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Crash performance of safety barriers on high-speed roads

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Abstract

The findings presented in this paper are based on Austroads-funded investigations of the in-service effectiveness of safety barriers on high-speed roads (that is, roads with 100 and 110 km/h speed limits). Based on past evaluations, the most promising was continuous application of flexible barriers on freeways addressing up to 86% of run-off-road and cross-median casualty crashes. Analysis of Victorian barrier crash data from high-speed roads suggested that the severity index for run-off-road casualty crashes (FSI ratio) was 0.58 for semi-rigid barrier crashes compared with 0.75 for tree crashes. Severity of run-off-road casualty crashes into semi-rigid barriers was comparable to those not involving a roadside hazard (FSI ratio of 0.55). In contrast, flexible barriers had the lowest FSI ratio of 0.38. Continuous flexible barriers appeared to be the most effective safety barrier solution among those reviewed.

Investigation of the effect of semi-rigid barrier offset from the edge line showed that the FSI ratio increased at a low rate with increasing barrier offset (~0.03, or 5% per m), although the relationship was not statistically robust. Combined with earlier research on barrier crash likelihood, the suggested ideal range for barrier installation could be in the range of 1.5 to 4 metres to allow for sealed shoulder provision. These findings may be useful in refinement of barrier selection and design guidance.

Keywords

Barrier offset, In-service, Run-off-road crash, Safety barriers, Severity

Introduction

This paper presents key findings arising from an investigation of the in-service effectiveness of safety barriers in controlling the likelihood and severity of run-off-road casualty crashes on high-speed roads. The findings presented here are drawn from a four-year Austroads study

on improvements to roadside safety in the Safe System context. They extend on the previous research by focusing on in-service performance of barriers of different types and at different offsets.

Background

Run-off-road casualty crashes contribute significantly to the nation's road toll. Across Australia, approximately 30% of fatalities and serious injuries are caused by run-off-road crashes. Approximately half of these fatalities occur in rural and regional areas [1, 2].

The Safe System vision underpinning the national (NRSS) and Victorian (VRSS) road safety strategies [1, 2] seeks to prevent run-off-road deaths and serious injuries. This is progressed through promotion of solutions which minimise the occurrence of such crashes (e.g. electronic stability control in vehicles, improved linemarking), and through provision of more forgiving roadsides when such crashes occur. This latter approach involves the application of various roadside design and safety solutions aimed at improving the chances of recovery back onto the road (e.g. sealed shoulders). Further, it includes solutions deflecting or dissipating the kinetic energy of an errant vehicle so that occupants do not sustain life-threatening injuries. Part of this suite of solutions involves the installation of safety barriers along roadsides and medians to shield errant motorists from more severe roadside hazards.

Role of safety barriers

An assessment of roadside hazards may find that their removal, relocation or modification is not feasible (for example, where there are major structures such as bridge abutments, drop-offs or significant roadside trees). In such cases, safety barriers are typically considered. In recent years, more barriers have been applied in medians on high-speed divided and undivided roads to address run-off-road and head-on crash risk [3].

Austroroads roadside design guidelines [3] suggest that the likelihood of a vehicle colliding with a barrier is higher than the likelihood of colliding with the hazard. This assumption is based on a longer length of exposure and a greater proximity to traffic. The key condition in selection of a barrier, therefore, is an expectation that the severity of a barrier vehicle impact would be lower than the severity of impact with the hazard being shielded. Thus the net result is expected to be an improvement in roadside safety or prevention of future crashes.

Methodology

There are many useful measures of safety barrier performance used in the context of standard crash tests. These are carried out under controlled impact speed, angle and vehicle mass conditions and produce such indicators of crash severity as Theoretical Head Impact Velocity (THIV), the Post-impact Head Deceleration (PHD) and the Acceleration Severity Index (ASI) [4]. Nevertheless, such tests cannot indicate how the barrier would perform when exposed to the vehicle fleet in a given jurisdiction, or when applied in a particular road environment. Crash tests are unlikely to provide reliable information about the change in likelihood of a casualty crash after installing a barrier at a particular offset from traffic.

This investigation sought to indicate in-service performance of different barrier options in high-speed road environments. The investigation focused on past evaluation studies and the development of crash severity indices. The aim was to provide performance indicators related to barrier crash likelihood and severity. Such indicators could be used in the comparison of different design options, for example.

The following sub-sections describe the methods applied in the investigations.

Literature review – crash likelihood

The study began with a review of recent barrier effectiveness evaluation studies. For this purpose, a search was undertaken of the Australian Transport Index (ATRI), the Transportation Research Information Service (TRIS), Transport Online and the internet to identify the relevant publications. The review sought to estimate run-off-road casualty Crash Reduction Factors (CRFs) for different barrier types and applications.

The approach of reviewing past studies of the crash reduction effectiveness of barriers was preferred to the comparative analysis of crash rates between locations with and without safety barriers. Preliminary data investigations suggested that locations with barriers generally had a higher casualty crash rate than the network average. This was unlikely to be a causal relationship but rather a reflection

of the installation of barriers at higher crash risk locations (e.g. curves). Accordingly, a review of before/after safety barrier evaluations was more likely to indicate the true effectiveness of barrier installation.

Data analysis – crash severity

A run-off-road crash database was created for the purpose of comparative investigation of average severity run-off-road casualty crashes into barriers of different types, in different high-speed road environments and at different offsets from traffic. Early in the investigation, it became clear that crash data were insufficient to provide meaningful analysis of crash cushions/attenuators, motorcyclist safety barrier retrofits, end treatments and transitions. Therefore, the investigation focused on barrier sections.

A database was developed to provide a sample of crashes for investigation. The database was prepared by extracting VicRoads crash data for speed environments of 100 km/h and 110 km/h. The crash period spanned ten years (2000 – 2009). Only run-off-road casualty crashes were extracted (excluding intersections). The crash data were limited to passenger vehicles and rigid trucks. A total of 12,216 crashes were extracted and, of these, 7655 were single vehicle into a single object crashes. Only 500 of these crashes were into a safety barrier (6.5%). Crashes were categorised into rural and urban.

The next step involved selection of a sample of crashes which included information relating to barrier type and barrier offset from the traffic lane. To obtain a representative sample of crashes into each barrier type, the adopted sampling regime was to select crashes from the sample of 500 barrier crashes, from each road environment, based on a random number generator. Final crash selection was dependent on clear police descriptions and location details, enabling the hit barriers to be located. This was subject to random error and some crashes had to be set aside. This method was considered to have minimised selection bias. A total of 289 crashes were included in this data set.

The detailed crash summary, police diagrams, satellite, aerial and site photography were used to determine barrier type and offset from the edge line. The offset information was accurate to the nearest 0.5 metre.

The next step focused on the development of FSI ratios¹ associated with different barrier types and different offsets in a given road environment. The FSI ratio is a useful indicator of how close a given crash scenario is to the Safe System ideal of zero fatal and serious injuries per crash. It can be used in assessing crash severity changes due to safety treatments (e.g. tree crashes compared with safety barriers).

Adjusted FSI ratios were calculated for the three barrier types (rigid, semi-rigid and flexible) on 100 km/h rural roads, 110 km/h rural freeways and 100 km/h urban freeways. Investigation of the role of barrier offset on crash severity was restricted to semi-rigid barriers due to the limited number of crashes for other barrier types in the sample. In order to compare different barrier types across road different road environments, individual FSI ratios needed to be adjusted for observed variations in vehicle occupancy. The method used to calculate the FSI ratio for barrier option i in road environment j is as shown in Equations 1 and 2.

The variability in vehicle occupancy was due to random and systematic variance. The systematic variance could have been caused by such factors as

- different transport function of some parts of the same road environment leading to different vehicle use and trip characteristics

- proximity of certain barrier options to urban centres, affecting vehicle occupancy.

The occupancy ratio itself is not relevant in the selection of roadside treatment options, hence the adjustment allowed each barrier option to be compared on its merit in reducing fatal and serious injuries.

Calculation of reliable FSI ratios relied on the feature of Victorian crash data system which records each person involved in a casualty crash, whether injured or not. Personal communication with VicRoads data systems staff confirmed that the accuracy of the record was close to 100%. This means that any over-inflation of FSI ratios due to under-reporting of persons involved in casualty crashes would have been low.

The precision of the FSI ratios was measured by 95% confidence limits, calculated as in Equation 3.

$$FSI\ ratio_{ij\ adjusted} = \frac{\Sigma FSI_{ij}}{\Sigma Crashes_{ij}} \times \frac{Average\ occupancy_j}{Average\ occupancy_{ij}} \tag{1}$$

Which can be further expanded to:

$$\frac{\Sigma FSI_{ij}}{\Sigma Crashes_{ij}} \times \frac{\Sigma Persons_j}{\Sigma Crashes_j} \times \frac{\Sigma Crashes_{ij}}{\Sigma Persons_{ij}} = \frac{\Sigma FSI_{ij}}{\Sigma Persons_{ij}} \times Average\ occupancy_j \tag{2}$$

where

$FSI\ ratio_{ij\ adjusted}$ = FSI ratio for roadside hazard i in road environment j , adjusted for average vehicle occupancy in that road environment.

ΣFSI_{ij} = Number of fatal and serious injuries for barrier option i and road environment j .

Average occupancy $_j$ = Average vehicle occupancy for road environment j , based on all run-off-road casualty crashes, not just those into barriers.

Average occupancy $_{ij}$ = Average vehicle occupancy barrier option i in road environment j .

$\Sigma Persons_j$ = Number of persons involved in run-off-road casualty crashes for road environment j .

$\Sigma Crashes_j$ = Number of run-off-road casualty crashes in road environment j .

$\Sigma Persons_{ij}$ = Number of persons involved in casualty crashes for barrier option i and road environment j .

$\Sigma Crashes_{ij}$ = Number of run-off-road casualty crashes for barrier option i and road environment j .

$$FSI_{95CL} = FSI \text{ ratio}_{ij \text{ adjusted}} \pm [t_{(A)} \times SE_{(A)} + t_{(B)} \times SE_{(B)}] \tag{3}$$

where

FSI_{95CL} = upper and lower confidence limit at a 95% level of significance.

$t_{(A)}, t_{(B)}$ = critical t-values for the 95% confidence interval given the degrees of freedom ($n - 1$), where n is the sample size. The t-value approaches 1.96 for large samples.

$SE_{(A)}, SE_{(B)}$ = standard error.

The standard error t-values and standard errors (SE) were calculated for each component of Equation 3, as shown in Equations 4 and 5.

FSI ratio_{ij adjusted} component	t-value	Standard error
$\frac{\sum FSI_{ij}}{\sum Persons_{ij}}$	$t_{(A)} = T_{INV}(0.05, \sum Persons_{ij} - 1)$	$SE_{(A)} = \frac{\sqrt{\sum FSI_{ij}}}{\sum Persons_{ij}}$ (4)

$\frac{\sum Persons_j}{\sum Crashes_j}$	$t_{(B)} = T_{INV}(0.05, \sum Crashes_j - 1)$	$SE_{(B)} = \frac{\sqrt{\sum Persons_j}}{\sum Crashes_j}$ (5)
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The size of the confidence interval range indicates the level of certainty in the result. That is, a narrow range indicates that the actual FSI ratio is equal to, or very close to, the calculated value.

Findings

Findings on the in-service performance of barriers in high-speed road environments are presented in three parts:

- literature review findings of crash reduction effectiveness of different barrier applications
- analysis of the severity of run-off-road casualty crashes into different barrier types
- analysis of the severity and likelihood of run-off-road crashes into semi-rigid barriers at different offsets from the traffic lane.

Crash reduction effectiveness of barriers (literature review)

Installation of barriers as a road safety treatment on high-speed roads has been the subject of numerous evaluations in Australia and overseas. Most studies identified in the literature review reported substantial reductions in

run-off-road casualty crash frequency. Table 1 lists results of several such evaluations of different barrier applications on high-speed roads. It is clear that barrier installations have contributed to substantial reductions in severe run-off-road crashes. This was even more evident when flexible barriers were applied.

The identified evaluations of median flexible barrier applications suggest very high crash reductions for severe run-off-road and cross-median head-on crashes. A common theme of these three examples was the continuous nature of barrier application, i.e. in long sections shielding all hazards regardless of their relative risk to errant vehicles.

The literature review also found several local studies dealing with the severity of run-off-road crashes into barriers. A New South Wales study found that a ratio of casualty crashes to all recorded crashes for flexible barriers was half of that for semi-rigid and rigid barriers [14]. A South Australian study [15] found that the lateral speed of

errant vehicles increased for some distance after leaving the carriageway, thus initially leading to potentially increased severity of crashes. The authors noted that a barrier placed 4 metres from the edgeline would be impacted at a lateral speed under 40 km/h, i.e. generally survivable for car occupants. Such offset would accommodate provision of a shoulder. A New Zealand evaluation of a narrow median flexible barrier on Centennial Highway noted that no fatalities were recorded during the evaluation period; however, property-damage crashes have risen sharply [16].

Severity of barrier crashes

FSI ratio analysis was carried out on a sample of run-off-road casualty crashes into barriers in three Victorian high-speed road environments: 100 km/h rural roads, 110 km/h rural freeways and 100 km/h urban freeways. Table 2 presents the results for these three road environments. The results for each barrier type were similar across high-speed road environments; thus, the data was combined to increase the statistical power of the analysis. The differences were well within the individual standard errors.

The prevailing high-speed conditions present in all three road environments were considered to be a strong common factor. The average occupancy was adjusted to reflect that of the combined road environments.

Table 2 also shows that flexible barriers recorded the lowest FSI ratio of all barrier types. It was also noted that a substantial sample of flexible barrier crashes could not be reasonably identified for rural 110 km/h freeways in the VicRoads records. The relative scarcity of such crashes in the road environment which carries a substantial length of flexible barriers should be considered an important finding. It suggests that the majority of crashes into flexible barriers did not result in recorded casualty crashes (property damage only crashes were not recorded in VicRoads' crash system).

These results are generally consistent with earlier results published in the Austroads study [17, 18]. They confirm that flexible barriers had the lowest run-off-road casualty crash severity of the three barrier types used in high-speed road environments.

Table 1. Crash reduction factors (CRFs) associated with safety barrier treatments

Barrier treatment	Crash type	CRFs
New guardrail	Run-off-road	4% all severities [5] 7% all severities [6] 47% injury crashes [6] 44% fatal crashes [6] 23% injury crashes [7]
	All types	42% injury crashes [8]
Change barrier along embankment to less rigid type (e.g. rigid to flexible)	Run-off-road	32% injury crashes [8, 9] 41% fatal crashes [8, 9] 35% injury crashes [7]
Installation of flexible barriers on freeway medians	Cross-median head-on	75% fatal crashes [10]
Installation of continuous flexible barrier on roadsides and in medians on a rural freeway	Run-off-road and cross-median head-on	79% injury crashes [11] 87% serious injury crashes [11]
Installation of continuous flexible barrier on roadsides and in medians on an urban freeway	Run-off-road and cross-median head-on	86% injury crashes [11] 83% serious injury crashes [11]
Installation of flexible median barriers on undivided rural highways (2+1)	All types, midblock sections only	46% - 74% serious injury crashes [12] 79% fatalities [12]
	Run-off-road to the right & head-on	46% injury crashes (estimate) [13]
	Run-off-road	24% injury crashes (estimate) [13]

Table 2. Adjusted FSI ratios for different barrier types on high-speed roads

Barrier type	Rural 110 km/h		Rural 100 km/h		Urban 100 km/h		Combined	
	FSI ratio	95CL:low, high; sample size n	FSI ratio	95CL:low, high; sample size n	FSI ratio	95CL:low, high; sample size n	FSI ratio	95CL:low, high; sample size n
Rigid	-	n=4	-	n=3	0.50	0.33, 0.68; 90	0.51	0.39, 0.62; 97
Semi-rigid	0.56	0.32, 0.79; 33	0.60	0.42, 0.77; 42	0.61	0.36, 0.85; 36	0.58	0.47, 0.69; 111
Flexible	-	n=1	-	n=5	0.33	0.07, 0.58; 19	0.38	0.18, 0.57; 25

Placing these results in context, the adjusted FSI ratio for a run-off-road casualty crash into a tree on high-speed roads was found to be 0.75, and 0.55 into a roadside without hitting a hazard (akin to a very wide clear zone scenario) [19]. It is clear that, in the investigated road environments, flexible barriers provided the most favourable crash severity outcome.

It should be noted that these findings were based on limited crash data from one jurisdiction. The confidence limits around the results show that the findings were of variable robustness. The key trends, however, are consistent with previous literature, e.g. [14].

Effect of barrier offset on barrier safety performance

There is currently little evidence relating to the effect that the position of a safety barrier has on the likelihood of a run-off-road casualty crash and its severity. The barrier design guidelines [3] suggest that barriers placed closer to the traffic will be hit more frequently. They also point out that the severity of crashes may increase with wider offset due to increased angle of impact. Little more detail is provided. This part of the paper seeks to provide more clarity in this area.

The effect on the FSI ratio of barrier offset from the traffic lane was investigated as part of the Austroads study. The database of 289 barrier crashes described earlier was expanded using random sampling to include some multiple-vehicle and multiple-object crashes, to boost the sample size at different offset values. Only semi-rigid barriers had a sufficiently large dataset to warrant further analysis. The data were combined across all three high-speed road environments. The adjusted FSI ratios were plotted against barrier offset to determine if there was any correlation between the two variables. Figure 1 presents the results. The barrier offset (to the nearest 0.5 m) was plotted against the mean FSI ratio for that semi-rigid barrier offset. The 95% confidence limits (dotted lines) indicate the robustness of each mean – the narrower the range, the more precise is the result.

The relationship suggests that barrier crash severity may be increasing with barrier offset. This would not be surprising as previous investigations showed that the impact angle tends to increase with depth of penetration of the roadside [15, 17]. Also, crash reconstructions [15] demonstrated that the lateral speed of a yawing errant vehicle increases for several metres after leaving the road. This would suggest a higher impact force and crash severity at greater offsets. Overall, the relationship in Figure 1 suggests a 40% increase in deaths and serious injuries per run-off-road casualty crash across the reported range of barrier offsets (≤ 0.5 to 7.0 m). This represents an approximate increase in

FSI ratio of 0.03 per each additional metre of offset, or 5%, from the FSI ratio of 0.55 at 0.5 m or less.

The relationship in Figure 1 is not statistically significant at $p \leq 0.05$, although the data points between 1.5 and 3.5 metres have a relatively low standard error, and this seems to confirm the overall trend. It should also be noted that the offset measurements were accurate to the nearest 0.5 m.

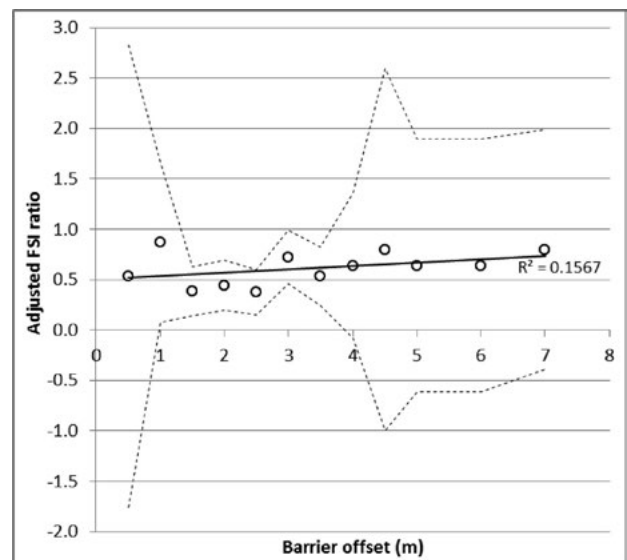


Figure 1. Changes in FSI ratio with semi-rigid barrier offset from traffic lane (high-speed road environments)

Drawing on the results from an earlier stage of the Austroads study [17], Figure 2 presents the changes in the relative risk of a run-off-road casualty crash into a semi-rigid barrier with its offset from the edge line (accurate to within 0.5 m). The dotted lines represent the 95% confidence intervals. The baseline risk of 1.0 was chosen to be in the run-off-road casualty crash rate in the offset range 2 – 3 metres, where the risk was lowest and the data most robust.

The same three high-speed road environments were used in the analysis, although the data were obtained through the creation of a different type of database. The graph shows that the likelihood of a run-off-road casualty crash was highest when the barriers were placed within the first one metre of the traffic lane. The risk remained relatively constant at greater offsets. The results in the first 3.5 metres were statistically significant at the $0.05 < p < 0.1$ level.

Discussion

The combined results from Figures 1 and 2 suggest a possible offset range in which semi-rigid barriers could be installed for a maximum safety benefit. Given the reduction in crash likelihood in the first 1.5 metres, a suggested minimum barrier offset could be 1.5 metres, where possible.

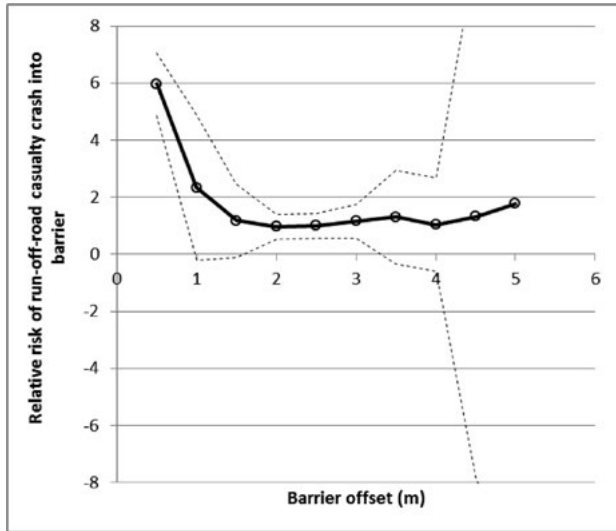


Figure 2. Change in relative risk of run-off-road casualty crashes into semi-rigid barriers with different offsets from the traffic lane (high-speed road environments)

Source: based on [12]

The upper end of the range is somewhat arbitrary as the precision of both relationships becomes very low at higher offset values. Given the low rate of the FSI ratio increase in Figure 1, an upper range for offset could be 3 – 4 metres to accommodate adequate shoulders which would further reduce run-off-road crash likelihood [19]. This could be a reasonable trade-off for a slightly higher FSI ratio. These suggested lower and upper offset limits apply to semi-rigid barriers in high-speed environments only.

The investigation reflected on the small amount of barrier run-off-road casualty crash data generated over ten years across an entire state. Only 6.5% of single vehicle crashes into a single roadside hazard involved barriers, and very few crashes involved flexible barriers. There has been a strong growth in installation of flexible barriers on high-speed roads since the early 2000s funded by the Traffic Accident Commission road safety programs. Estimates of safety barrier length by state in Jama et al. [20] suggested that flexible barriers constituted 27% of barrier length in Victoria. Run-off-road casualty crashes into flexible barriers constituted only 10% of the barrier crash sample in the Austroads study (in road environments with speed limits between 60 and 110 km/h). When considering this in the context of substantial CRFs for flexible barriers, it would be reasonable to conclude that flexible barriers rarely result in casualty outcomes.

Given the variable statistical robustness of the results, the observed findings should be viewed with caution when considering changes to design practice. Also, findings from one state are not necessarily applicable across all jurisdictions. Nevertheless, it can be summed up that the

findings presented in this paper appear to confirm the current design guidance, and could be considered in its future refinement.

Conclusions

The findings presented in this paper are based on Austroads-funded investigations of the in-service effectiveness of safety barriers, carried out as part of a broader four-year study into improvements to roadside safety. This paper focused on high-speed roads.

The paper proposed a number of Crash Reduction Factors (CRFs) based on past barrier effectiveness evaluation studies. It was found that continuous installation of flexible barriers on urban freeways reduced the incidence of run-off-road casualty crashes by as much as 86%. This result implied that the application of continuous flexible barriers was the most effective safety barrier solution among those reviewed.

Analysis of ten years of Victorian crash data based on 100 km/h rural roads, 110 km/h rural freeways and 100 km/h urban freeways showed that run-off-road casualty crashes into semi-rigid barriers were 23% less severe than similar crashes into trees in the same high-speed road environments (FSI ratio of 0.58 vs. 0.75). The severity of run-off-road casualty crashes into rigid or semi-rigid barriers was comparable to those not involving roadside hazards, as in cases of very wide clear zones (0.58 vs. 0.55). The least severe outcome was for crashes into flexible barriers, with the FSI ratio of 0.38.

It was noted that run-off-road casualty crashes into flexible barriers were substantially under-represented in the crash sample. When considering this in the context of substantial CRFs and low FSI ratio for crashes into flexible barriers, it would be reasonable to conclude that flexible barriers rarely result in casualty outcomes. When they do, these outcomes are less severe than for similar crashes into other barriers or into roadsides without hazards.

Further analysis of semi-rigid barriers showed that their offset from the edge line may have the effect of increasing the severity of the barrier crash. It was estimated that the FSI ratio increased at a rate of 0.03 per each additional metre of offset, or by 40% over the reported range between 0.5 and 7 metres. Also, results drawn from another investigation in the same study showed that the relative likelihood of a run-off-road casualty crash reduced most sharply in the first 1.5 metres from the edgeline and remained relatively constant at wider offsets. Hence, the findings suggest a possible ideal range for barrier placement would be between 1.5 metres and about 3 – 4 metres to allow road space for a sealed shoulder where required.

Overall, the study findings appear to confirm the current design guidance on high-speed roads. In particular, the findings strongly support the use of flexible barriers. The findings may help to refine this practice through more risk-conscious selection of barrier offsets.

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Notes

¹ FSI ratio is a crash severity index. In this study it is an averaged ratio of fatal and serious injuries sustained per run-off-road casualty crash into a given roadside hazard [19].

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