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Insights Into Wire Rope Safety Barrier Crashes Based on Police-Reported Statistics and Narratives

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Abstract

Wire rope safety barrier (WRSB) is known to be highly effective in reducing the severity of off-road or off-path crashes, however fatal and serious injury outcomes still occur in a small percentage of WRSB-involved crashes. Yet, there is little research on why some WRSB crashes result in severe injury while the majority of crashes involve minor injury outcomes. This paper includes detailed analysis of off-path crashes involving WRSB to better understand associated factors that contribute to severe injury outcomes. Three datasets were analysed: four years of NSW police-reported crash data (2014-2017); ten years of Victorian police-reported crash data and police narratives (2008-2017); five years of police narratives from the US (2001-2005). Results supported earlier research that indicated a relatively low percentage of WRSB crashes involved fatal and serious injury outcomes. Yet, adverse vehicle dynamics were also observed, such as vehicle ricochetting and barrier override, suggesting barrier safety performance could be improved. Some crashes also involved impact angles greater than those used in crash tests, supporting earlier, more detailed research that the full range of real-world crash conditions involving WRSB are not covered in barrier test protocols, and these might be the conditions contributing to severe injury outcomes. The findings provide insight into the potential factors associated with the serious injury outcomes of crashes and can guide further improvements in this effective highway crash countermeasure. Future research should include detailed analysis of real-world crashes to identify factors contributing to adverse crash dynamics, injury outcomes and subsequent implications for barrier design.

Key Findings

- No clear identifiable crash factors were associated with FSI outcomes of WRSB crashes
- Adverse crash barrier dynamics were observed in some WRSB crashes
- The impact angles involving WRSB were often larger than those crash tested
- It is possible that crashes with larger impact angles or adverse dynamics produce FSI outcomes

Introduction

Theoretically, the severity of wire rope safety barrier (WRSB) crashes is expected to be low, due to the deflecting

tensioned wire ropes producing a more gradual deceleration of the vehicle, and exposing vehicle occupants to lowered crash energy (Patel et al., 2017). This is supported by numerous empirical evaluations of WRSB both in Victoria, Australia and internationally. The incidence of serious ca-

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sualty – that is fatal and serious injury (FSI) – off-path¹ or head-on crashes was found to be reduced by between 75% (e.g., Carlsson, 2009; Chitturi et al., 2011; Churchill et al., 2011) and 85% after installation of WRSB (Candappa et al., 2012; Cooner et al., 2009; Zou et al., 2014).

Yet FSI crashes involving WRSB still occur. There is limited research on these crashes, despite ongoing focus of eliminating FSI outcomes in crashes. Moreover, while the deforming nature of WRSB is predominantly a positive feature, it can also mean that vehicle interaction with the barrier is not as predictable as other countermeasures, for example, concrete barrier impacts (Hammonds & Troutbeck, 2012). Because an impacting vehicle retains its shape rather than being deformed by a much more rigid barrier surface, crash dynamics are dependent on not only the typical factors such as height of vehicle centre of mass, frontal and side geometry of vehicle, but also on interactions between the ropes with the side of the vehicle (including the wheels) during an impact. This leads to some safety concerns that are particular to WRSB design. There are also issues with the ability of WRSB to restrain heavy vehicles and motorcyclists; as well as the potential for secondary crashes if deflections of the WRSB are excessive, suggesting some pertinent safety issues persist in relation to WRSB performance (Marzougui et al., 2012).

Despite these concerns, little is known in the publicly-available literature about how the full range of passenger vehicles interact with WRSB, nor the specific factors related to real-world FSI crash outcomes. While the above-mentioned macro before-after studies of crash numbers indicate overall high levels of reduction in injury severity, they generally provide little detail of the remaining crashes with fatal and serious injury outcomes.

With ongoing installation programs of WRSB locally and internationally, there is a growing need to better understand these crashes. Of the limited studies that have investigated these aspects (e.g., Marzougui et al., 2012; Ray et al., 2009; Sicking & Stolle, 2012), the focus has been predominantly restricted to median crashes involving US road configurations. The US studies recorded several concerning adverse WRSB-vehicle interactions (i.e., crash dynamics that contain the risk of a secondary collision with high risk of serious injury), including barrier penetration (through vehicle under-ride or over-ride of the barrier) and vehicle rollover (e.g., Coon et al., 2002; Russo & Savolainen, 2018). As these findings often involved crashes into only the median on right-hand drive roads with wider road geometry, with WRSB designs sometimes different to the standard designs used in Victoria, Australia, the applicability and verification of the findings within Australian settings need to be investigated.

This paper looks at the detail of passenger vehicle crashes into WRSB, with the objective of identifying po-

tential factors related to serious injury. The focus is on high-speed roads only, where the majority of FSI crashes into WRSB occur, to minimise effects of more complex road geometry and traffic configurations. As these data have not been previously investigated, a broader purpose of this study is to help inform areas of lowered safety performance of WRSB to further align its use to Safe System ideals (Larsson & Tingvall, 2013), the basis for the Victorian road safety strategy.

Method

To address the scarcity of data on WRSB crashes as well as detail on vehicle interaction with the barrier, three data sources (Dataset A, Dataset B and Dataset C) were utilised to provide the qualitative and quantitative data needed to meet the study objectives (Table 1). These were analysed with respect to typical characteristics of crashes involving WRSB. Care was taken to limit data contamination across databases by only combining datasets with common elements.

Data sources

Dataset A included a combination of Australian WRSB crashes in New South Wales (NSW) and Victoria, provided by state government departments in each state. NSW crash data, provided by Transport for NSW, comprised four years of property damage and injury crashes (for the years 2014–2017 inclusive). Victorian crash data were provided by Victorian Road Authority, VicRoads, (now the Department of Transport and Planning) and included ten years of all-injury WRSB crashes from the Victorian crash database (2008–2017). The dataset was anonymised by VicRoads staff who redacted any personal identifying information.

Dataset B was provided by Victoria Police and included narratives of WRSB all-injury crashes completed by police officers attending WRSB crashes in Victoria. These police reports provide valuable, albeit mostly subjective, information on how the crash occurred, loss-of-control causation (i.e., medical conditions or speeding), crash factors, vehicle interaction with barriers (such as vehicle ricochet after barrier contact or vehicle mounting of barrier) and any secondary crashes. Injury outcomes were classified into fatal, serious (hospital admission) and other injury. An example of a typical crash description from this dataset is “... veh (model type) travelling on a 100 km/h road along road x. Driver has lost control on a straight section of road colliding with the centre wire rope barrier. Veh has become airborne, sliding along the top of the wire barrier, coming to rest on barrier...”. In the absence of this police description, only quantitative data would be available, providing the speed limit, the alignment of the road (bend or straight),

¹ “off-road” refers to crashes in which vehicles travel off the road; “off-path” refers to all crashes in which vehicles do not stay on the designated direction of travel including those that veer into opposing traffic. The latter term has been used as the general term in this paper to include all crashes that can be addressed by wire rope safety barrier.

Table 1. Description of data available from the datasets

Datasets	Characteristics	Number of crashes	Crash characteristics studied
Dataset A	Aggregate NSW and VIC data	404	Broad characteristics of WRSB fatal and serious injury crashes
Dataset B	Victorian Police reports	82	Impact angle characteristics (numerical)
Dataset C	US Police reports	155	Cause of vehicle loss-of-control
		185	Impact angle characteristics (word descriptions)
		133	Impact speed characteristics
		36	Barrier deflection characteristics
		174	Vehicle damage characteristics

and that the vehicle veered off to the right, colliding with a “barrier”.

Dataset C comprised similar crash narratives of WRSB crashes obtained from a report on the evaluation of approximately 80 km of WRSB crashes in the US (Agent & Pigman, 2008) that included the raw data in an appendix. Permission to use the data was obtained from the authors. Data included crashes involving two barrier manufacturer designs, Trinity and Brifen. The restrictions identified earlier with regard to relevance of US data in Australian settings still apply. Yet, the large proportion of the dataset containing data on Brifen barrier, common to Australian settings, helped address the issue of data relevance to some extent. Moreover, this dataset provided data on additional aspects of interaction with WRSB, not previously identified (Marzougui et al., 2012; Sicking & Stolle, 2012), including references to barrier impact conditions, vehicle damage, barrier deflection, as well as cause of vehicle departure from road. The benefit of understanding additional aspects of the crash issue was considered to outweigh the possible data limitations. Necessary care was taken, however, to keep separate the data sources where necessary so as to not contaminate or distort findings.

Data extraction

Case selection for Dataset A included injurious, single-vehicle WRSB crashes on high-speed roads (speed limits of 90–110 km/h) using both Victorian and NSW data. The Victorian data included injury crashes in Victoria (2008–2017 inclusive) provided by VicRoads per the following criteria:

- single-vehicle crashes on mid-blocks (i.e., excluding intersections), with Definition for Classifying Accidents (DCA) codes, as defined by VicRoads, for:
 - “off-path crashes on a straight section” (170–173)
 - “off-path on a bend” (180–183)
 - “vehicle loss-of-control while overtaking” (151)

Crashes into barriers were identified through the VicRoads Road Crash Information Services sub-category of crashes involving a “fixed roadside object”, with crashes involving only WRSB identified through text analysis. A text search of each police report was completed using typical

terms for the barrier (e.g., “wire”, “rope”, “cable”, “flexible”, “tension”, “barrier”). Unless the police identified the specific barrier type as part of the crash description, the crash record was not included. Duplicates were removed, producing a dataset of 82 WRSB crashes. The police reports were manually examined for any notable characteristics pertinent to WRSB crashes. These included descriptions of vehicle loss-of-control, medical conditions or impairment of driver, and road maintenance issues along with descriptions of vehicle-barrier interaction and subsequent trajectory, and unexpected aspects of crashes. In particular, crash dynamics such as tendency for vehicle ricochet and secondary collisions, under- and over-riding of the barrier, and vehicle rollover were noted. Where sketches of the crash were provided, angle of vehicle contact into barrier was used as an estimate of impact angle.

NSW crash data were extracted by Transport for NSW per the following criteria for the defined category of off-path crashes:

- property damage and injury crashes for the years 2014–2017 inclusive, involving the Road User Movement (RUM) code as defined by Transport for NSW:
 - “head-on” (20)
 - “overtaking” (50–55)
 - “off-road on straight” (70–79)
 - “off-road on bend” (80–89)

It is noted that while the selected crash type categories included head-on crashes, no head-on crashes involving WRSB were in the final dataset, maintaining consistency with the Victorian dataset. Injury crashes involving barriers as the fixed roadside object were selected (producing 2,665 cases) and further filtered to those involving WRSB (367 cases). The combined dataset was then further narrowed by selecting only crashes involving speed-limited routes of 90–110 km/h (322 cases). Aspects such as impact angle were not available in the NSW dataset while other variables such as fatigue and drowsiness were available but due to very low numbers were not included in the final analysis.

Data from 185 US crashes into WRSB were extracted from a US study with author approval (Agent & Pigman, 2008). Data included off-path median crashes into WRSB at speed limits of 55–70 mph (or approx. 90–110 km/h) over the period of 2001–2005. Descriptions were analysed us-

ing the same method as for the Victorian dataset, i.e., vehicle loss-of-control, medical conditions or impairment of driver and road maintenance issues, descriptions of vehicle-barrier interaction and subsequent trajectory, and notable crash aspects. In particular, cause of loss-of-control, vehicle damage and crash impact conditions as well as dynamics such as the tendency for vehicle ricochet and secondary collisions, under- and over-riding the barrier and vehicle rollover were noted. In the case of the US data, impact speed and impact angle and barrier deflection were available in the descriptions and included in the analysis. Deflection distance was converted from feet as reported in the Agent and Pigman (2008) study to metres. Distances were categorised within a half metre to provide a broad idea of deflection widths.

Statistical analysis

Statistical analysis was completed using SPSS (Version 25). Details such as impact angles, any references to less typical vehicle interaction with barriers, and possible medical causes of crashes were introduced as new variables. Injury severity was recoded as a new variable using FSI (fatal and serious injury) and NFSI outcomes (Non-FSI outcomes). For a uniform definition of serious injury across datasets, only crashes classified as “serious injury” (and not “moderate injury” used within the NSW dataset) were included under the category of FSI outcomes. Driver age was subdivided into younger drivers (<25 years), older drivers (>65 years) and those aged 25–65 years (Commonwealth of Australia, 2018). Analysis focussed on identifying the characteristics of WRSB crashes associated with FSI outcomes. Statistical methods involved cross-tabulation, Chi-Square tests and Fisher’s Exact test where required. As the police-reported specific barrier dynamics details were unsuited for statistical analyses, general descriptions and case frequencies were graphed and discussed. Impact speeds were based on police estimates from crash reports. Impact angles into WRSB were either estimated from police reports (Dataset B) or inferred from text descriptions (Dataset C).

Results

All injury WRSB crash characteristics

Based on Victorian and NSW crash data (Dataset A) approximately one in five WRSB crashes resulted in fatal or serious injury (Table 2) with the rest involving minor injuries (n=404). The majority of the crashes involved: passenger vehicles (94%); occurred on divided roads (83%), straight sections of road (62%), and; roads with speed limits of 100 or 110 km/h (96%).

The crash-involved driver was typically male (70%), and aged between 25–65 years old (63%). Crashes mainly occurred in clear weather (74%).

Fatal and serious injury WRSB crash characteristics

Based on Victorian and NSW crash data (Dataset A), approximately three-quarters of FSI WRSB crashes involved: passenger vehicles (78%); occurred on divided roads (83%), straight sections of road (62%), and; roads with speed limits of 100 or 110 km/h (96%). The crash-involved driver was typically male (69%) and aged between 25–65 years old (62%). Crashes mainly occurred in clear weather (74%).

Road user characteristics

Based on Victorian and NSW crash data (Dataset A) a statistically significant difference was evident in FSI crashes involving older drivers (>65 years) compared to those involved in other injury crashes, when compared to the base case of drivers (25–65 years) (n=285, p=0.023). Along with older road users, motorcyclists were found to be heavily over-represented in FSI crashes (n=397, p<0.0001), involved in 20% of FSI crashes (Table 3). By way of comparison, across all non-metro areas of Victoria and NSW in 2015 (not just the high-speed roads that are under consideration here), cars were estimated to comprise 66% of vehicle kilometres travelled (VKT) and motorcycles 1.4% (BITRE, personal communication, 2015).

Crash detail characteristics

Based on Victorian and NSW crash data (Dataset A) no statistically significant differences were found in WRSB crash characteristics involving fatal and serious injury outcomes (FSI) compared to other injury outcomes (OI) for the parameters investigated in Table 4.

Vehicle-barrier interaction

Based on US police narratives (Dataset C), just under a third of WRSB crashes resulted from collision avoidance, often when another vehicle was changing or merging lanes (Figure 1). Vehicles also impacted WRSB in secondary crashes, when a vehicle clipped another vehicle and then collided with the barrier. Fatigue, sleep, or driver distraction was identified by the driver or attending officer, as another causal factor in crashes.

Impact speed characteristics

Based on US police narratives (Dataset C), crash impact speeds were mostly within the posted speed limit range of 90 and 110 km/h (55–70 mph). A few crashes exceeded these speed limits, with the highest impact speed at an equivalent speed of 160 km/h (99 mph), while some crashes involved low impact speeds of 50 km/h or less (35 mph or less). Between 20–30% of the crashes involved some injury. Overall, ratio of injury to non-injury crashes was <1 except in the cases where WRSB crashes involved travel speeds greater than the speed limit. It is noted that these data only indicate whether an injury was involved in the crash, not the level of injury.

Table 2. Characteristics of WRSB crashes

Variable	N	%	Variable	N	%
Injury type			Carriageway		
Fatal	9	2%	Divided	337	83%
Serious Injury	71	18%	Undivided	51	13%
Other/Non-Injury	324	80%	Unknown	16	4%
Total	404	100%	Total	404	100%
Sex			Alignment		
Male	279	69%	Curve	155	38%
Female	116	29%	Straight	249	62%
Unknown	9	2%	Unknown	0	0%
Total	404	100%	Total	404	100%
Age of driver (years)			Speed limits		
<25	106	26%	90 km/h	19	5%
25-65	255	63%	100 km/h	205	51%
>65	30	7%	110 km/h	180	45%
Other/Unknown	13	3%	Unknown	0	0%
Total	404	100%**	Total	404	100%**
Road user			Season		
Car	379	94%	Autumn/Winter	200	50%
Motorcycle	18	5%	Spring/Summer	204	50%
Other/Unknown	7	2%	Unknown	0	0%
Total	404	100%**	Total	404	100%
Day of the week			Weather		
Weekday	286	71%	Inclement	101	25%
Weekend	118	29%	Clear	297	74%
Unknown/Other	0	0%	Unknown	6	1%
Total	404	100%	Total	404	100%

Notes:

1. Based on Dataset A – 404 crashes, Vic and NSW data
2. ** does not add to 100% due to rounding error

Impact angle characteristics

According to Victorian police narratives (Datasets B), impact angles were predominantly in the range of 30-45 degrees, with around 70% of impact angles over 29 degrees. Several crashes involved impact angles over 45 degrees, with one crash described as “going head-on into the barrier” (i.e., 90 degrees) ([Figure 2](#)). Text descriptions in US police narratives (Dataset C) indicated a roughly equal number of shallow-angled crashes (24 crashes involved angles described as “shallow”, “sideswipe” or “small angle”), and crashes involving substantial angles (21 crashes involved angles described as “substantial”, “significant”, “steep” or “sharp”). Some of the factors related to these larger impact angles across both datasets involved wet roads, collisions at excessive speed, and secondary crashes where the vehicle spun or ricocheted into the barrier as a result of the primary collision. Data on impact angles from both Datasets B and C were not combined due to the different forms of output (text versus numerical estimates).

Barrier deflection characteristics

Of the US police crash reports recording deflection (36 out of the 185 crashes in Dataset C), around half involved deflections of under 1 m (55%). The rest was greater than 1 m, with one case recording a barrier deflection of over 3 m.

Vehicle damage characteristics

Based on US police crash narratives (174 of the 185 crashes in Dataset C), half the crash-involved vehicles sustained moderate damage, and just over 10% of crash-involved vehicles sustained very severe damage. Percentage of crashes involving injury from vehicles in the ‘very severely damaged vehicle’ category was close to 40% compared to 10% of crashes involving vehicles in the ‘moderately damaged vehicle’ category. That is, from this data sample, it seems that vehicle damage has some correlation with occupant injury.

Table 3. Analysis of differences in road user and crash type characteristics in WRSB crashes between FSI and Non-FSI outcomes

	FSI outcome		Non-FSI outcome		Probability
	N	%	N	%	Chi Square/Fisher's Exact
Sex					
Male	57	73%	222	70%	0.801
Female	21	27%	95	30%	
Total	78	100%	317	100%	
Age					
<25 years	18	23%	88	28%	0.926 [#]
25-65 years (base case)	49	62%	206	66%	0.023 [*]
>65 years	12	15%	18	6%	
Total	79	100%	312	100%	
Vehicle Type					
Car	62	78%	317	98%	<0.0001
Motorcycle	16	20%	2	1%	
Other/Unknown	2	3%	5	2%	
Total	80	100%**	324	100%**	
Crash Type					
Off-path no object involved	31	39%	111	35%	0.565
Off-path into object	48	61%	209	65%	
Total	79	100%	320	100%	

Notes:

1. Based on Dataset A – 404 crashes, Vic and NSW data;
2. [#]Probability of younger road users compared to base case
3. ^{*}Probability of older road users compared to base case
4. ^{**} Does not add to 100% due to rounding error

Table 4. Analysis of differences in crash characteristics in WRSB crashes between injury severity levels

	FSI outcome		Non-FSI outcome		Probability
	N	%	N	%	Chi Square/Fisher's Exact
Carriageway					
Divided	65	84%	272	87%	0.614
Undivided	12	16%	39	13%	
Speed limits					
90 km/h	3	4%	16	5%	1.00 [#]
100 km/h	49	61%	156	48%	0.085 [*]
110 km/h	28	35%	152	47%	
Alignment					
Curve	32	40%	123	38%	0.892
Straight	48	60%	201	62%	
Season/weather					
Autumn/Winter	32	40%	84	53%	0.140
Spring/Summer	48	60%	75	47%	
Inclement	18	23%	83	26%	0.259
Clear	60	77%	237	74%	

Notes:

1. Based on Dataset A – 404 crashes, Vic and NSW data
2. [#]Probability of 90 km/h compared to 110 km/h
3. ^{*}Probability of 100 km/h compared to 110 km/h

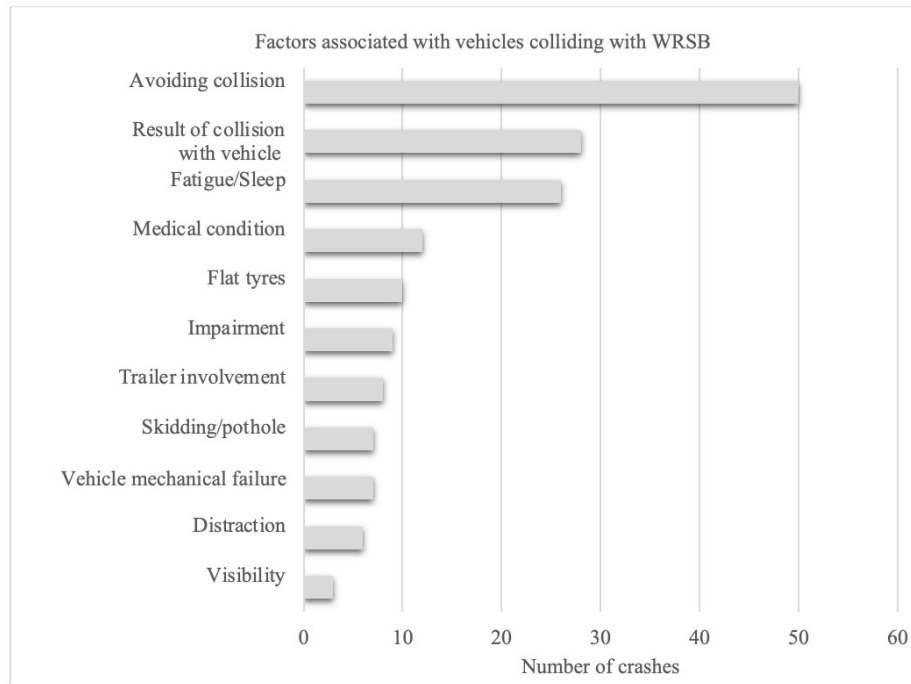


Figure 1. Reasons provided in police-descriptions of crash for vehicle loss-of-control

Notes:

1. Based on Dataset C: 155 of 185 crashes reported cause of vehicle loss-of-control in WRSB crashes (causes were not mutually exclusive)

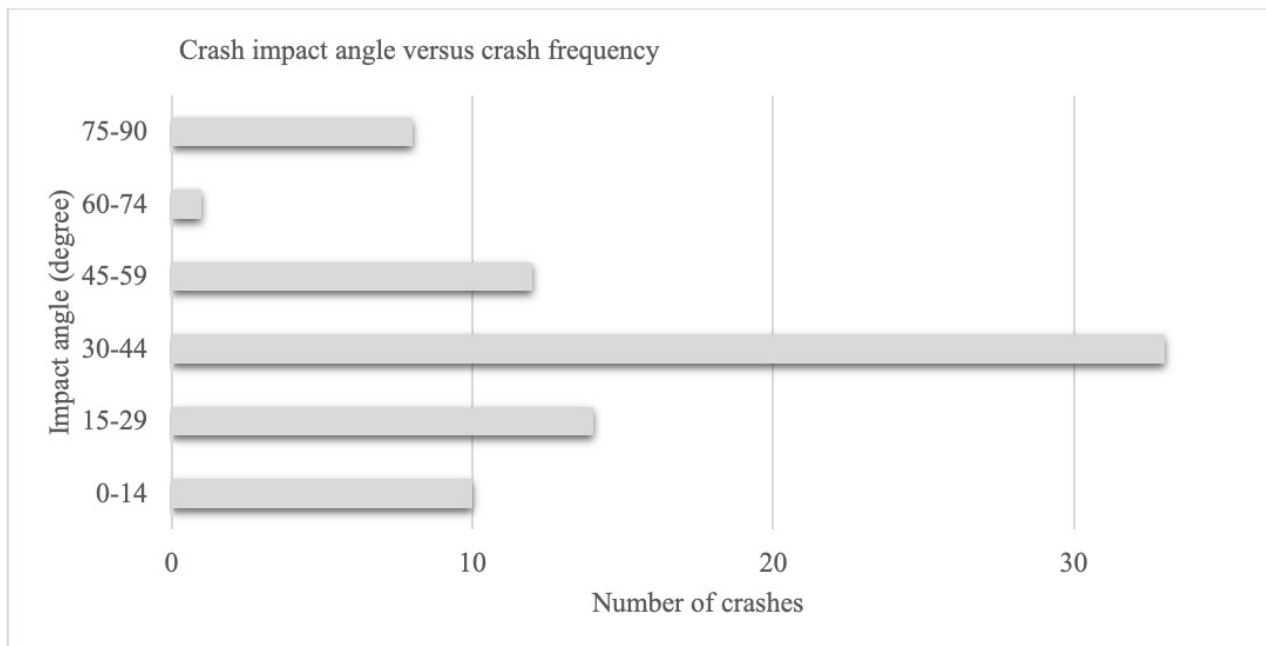


Figure 2. Frequency of crash impact angles involving WRSB

Notes:

1. Based on Dataset B: 78 of 82 police reports that indicated impact angle on a diagram.

Crash dynamics

Based on 267 police crash narratives (Datasets B and C) description of vehicle dynamics after WRSB impact included vehicle “loss-of-control” (subsequent to the impact), rope

entanglement, vehicle ricochet, under-riding and over-riding. Under-riding refers to vehicle travel under the lowest wire rope and over-riding refers to vehicle travel over the highest rope. Vehicle ricochet or zig-zag, refers to when the barrier-impacted vehicle is redirected back into the travel

lane and potentially into other traffic travelling at high speeds. Crash dynamics such as these are identified as adverse, given they are likely to lead to vehicle loss-of-control that could lead to vehicle rollovers or secondary crashes (into hazards the barrier was intended to protect against).

Nearly half of the crashes (41%) involved some form of vehicle loss-of-control. Large stopping distances of over 50 m were involved in 25% of the crashes (increasing the likelihood of secondary crashes); vehicle ricochet and barrier over-riding or mounting, were each involved in around 10% of crashes (11% and 8% respectively), while under-riding was the least frequent adverse crash dynamic (4%). Incidence of barrier penetration was rare. Where fatal or serious injury was recorded, these mostly included cases of drivers under the influence of alcohol or drugs, excessive speed, and driver inexperience, which contributed to lowered control of vehicle and crash conditions typically outside of Safe System design. Airbag deployment was also noted in one case where vehicle contact only involved the WRSB. Although “cable snapping” was noted in one report, ambiguous wording made it difficult to confirm. It must be noted that a combination of these dynamics could be involved in any one crash, and were not mutually exclusive across crashes.

Crash dynamics and corresponding injury

Using Dataset B, around half the crashes with adverse dynamics such as under-riding or mounting resulted in serious casualty and the other half in other injury. When considering the effect of adverse vehicle dynamics on injury severity based on this small data sample, it appears that the involvement of adverse crash dynamics does not necessarily produce more severe crash outcomes.

Case study crash conditions leading to fatal and serious injury outcomes

Results of the study analysis presented several possible conditions under which fatal or serious injury outcomes resulted from collision with WRSB. Many crashes included crash conditions outside intended Safe System design. As an example, a younger driver was travelling at extreme speeds in wet weather, lost control, and collided with WRSB, then spinning out of control and colliding with a gantry. The driver was deceased as a result of the crash. This was recorded as a crash involving WRSB that resulted in death although the extreme impact speed was likely to have been the key contributory factor to the fatal outcome.

Of note are the crashes that did not involve such conditions, and yet resulted in fatal or serious injury outcomes. Some crashes involved WRSB but this was not necessarily a contributory factor. For example, a barrier over-ride involved a younger driver losing control in inclement weather. The driver crossed onto the wrong side of the road, colliding with a steel guardrail before the car became airborne and travelled over the WRSB onto the other side of the carriageway, without making contact with the WRSB, the vehicle landing on its roof. In this situation, barrier over-ride involved a secondary collision where impact tra-

jectory was greatly determined by the initial impact with the guardrail. In this case too, the crash is recorded as a WRSB-involved serious casualty, yet the WRSB was not directly involved in the final injury outcome.

In contrast, and of key interest, was a crash in which the only object hit was a WRSB, and resulted in the fatal outcome of an occupant. This involved a middle-aged passenger who sustained a rib injury following the collision with the WRSB. From the crash description, no additional crash circumstances appeared to have contributed to the injury outcome, and yet resulted in the eventual death of the passenger (fatal outcome was subsequent to the 30-day definition of fatal outcome).

Discussion

Based on statistical analysis of detailed data on WRSB crashes, factors such as road alignment, time of crash, speed limit and weather were not found to be directly associated with fatal or serious injury resulting from WRSB crashes. While motorcyclists and older drivers were found to have a heightened probability of FSI outcomes in WRSB crashes when compared to the base case variable, the heightened risk is more likely related to the inherent road user vulnerability than contact with the WRSB. For example, older road users are likely to be more vulnerable in crashes, due to declining health and increased frailty (Dis-sanayake & Lu, 2002; Oxley et al., 2006; Transport for NSW - Centre for Road Safety, 2017). Drivers aged over 65 years old were found to be twice as likely to die in a frontal crash than drivers aged 30-34 years and three times more likely to die in a side-impact crash (Braver & Trempe, 2004). Similarly, drivers over the age of 75 years were found to have more than five times the risk of being killed in a crash, compared to the average of all ages (European Commission, 2019). Likewise, in the event of a high-speed collision, being unprotected by a vehicle structure, motorcyclists are exposed to large crash forces likely to be beyond human biomechanical tolerances (Bambach et al., 2012; TAC, 2017; Tingvall & Haworth, 1999). As a result of this, as well as the involvement of factors such as excessive speed (Bambach et al., 2012) and alcohol (Bambach et al., 2012; NHTSA, 2020; Transport for NSW, 2017), fatality rates in motorcyclist crashes are likely to be greatly heightened (NHTSA, 2020).

Several of the WRSB crashes involving fatal or serious injury outcomes also involved extreme conditions such as excessive speed likely to contribute to the severe injury outcomes. Notwithstanding this or the intrinsic vulnerabilities of road users, adverse vehicle dynamics were also found to be involved in many severe injury WRSB crashes. Yet these dynamics were also involved in crashes resulting in minor injury outcomes, suggesting that the dynamics in themselves were not necessarily the primary cause of fatal or serious injury. Nonetheless, these dynamics leave open the possibility of serious injury outcomes in WRSB collisions. For example, if a vehicle on a freeway collided with WRSB and then ricocheted back onto the freeway with other vehicles travelling at 100 km/h, potential for serious injury

would be high. Similarly, crashes that involved barrier penetration and hit a tree beyond the barrier, or rolled over the barrier and down an embankment, were also likely to result in FSI outcomes. Many of these dynamics involved other contributory factors such as driver or rider inexperience, secondary collisions, or included a combination of dynamics, rendering it difficult to isolate specific aspects directly related to the severe outcomes.

The occurrence of these adverse dynamics in crashes involving WRSB is also evidenced in past literature. Around 3% of the crashes into WRSB were found to penetrate the barrier, 10% did not strike the barrier at all, and around 6% involved a vehicle rollover (Russo & Savolainen, 2018). Crashes that penetrated the WRSB often involved an impact angle of 25 degrees (Coon et al., 2002) and vehicle prying of cables, while rollovers were associated with wheel entrapment (Sicking & Stolle, 2012). Dynamic deflections of barrier were found to be up to 3.5 m (Alberson et al., 2003; Coon et al., 2002; Grzebieta et al., 2002). Vehicle mounting of the barrier upon contact was not specifically referred to in the US median crashes although evident in findings from this study. Adverse dynamics were also evident within some crash tests of WRSB where, for example, one vehicle rolled on impact with the WRSB (Grzebieta et al., 2002) or pitched and yawed to a dangerous degree (Hammonds & Troutbeck, 2012). Large impact angles were evident in some earlier studies as well (e.g., Abraham et al., 2016; Sicking & Stolle, 2012). However, the distribution of impact angles evident from the data in the current study varied from other studies (e.g., Albuquerque et al., 2010), posing some uncertainty in the validity of the findings. One factor contributing to this difference is in the crash detail and crash numbers involved in the study. Impact angles in this study were gathered from police reports that did not distinguish between primary and secondary crashes. After an initial crash, a secondary crash may involve a rollover, spin or ricochet into the barrier, resulting in barrier impacts at far greater angles than a typical departure angle. While data on impact angles from earlier research were also determined using police officers (e.g., Albuquerque et al., 2010), the data collections were through more detailed crash investigation, presumably allowing for greater distinction between such crash categories. Significantly larger crash numbers used in some of the studies would have also likely mitigated the current skew towards larger angles evidenced in this study. Moreover, earlier research was US based, with different road geometry, vehicle models and driving behaviour (Candappa, 2020) presenting further difficulties in data comparison. As a result, while the data on impact angles might provide only a broad understanding of the typical barrier impact angles and are difficult to verify, it provides much needed insights into WRSB crash characteristics. Local data availability for barrier crashes is still in its preliminary stages, with much scope for improvement in data collection practices as well as result accuracy. Thus, each stage of data analysis provides a foundation for progress in this field, necessitating the inclusion of such preliminary results.

The lack of detailed investigation into barrier crashes in general means police officers can only determine poten-

tial contributing factors to the crashes they attend from the post-crash evidence, driver and eyewitness accounts. These determinations are without the benefit of an in-depth crash investigation by experts and the access to the richer, more detailed information this would yield. In particular, barrier failure will also be affected by the existing condition and installation aspects of the WRSB at the time of impact – that is whether the barrier was operational, the tension of the wires, installation aspects that might not be best practice – yet this detail is not available in existing crash datasets. Additionally, due to the increased likelihood that crashes with WRSB result in minor or nil injury, it is possible that less severe or non-injurious crashes go unreported (VicRoads, 2019), potentially skewing findings towards higher levels of injury. This, along with the lack of exposure data for both barrier installations and vehicle volumes, create difficulty in establishing the exact crash risk for various road users. Additionally, but not unique to this dataset, is the difficulty of verifying on-site data collected on post-crash observations. For example, the noted cable “snapping” is surprising given the rupture load of wire rope is likely to be greater than typical vehicle loads (Stolle & Reid, 2011), however, the circumstances of this cannot be verified. Similarly, data on impact angles are not easily verified. In contrast, rather than being a limitation, the use of both Australian data and US data with likely differences in vehicle fleet and driver characteristics, presents the clear advantage of widening the sample of vehicle types interacting with the barrier.

Application and future research

Several observations can be made in light of these findings. Study findings reinforce the overall effectiveness of WRSB in reducing the potential for severe crash outcomes. Data indicate that even in cases where adverse crash dynamics were evident, the crash outcomes may not necessarily be severe, suggesting a level of protection is afforded by the barrier. While validating the continued use of WRSB, current findings can be enhanced through a larger database, with more in-depth analyses of WRSB crashes, particularly in relation to the effect of crash dynamics on injury outcome.

Evidence of adverse dynamics in many WRSB crashes indicate an unpredictability in vehicle interaction with the barrier that can possibly lead to more severe injury outcomes, or secondary collisions. Given the purpose of roadside barriers is to minimise injury by preventing impacts with hazards and secondary collisions (e.g., Grzebieta et al., 2002; Hammonds & Troutbeck, 2012), these dynamics suggest WRSB design may not always meet its purpose of effectively capturing all errant vehicles. Yet, detailed analysis of WRSB crashes did not help to identify the conditions under which these dynamics are more likely. Future research could include on-site investigations of real-world case studies to more thoroughly identify triggers to adverse dynamics.

Incidence of barrier deflection of over 3 m is noteworthy given typical working width is considered to be less than 2.5 m (Austroads, 2009). Similarly, while findings of real-world impact angles from this study are only preliminary, they

do support earlier research (Abraham et al., 2016) which suggests the barriers are being tested at crash test conditions below potential real-world conditions. Crashes occurring outside tested conditions could be contributing to unexpected injury outcomes. Thus, consideration can be given to undertaking detailed investigation of WRSB crashes with the intent of verifying the need for extending the range of testing conditions to better address WRSB crashes that result in fatal or serious injury outcomes.

Such research can then be used to improve barrier design and on-site application guidelines to enhance the safety performance of wire rope safety barrier, aligning the barrier to Safe System objectives of eliminating fatal and serious injury crash outcomes.

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Author contributions

Nimmi Candappa designed the study scope, accessed the data, completed the analyses, drafted the paper and revised

the draft based on reviewer comments. Janneke Berecki-Gisolf conceived analysis design, supervised the analyses and reviewed the draft article for statistical accuracy. David Logan reviewed the draft for content accuracy. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare that there is no conflict of interest.

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Data availability statement

Raw data for this study comprised crash data available from the Victorian Road Authority, VicRoads, (now the Victorian Department of Transport and Planning), and Transport for NSW. US data were accessed from the Agent & Pigman, 2008 study as detailed in the References

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Appendix A. Summary of crash dynamics and vehicle-WRSB interaction based on 82 police narratives (Dataset A)

Crash dynamics	N
Cause of Road departure	
Off path due to:	
Driver changing lanes	3
Loss of control	28
Bald/flat tyres	3
Distraction	2
Braking hard	5
Visibility (fog)	3
Medical condition	7
Fatigue/sleep involved	17
Alcohol/drugs	3
Road User	
Heavy vehicle driver	1
Motorcycle rider	5
Older driver	6
Younger driver	29
Pre -Crash Factors	
Rain/Wet surface	9
Crash on a curve	15
Crash involving excessive speed	6
Impact angle estimated as >30	39
Between barrier lengths	2
Secondary collision	5
Vehicle spins/ rolls into WRSB	6
Impact speed	-
Post-Crash Details	
Other objects involved in crash	4
Barrier penetration	1
Cable snaps	1
Override/Mounts WRSB	8
Underride	0
Rollover/LOC after collision	13
Vehicle entanglement in barrier	8
Ricochet/crossing lanes	21
Vehicle stopping distance >50m	10
Crash Outcomes	
FSI outcomes	32
Road user death	3
Vehicle badly damaged/towed	16
Air bag deployment	2