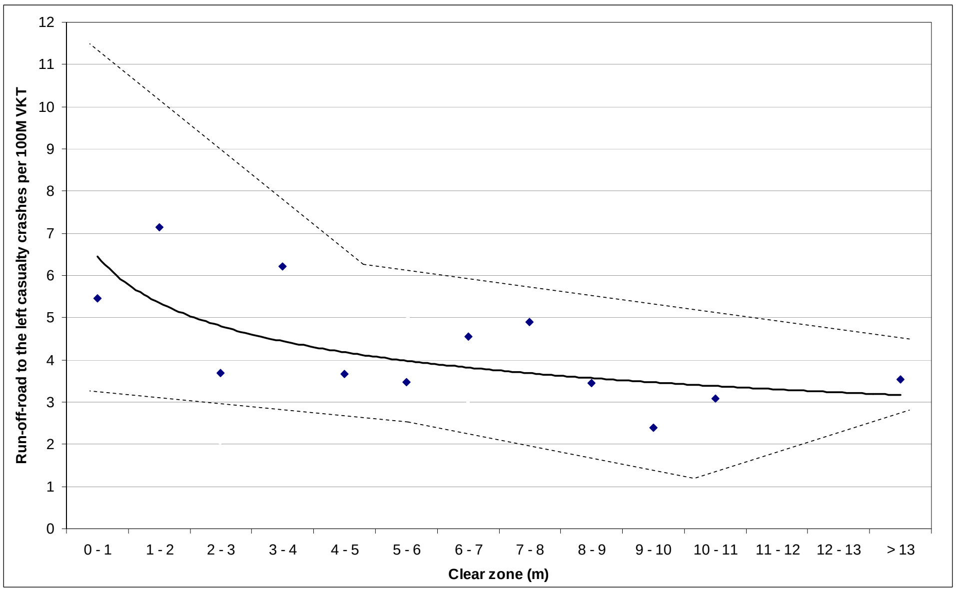


Figure 4: Run-off-road to the left crash rate in different clear zone widths with 95% confidence limits

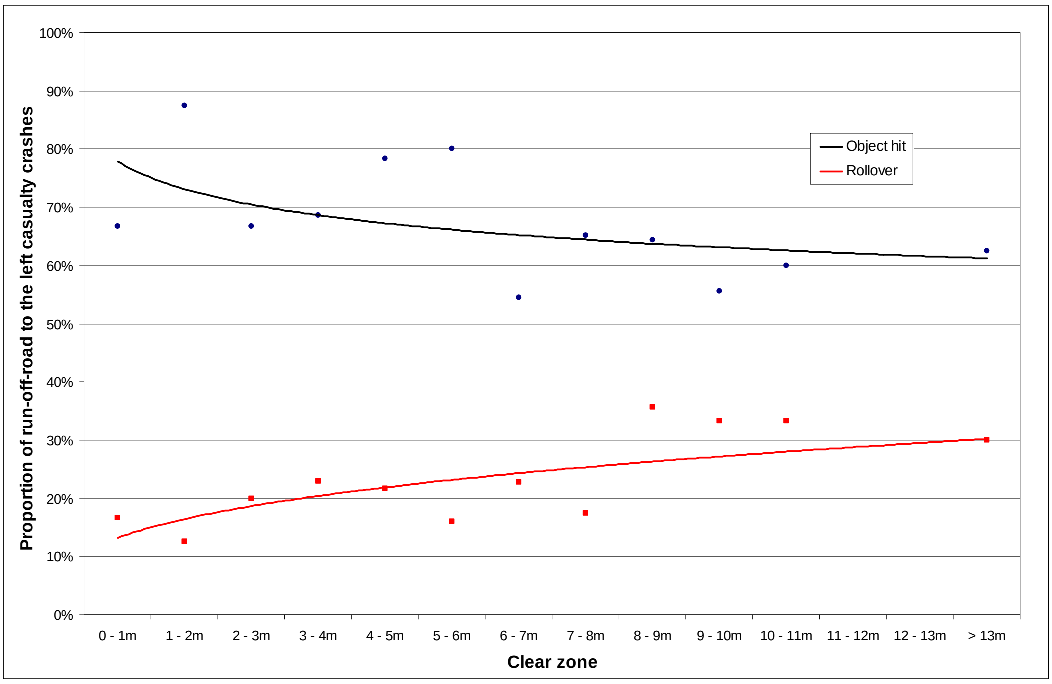


Figure 5: Proportions of ROR to the left crashes where object was hit or rollover occurred

A negative binomial log-linear model (Equation 2) was created for predicting run-off-road casualty crashes to the left per one-way 60 m segment over a 5-year period (100 km/h speed limit, no barriers on the left-hand-side present) from the following variables:

- one-way AADT in the direction of travel
- curve radius
- grade
- traffic lane plus sealed shoulder width
- clear zone width.

$$ROR2L = e^{(\beta_0 + \beta_1 AADT_{one} + \beta_2 Radius + \beta_3 Grade + \beta_4 TLSS + \beta_5 CZ + \varepsilon)} \qquad 2$$

where

ROR2L = ROR to the left casualty crashes per one-way 60 m segment
β_0 = model intercept
$\beta_1 ... \beta_5$ = parameter estimates dependent on the category of variable
$AADT_{one}$ = one-way AADT category (in the direction of travel)
Radius = curve radius category
Grade = grade category
TLSS = traffic lane plus sealed shoulder width category
CZ = clear zone width category
ε = residual (or error) variance that cannot be explained by the negative binomial model.

The model effects of all independent variables are shown in Table 2. The variable categories have no absolute value, rather they define the value of the parameter estimate (β_n in column 3). The exponent of the parameter estimates ($e^{\beta n}$ in column 5) can be interpreted as a form of relative risk value for any stated variable category. This means that the following interpretations can be made based on each of the variables, given that all other variables in the model were held constant. All statements refer to ROR to the left casualty crashes and are statistically significant at $p \leq 0.05$, unless stated otherwise:

- Crash likelihood is 1.8 times higher on road sections with one-way AADT greater than 1,200 vpd compared to road sections with less than 1,200 vpd one-way AADT.
- Crash likelihood is 2.4 times higher on curves with radius of less than or equal to 600 m than on curves with radius of more than 1,500 m (relatively straight).
- Road sections with a downhill grade have a crash likelihood 1.3 times higher than road sections with positive grade, or with no grade.
- Road sections with seal width of less than 7 m have a crash likelihood 1.2 times that of road sections with seal width of more than 7 m (not statistically significant).
- Crash likelihood is 2.2 times higher on road sections with a clear zone of 2 m than on road sections with clear zones of 8 m or wider
- Road sections with clear zone of 4 to 8 m have a crash likelihood 1.3 times higher than sections with a clear zone of 8 m or wider.

Table 2: Parameter estimates and model effects of negative binomial log-linear model predicting ROR to the left casualty crashes per 60 m from the model variable categories

Predictors	**Categories**	**Parameter estimates (β_n)**	**Parameter estimate standard errors**	**Exponent of the parameter estimates ($e^{\beta n}$)**	**Statistical significance (Wald chi-square statistic)**
Intercept		-5.808	0.153	0.003	$p \leq 0.001$
AADT (one-way)	≤ 1200 vpd	-0.605	0.134	0.546	$p \leq 0.001$
	>1200 vpd	0	–	1	–
Curve radius (m)	≤ 600	0.891	0.135	2.437	$p \leq 0.001$
	600 – 1500 m	0.352	0.203	1.422	$p \leq 0.1$
	> 1500 m	0	–	1	–
Grade (%)	Negative	0.264	0.120	1.302	$p \leq 0.05$
	Positive or zero	0	–	1	–
Traffic lane plus sealed shoulder width (m)	< 3.5 m	0.193	0.128	1.213	$p > 0.10$
	≥ 3.5 m	0	–	1	–
Clear zone (m)	≤ 2 m	0.786	0.216	2.194	$p \leq 0.001$
	2 – 4 m	0.473	0.167	1.606	$p \leq 0.05$
	4 – 8 m	0.238	0.144	1.268	$p \leq 0.1$
	≥ 8 m	0	–	1	–

To help illustrate these effects, Equation 2 was solved for all the variable categories in the model. The sample mean run-off-road to the left casualty crash value per kilometre (one-way) was very low: 0.067. This reflects the low frequency of this type of crash given low traffic flow on rural highways. It was thus more meaningful to present the model outputs as crash modification factors (CMFs) dependent on the combination of road features, including clear zone width. Table 3 shows changes in predicted level of risk of run-off-road to the left casualty crashes based the predicted crash value. The sample mean of 0.067 crashes per km was set as the CMF of 1.0. Colour coding was applied for clarity: pale yellow represents the predicted casualty crash value being below the sample mean (CMF less than 1.0), dark yellow are scenarios with risk between the mean and double the mean (CMF between 1 and 2), orange represents scenarios where the risk is two to three times the mean value. Red colour represents an extreme risk condition where the predicted crash value was more than three times the sample mean.

From these results one can conclude that clear zones exceeding 8 m should be preferred in all new road design scenarios to reduce the ROR to the left crash frequency. This clear zone width category consistently produced the lowest relative risk levels. If the roads with clear zones in the 4 – 8 m range were to be mass-converted into roads in the ≥ 8 m category, then their run-off-road to the left casualty crashes would decrease by about 21%. Roads with little or no clear zone (≤ 2 m) would benefit the most from introducing clear zones over 8 m wide – a 54% reduction in run-off-road to the left casualty crashes. The model also suggests alternatives to clear zone widening which may yield similar crash reduction benefits, e.g. widening of sealed pavement through sealing of shoulders.

Table 3: Crash modification factors for run-off-road to the left casualty crashes

Curve radius (m)	**Grade (%)**	**Traffic lane plus sealed shoulder width (m)**	**Clear zone (m)**	**AADT (one-way) (vpd)**	
				≤ 1200	**> 1200**
≤ 600	Negative	< 3.5	≤ 2	3.44	6.31
			2 – 4	2.52	4.61
			4 – 8	1.99	3.64
			≥ 8	1.57	2.87
		≥ 3.5	≤ 2	2.84	5.20
			2 – 4	2.08	3.80
			4 – 8	1.64	3.00
			≥ 8	1.29	2.37
	Positive	< 3.5	≤ 2	2.64	4.85
			2 – 4	1.94	3.55
			4 – 8	1.53	2.80
			≥ 8	1.21	2.21
		≥ 3.5	≤ 2	2.18	3.99
			2 – 4	1.60	2.92
			4 – 8	1.26	2.31
			≥ 8	0.99	1.82
600 – 1500	Negative	< 3.5	≤ 2	2.01	3.68
			2 – 4	1.47	2.69
			4 – 8	1.16	2.13
			≥ 8	0.92	1.68
		≥ 3.5	≤ 2	1.66	3.03
			2 – 4	1.21	2.22
			4 – 8	0.96	1.75
			≥ 8	0.75	1.38
	Positive	< 3.5	≤ 2	1.54	2.83
			2 – 4	1.13	2.07
			4 – 8	0.89	1.63
			≥ 8	0.70	1.29
		≥ 3.5	≤ 2	1.27	2.33
			2 – 4	0.93	1.70
			4 – 8	0.74	1.35
			≥ 8	0.58	1.06
> 1500	Negative	< 3.5	≤ 2	1.41	2.59
			2 – 4	1.03	1.89
			4 – 8	0.82	1.50
			≥ 8	0.64	1.18
		≥ 3.5	≤ 2	1.16	2.13
			2 – 4	0.85	1.56

			4 – 8	0.67	1.23
			≥ 8	0.53	0.97
	Positive	< 3.5	≤ 2	1.09	1.99
			2 – 4	0.79	1.45
			4 – 8	0.63	1.15
			≥ 8	0.49	0.91
		≥ 3.5	≤ 2	0.89	1.64
			2 – 4	0.65	1.20
			4 – 8	0.52	0.95
			≥ 8	0.41	0.75

Discussion

The analysis presented here presents an important step towards the revision of clear zone selection guidelines. The research produced clear indicators of the road design parameters which influence the safety performance of rural undivided highways. The results of the statistical modelling were reasonably robust – all exponents of the parameter estimates (i.e. CMFs), except one, were statistically significant at $p \leq 0.1$ and most were significant at $p \leq 0.05$. Additional regression analysis carried out by Jurewicz and Pyta [10] indicated that the observed relationships for run-off-road casualty crashes to the left reported in this paper were very similar for those for all run-off-road casualty crashes. This indicates that the likelihood of run-off-road casualty crashes to the right (43% of all run-off-road casualty crashes in the sample) was controlled by the same road design parameters as those crashes to the left.

A possible approach to selection of clear zones based on managing crash outcomes, could involve setting an intermediate run-off-road to the left casualty crash safety target based on Table 3 results (e.g. CMF of 0.5, i.e. half of the current mean value). When the combination of design parameters suggests that crash frequency would exceed this target, a clear zone wider than 8 m should be considered to move to a lower figure. Also, clear zone widths of less than 2 m should be avoided. Such an approach would require further development, especially addition of batter slope as a model variable. A more detailed statistical modelling could be carried out based on a larger sample of casualty crashes. Alternatively, a more pragmatic but less statistically robust approach could be developed by interpolating between the existing categories. Additional crash modification factors could be incorporated from other research, e.g. the effect of roadside slope on run-off-road casualty crashes or effects of the operating speed. Clear zones would be selected on the basis of reducing the crash modification factor below an agreed value.

Another application of these results could be in road design. For example, given a set AADT, curvature and grade site constraints, a designer may manipulate the traffic lane plus sealed shoulder width and clear zone width to arrive at the most cost and crash risk optimised solution (a benefit cost ratio approach using predicted casualty crashes from the model). While this approach would not achieve the Safe System roadside conditions, it would be a step towards the Safe System outcomes in conjunction with other supporting treatments (e.g. audio-tactile edge lines, good delineation and skid resistance and speed management).

Finally, the relative risk values produced by the model could be applied in updating of existing risk assessment models such as NetRisk or iRAP.

Any improvement initiatives based on the model results would need to be subject to a thorough economic evaluation of alternative options, monitoring of crash performance and post-implementation evaluation.

Future modelling of clear zones should seek to include the batter slope as a model variable, including both cut and fill slopes. The study should be extended to include other road stereotypes such as divided highways/freeways and urban roads. The influence of changing the operating speed would be of particular interest as speed limit reductions may be a cost-effective treatment in many high risk locations.

Conclusions

It was shown that a substantial proportion of run-off-road casualty crashes to the left occur in very wide clear zones. Hence, even very wide clear zones cannot be considered a primary Safe System solution (i.e. preventing deaths and serious injuries), but rather a harm reduction supporting solution. Nevertheless, it has been shown that providing wider clear zones reduces the likelihood of run-off-road casualty crashes to the left.

Statistical modelling resulted in a statistically significant run-off-road to the left casualty crash prediction model based on several key road design variables. The model supports the need for wider clear zones on rural undivided roads and quantifies the crash risk reductions which may be expected for incremental clear zone width increases. This model may be used to provide input into future revisions of clear zone selection guidelines based on the key road design parameters.

The results of the modelling could be used for clear zone selection based on reducing the risk of run-off-road to the left casualty crashes. This harm reduction approach would encourage selection of wider clear zones than 8 m when the effect of other design parameters suggests a crash frequency above a chosen safety target.

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