

# FINAL REPORT

## **R90: Effects of Roadside Slope on Crash Severity Outcomes Year 1 (2019/20)**

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# Summary

This research project involved an investigation and evaluation of the severity of run-off-road crashes associated with roadside slope (embankment) with different configurations. Technical guidance for design pertaining to the aggressiveness of roadside slopes with different characteristics resulting from run-off-road crash is limited. For improved confidence in the safety level provided by different slopes the main aim of the project was to quantify the risks associated with vehicle recovery on different batter slopes and heights (e.g. 4:1 and 6:1), so that the safety benefits of each slope configuration could be demonstrated.

This report presents the result of an investigation into the relationship between run-off road crashes and slope characteristics. It details current national and international design practices, impact of slope features on the likelihood and severity of run-off-road crash and determination of rollover-risk.

The study analysed slope and historical crash data but failed to identify significant relationship between run-off-road crash risk and slope due to the poor categorisation of the slope data.

Furthermore, the project was impacted by the publication of an update the Austroads *Guide to Road Design (AGRD) Part 6* in 2020. The new guide uses risk assessment and addresses potential concerns over the use of 4:1 slopes rather than safety barriers. However, the Trauma Indices for slopes are based on the severity indices in the 2010 version of AGRD Part 6. Given that these severity indices are not based on well-founded research, they will need to be updated. As a result, the study's objectives were revised to review and update the Trauma Indices for slopes in the updated guide.

Updates to Trauma Indices have been proposed but due to the different FSI rollover rates in Queensland, further research based on local conditions is required before the Trauma Indices in AGRD Part 6 can be updated. Until the new model is established, and a better idea of how it works in practice is established, it is unknown how the learnings from this project can best be implemented into practice.

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# 1. Introduction

## 1.1 Background

The crash outcome and the ability of road users to either recover or safely stop in run-off-road events where a roadside slope is encountered (and where no object is impacted) is a function of the steepness of the slope, its height and the level of roughness of the pavement surfacing. A vehicle that runs off the road and does not hit an object is at risk of rolling over due to the presence of a roadside slope. Generally, the steeper the slope, the higher the probability of a vehicle rollover.

Rollovers are the leading cause of fatalities in single vehicle run-off-road (SVROR) crashes (Sheikh et al. 2019). DeLeys and Parada (1986) reported that the number of occupants fatally injured in rollover crashes is nearly twice that for all other crash types. It is thus important to select a roadside slope that takes into consideration the associated risk of vehicle rollover.

Technical guidance pertaining to the aggressiveness of roadside slopes with different characteristics resulting from run-off-road crash is limited and there are clear gaps within the evidence-based research. For example, practice is to construct embankments with a slope of 1 (vertical):4 (horizontal) as a default, although the level of safety provided by a 4:1 slope compared to an alternative slope design – or to an alternative measure such as a safety barrier or guardrail – is difficult to quantify.

Queensland Department of Transport and Main Roads (TMR) has a responsibility to manage safety risks along its network. Roadside slope design is part of its 'safer roads' responsibility and, as such, it should be managed according to the safe system framework that TMR has adopted to manage road safety on its network.

This report presents the result of an investigation into the relationship between run-off road crashes and slope characteristics. It details current national and international design practices, impact of slope features on the likelihood and severity of run-off-road crash and determination of rollover-risk.

## 1.2 Aims and Objectives

The aim of the project was to provide enhanced, evidence-based guidance for practitioners tasked with the design of safe roadside slopes. Ideally, the guidance would enable a practitioner to select a safe slope configuration (as compared to alternatives such as a barrier) using the risk model for a specific location.

Due to the lack of quality slope data from TMR the study objectives were revised to cover the following:

- Review current TMR practices and local and international literature regarding the relationship between rollover accidents and slope configuration.
- Determine the rollover rate and expected number of fatal or serious injury (FSI) crashes for different roadside configurations
- Review and update the Trauma Indices for slope design recommended in the *Austroads Guide to Road Design (AGRD) Part 6* (AGRD Part 6) (Austroads 2020) based on the findings of this study.

## 1.3 Report Structure

The report consists of the following sections:

- Section 2 – study methodology, including the tasks undertaken
- Section 3 – literature review
- Section 4 - suggested updates to AGRD Part 6.
- Section 5 – conclusions and recommendations.

## 2. Methodology

### 2.1 Literature Review

The literature reviewed involved the following:

- Review of TMR current guidance/practice for determining if a roadside slope is 'safe' or 'unsafe' in terms of a risk model. This included a review of AGRD Part 6 and a review of logic/risk mapping considered in the RISC tool (Austroads 2010).
- National and international literature review of alternative guidance/practice for determining if a roadside slope is 'safe' or 'unsafe'.

### 2.2 Crash Analysis

An analysis of the latest five years (2014–18) run-off-road crashes was undertaken to identify the impact of slope parameters on the likelihood and severity of these crashes. The crash types considered are shown in Table 2.1.

Table 2.1: Slope parameters and likelihood of crashes

DCA Group	DCA code	Comments
15	701, 702	All crashes in this group included in analysis
16	703, 704	Only crashes where first object hit is an embankment or ditch
18	801, 802	All crashes in this group included in analysis
19	803, 804	Only crashes where first object hit is an embankment or ditch

The following data sets were obtained for the analysis:

- crash data (2014–18)
- object hit data
- slope data (including location of slope, slope type, slope angle and slope height)
- Police description of crash records.

The Police descriptions of the crash records were used to link crashes that occurred on a slope at the side of the road and the slope where the crash occurred. The following assumptions were made.

- Crashes linked to only one slope were assigned to that slope.
- Crashes linked to two or more slopes were assigned to the appropriate slope after a review of the crash report (Police description of the crash).
- Crashes not linked to a slope – occurred on flat land.

The total number of crashes satisfying criteria was 2471, comprising the following:

- 566 linked to at least one slope record
  - 277 crashes linked to one slope record
  - 289 crashes linked to two or more slope records
- 1905 not linked to any slope record.

### 2.3 Identification of Roadside Slope Risk

A review of available data, and a crash analysis, found that the classification of the slope angle was too coarse. This was a major limitation as it prevented the accurate determination of the relationship between crash severity outcome and slope height. As a result, it was not possible to determine slope risk and the safety level of a particular slope. . It was therefore decided to revise the project scope to include a review and update of the Trauma Indices in the AGRD Part 6 (Austroads 2020) based on recent research as outlined in Section 2.4.

## 2.4 Update to Trauma Indices for Roadside Slope

The tasks involved in updating the Trauma Indices in AGRD Part 6 (Austroads 2020) included the following:

- Review of AGRD Part 6. The publication of AGRD Part 6 (Austroads 2020) rendered the review of current practice obsolete because the updated Guide employs a different philosophy in the way risk is determined.
- Determine rollover rate and the proportion of rollover FSI crashes. The following tasks were undertaken:
  - analyse five years (2014–18) crash data on Queensland roads to determine the proportion of rollover crashes that resulted in an FSI
  - compile rollover probability levels and the proportion of rollover crashes that resulted in an FSI based on the recent literature.
- Determine Trauma Indices related to slope based on rollover severity rate and the probability of rollovers. The Trauma Index is computed as the product of the rollover severity rate and the average rollover probability level.

## 3. Literature Review

A summary of the findings of the literature review follows. The full report is presented in Appendix A.

### 3.1 Existing Practice

Generally, the methodology for slope design and treatment adopted in Australia prior to the publication of AGRD part 6 (Austroads 2020) and internationally is largely the same; however, there are variations in the technical specifications used between jurisdictions and other countries. For example, the 'area of interest'/clear zone concept is generally adopted, but there are some differences in the variables used to determine the clear zone width. The criteria used to classify embankments as aggressive (hazardous) also vary between countries, with criteria for classifying a slope as an aggressive object (hazard) ranging from 1:1 to 3:1.

Slope design and treatment parameters adopted in Australia and selected European countries are shown in Table 3.1. As the design and treatment parameters adopted in new AGRD Part 6 (Austroads 2020) are based on risk assessment, they were not included in the comparison; only the design features reported in the Austroads 2010 guidelines and the various jurisdiction supplements are summarised.

**Table 3.1: Comparison of slope design parameters between countries**

Parameters	AGRD Part 6 (Austroads 2010)	TMR	NSW RMS	VicRoads	MRWA	Finland	France	UK	Germany/Netherlands	Spain	Sweden	Issues/Limitations
Critical slope • cars • trucks	See Table A.1 3:1 4:1	Same as Table A.1 3:1 4:1	Same as Table A.1 3:1 4:1	Same as Table A.1 3:1 4:1	Supplement 4:1 10:1	X X	>1:1 X	>1.1; height >0.75m X	>3:1 X	n.a <sup>1</sup>	n.a	Variation in values/parameters between countries
Fill slope (batter) • maximum slope • slope height • Offset to roadway	See Table A.2 4:1 >1.5m ✓	See Table A.2 4:1 >1.5m ✓	See Table A.2 4:1 >1.5m ✓	See Table A.2 4:1 >1.5m ✓	Based on slope height: 6:1 for height 0.3–1 m, 4:1 for height > 1 m All slopes >3m high	X >2m X	1:1 4m X	>1.1; height >0.75m >6m <4.5m for >80km/h	>3:1 X X	X X X	X X X	Variation in values/parameters between countries
Cut slope • maximum slope • slope height • Presence of ditch	See Table A.2 2:1 X ✓	Same, Table A.2 ✓ X ✓	Same, Table A.2 ✓ X ✓	Same, Table A.2 ✓ X ✓	Cut slopes to be constructed flatter than 1:1	X X ✓	>1.5:1 >0.5m ✓	X X ✓	>3:1 X ✓	X X X	X X X	Variation in values between countries
Rock slope • maximum • slope height • offset to road • Presence of ditch	See Table A.2 0.25:1 X ✓ X	Same as Austroads ✓ X ✓ X	Same as Austroads ✓ X ✓ X	Same as Austroads ✓ X ✓ X	Same as Austroads ✓ X ✓ X	7:1 All 2–3m ✓	X X X X	>2:1 <1.5m <4.5m X	X X X X	X X X X	X X X X	Variation in values between countries
Area of interest /Clear zone	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
<b>Clear zone parameters</b>												<ul style="list-style-type: none"> <li>• Not applicable to all vehicle types</li> <li>• Applicable to low departure angles; likelihood of vehicle recovery reduces with increase in departure angle</li> <li>• Does not capture risk to vehicles that are known to travel further than clear zone width</li> <li>• Suggested clear zone widths are a general approximation of the needed clear zone distance (based on AASHTO, 1996)</li> </ul>
• Road type	X	X	X	X	X	X	✓	✓	✓	✓	X	
• Traffic volume	✓	✓	✓	X	✓	✓	✓	X	✓	✓	✓	
• Design speed	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
• Embankment slope	✓	✓	✓	X	✓	✓	✓	X	✓	✓	✓	
• Horizontal alignment	✓	✓	✓	X	✓	✓	X	X	✓	✓	X	
• Lane width	X	X	X	X	X	X	X	X	X	✓	✓	
• Percent heavy vehicles	X	X	X	X	X	✓	X	X	X	X	X	
Quantitative evaluation methods	Simple manual	X	X <sup>2</sup>	✓	✓	n.a	n.a	n.a	n.a	n.a	n.a	Preferred method varies between jurisdictions
	Detailed manual	X	X <sup>2</sup>	✓	X	n.a	n.a	n.a	n.a	n.a	n.a	
	RISC	✓	X <sup>2</sup>	✓	✓ (recommended)	n.a	n.a	n.a	n.a	n.a	n.a	
	RSAP	X	X <sup>2</sup>	✓ (recommended) <sup>3</sup>	✓ (for info only) <sup>4</sup>	n.a	n.a	n.a	n.a	n.a	n.a	
	Hazard risk assessment	X	✓	✓	X	n.a	n.a	n.a	n.a	n.a	n.a	
Severity Index	See Appendix D Based on AASHTO 1996	✓ modified	✓	✓	✓	n.a	n.a	n.a	n.a	n.a	n.a	Recent research indicates SIs in RISC and RSAP are too high
Treatments selection process	Embankment warrant for high speed roads <sup>5</sup>	Generalised hazard assessment <sup>7</sup>	✓	Only used as general guidance.	✓ <sup>8</sup>	Determined via FSI reduction estimates	n.a	n.a	Via road safety policy including risk assessment	n.a	n.a	

Parameters	AGRD Part 6 (Austroads 2010)	TMR	NSW RMS	VicRoads	MRWA	Finland	France	UK	Germany/Netherlands	Spain	Sweden	Issues/Limitations
	Embankment assessment process <sup>6</sup>		✓	✓	✓		n.a	n.a		n.a	n.a	
Treatment types	<ul style="list-style-type: none"> <li>Flatten to 4:1 slope or flatter (preferred)</li> <li>Barriers</li> </ul>	Barriers preferred on 2:1 fill slopes with height >2m.	<ul style="list-style-type: none"> <li>Flatten to 4:1 slope or flatter</li> <li>Barriers</li> </ul>	Barriers for >=80 km/h Flattening for <80 km/h	Determined via evaluation by RISC	<ul style="list-style-type: none"> <li>Barriers</li> <li>Slope flattening</li> </ul>	<ul style="list-style-type: none"> <li>Barriers</li> <li>Flattening</li> </ul>	Barriers once classify as hazards	<ul style="list-style-type: none"> <li>Barriers</li> <li>Flattening</li> </ul>			

1. n.a.: not available.

2. Not to be used to establish the absolute need to erect a road safety barrier.

3. Recommended to be used in accordance with VicRoads Safe System Assessment Guidelines (VicRoads 2019a).

4. Accepted but only to be used for additional information.

5. Generally, no treatments are required for slopes with height < 1 m; slopes with slope height ≤ 7 m may not warrant treatment.

6. Slopes 4:1 or steeper with height over 1.5 m generally require treatments.

7. TMR requires all embankments to be assessed using the 'Generalised hazard assessment'.

8. Amended, treatments required for all roadside slopes with height ≥ 3 m and 3:1 or flatter slopes may require treatment.

✓ – Parameter considered

X – Parameter not considered

Sources: Austroads (2010), Dupre et al. (2006), RTA (2008), TMR (2014, 2017, 2020), VicRoads (2019a, 2019b), Main Roads WA (2019a, 2019b).

## 3.2 Impact of Slopes on Crashes

The ability of road users to either recover or safely stop in run-off-road events where a roadside slope (embankment) is encountered (and where no object is impacted) is a function of roadside slope steepness, height, and the roughness of the pavement surface. Research indicates that slopes have a large impact on the likelihood and severity of run-off-road crashes. Prior to 1960, run-off-road crashes were commonly perceived as the fault of careless drivers until Stonex (1960) reported that vehicles could potentially lose contact with the ground on 4:1 slopes. A later study by Schoon (1997) found that vehicles could stay in good contact with the ground on 4:1 slopes but steering manoeuvres would be compromised when attempting to regain control.

Some of the options provided to reduce the severity of crashes associated with roadside slopes are as follows (AASHTO 2011):

- Provide a flatter slope between the shoulder edge and the ditch bottom.
- Locate the ditch farther from the roadway.
- Slopes should be 3:1 or flatter to accommodate maintenance equipment.
- Slopes steeper than 3:1 should be evaluated with regard to soil stability and potential crash severity.
- Retaining walls should be considered where there will be a slope steeper than 2:1.
- A slope of 6:1 or flatter on embankments should be provided where practical.
- For moderate heights with good rounding, steeper slopes up to about 3:1 can also be traversable but are not always recoverable.

A summary of the impact of slope on the likelihood and severity of run-off-road crashes is presented in Table 3.2.

**Table 3.2: Slope parameters and likelihood of crashes**

Parameter	Impact on crashes	Appendix A
Slope (gradient)	<ul style="list-style-type: none"> <li>• The number and severity of crashes increases with slope steepness (Elvik et al. 2009).</li> <li>• Crash rate increases with increase in slope steepness (Graham &amp; Harwood 1982; Zegeer et al. 1988).</li> <li>• Rollover occurs at all slopes, including on flat terrains (Sheikh et al. 2019).</li> <li>• The probability of a rollover increases with increase in slope steepness (DeLeys &amp; Parada 1986; Lynam &amp; Kennedy 2005; Sheikh et al. 2019).</li> <li>• The probability of a rollover on a 2:1 slope is approximately nine times more likely than on a 10:1 slope (Carrigan &amp; Sheikh, 2017).</li> </ul>	<p>A.4.2</p> <p>A.4.2</p> <p>A.4.3</p> <p>A.4.6</p> <p>A.4.6</p>
Slope width	<ul style="list-style-type: none"> <li>• The probability of a rollover increases with slope width from 2.4 m to 4.9 m and decreases after that for all slopes, except for flatter slopes, which remain at nearly the same rollover probability as 4.9 m slope width (Carrigan &amp; Sheikh 2017); Sheikh et al. 2019).</li> </ul>	<p>A.4.4</p> <p>A.4.6</p>
Slope height	<ul style="list-style-type: none"> <li>• The likelihood and severity of rollover crashes increases with slope height; rollover frequency increases sharply for heights/depths greater than 0.9 m (DeLeys &amp; Parada 1986).</li> <li>• Crash rate increases with increase in slope height (Reid et al. 2014).</li> <li>• Crash rates on a 3:1 slope greater than 1 m high are about four times more than a 1 m high slope (Pardillo-Mayora, Domínguez-Lira &amp; Rafael Jurado-Pina 2010).</li> <li>• For moderate heights with good rounding, a 3:1 slope can also be traversable, but are not always recoverable (AASHTO 2011).</li> </ul>	<p>A.4.6</p> <p>A.4.5</p> <p>A.4.5</p> <p>A.4.1</p>
Lane width	<ul style="list-style-type: none"> <li>• The crash rate for single-vehicle crashes reduces with an increase in lane width for all slopes (Zegeer et al. 1988).</li> </ul>	<p>A.4.3</p>
Shoulder width	<ul style="list-style-type: none"> <li>• The probability of a rollover is higher on roads with narrow shoulder widths (less than 1.2 m) compared to shoulder widths greater than 1.2 m (Sheikh et al. 2019).</li> </ul>	<p>A.4.6</p>
Encroachment distance	<ul style="list-style-type: none"> <li>• The risk of a rollover increases with increase in encroachment distance from the roadway (Carrigan &amp; Ray 2019).</li> <li>• The proportion of rollover crashes increases with encroachment distance while the proportion of hit-object crashes decreases (Austroads 2011).</li> </ul>	<p>A.4.7</p> <p>A.4.7</p>

Parameter	Impact on crashes	Appendix A
Departure angle	<ul style="list-style-type: none"> <li>The median departure angles for run-off-road crashes range from 13.8 degrees to 19.9 degrees (DeLeys &amp; Parada 1986; Sheikh et al. 2019).</li> </ul>	A.4.6
Vehicle type	<ul style="list-style-type: none"> <li>Variations exist in rollover probability by vehicle class; for passenger vehicles rollover crash rates increase with vehicle size (DeLeys &amp; Parada 1986).</li> <li>Utility vehicles have the highest rollover frequency (40 to 60% rollover rate), which is about three to five times more compared to passenger cars; this is due primarily to their high centre of gravity. (DeLeys &amp; Parada 1986).</li> <li>Carrigan and Sheikh (2017) reported no significant differences in the probability of rollover crashes according to vehicle type. They therefore recommended further studies to confirm this finding.</li> </ul>	A.4.9
Rollover	<ul style="list-style-type: none"> <li>Rollover, recoverable and non-recoverable events can occur for all slopes; ranging from 11% (10:1 slope) to 31% (Sheikh et al. 2019).</li> <li>The probability of a rollover increases with slope steepness (Sheikh et al. 2019).</li> </ul>	A.4.6
Severity index	<ul style="list-style-type: none"> <li>The severity indices for embankments in the US RSAP and RISC model are over-estimated by between 10% (for flatter slopes) to 50% (for steeper slopes) (Schrum et al. 2014).</li> </ul>	A.4.11

### 3.3 Discussion and Summary of Findings

Generally, the process for the design and treatment of embankment slopes used around the world is similar but variations exist with respect to the technical specifications used. There is also limited research available on the lateral distance that an errant vehicle that leaves the roadway may traverse. The distance travelled will depend on a range of variables, including speed, angle of departure and the surface type / condition. It is estimated that 15 to 20% of vehicles that leave the road will travel beyond the clear zone (VicRoads 2019b). An ARRB study (Jurewicz & Pyta 2010) reported that about 30% of run-off-crashes occurred beyond 13 m from the road. Hence, clear zones may only be used to identify the part of the roadside that is of greatest risk to errant vehicles and to inform decisions on prioritising treatment options.

It is noted in Austroads (2020) that, even if rigid hazards (poles, trees, etc.) could be removed from a roadside area that is sufficiently wide to ensure that vehicle occupants are protected from the likelihood of severe injury, there is still a risk of an errant vehicle rolling over, particularly if the ground surface is rutted (Austroads 2020).

A study by Carrigan & Sheikh (2017) found that the variation in the probability of rollover crashes by vehicle type was statistically insignificant. This finding differs from earlier studies and so further research is warranted to confirm this. They also found the impact of slope width on the probability of rollover crashes was statistically insignificant excluding the 2:1 slope. This led them to recommend that further research be conducted on the effect of slope width in order to provide guidance on limiting slope width, particularly on steep slopes.

Sheikh et al. (2019) indicated that vehicles rollover can occur on all slopes, though the average rollover probability increases with slope steepness for slope widths up to 4.9 m and decreases after that. They concluded that the average rollover probability for a 2:1 slope was approximately 30%, or three times that of 10:1 slope (10%). Based on the Safe Systems approach, all hazards that pose a risk of high severity crashes, regardless of how far they are from the road, need to be identified and treated. This implies that the use of a 4:1 slope as a default for hazard identification (as per Austroads (2010)) and 6:1 in Austroads (2020)) may not lead to optimum safe roadsides and that slope height and width should be considered.

## 4. Crash Analysis

### 4.1 Slope-related Crashes on Queensland State Roads

This section presents an analysis of the results of 2 471 run-off-road crashes that satisfied the selection criteria specified in Section 2.2. The detailed results are provided in Appendix B. As stated in Section 2.3 the categorisation of the slope data by slope angle is too coarse and inappropriate, hence care should be taken when applying or interpreting the results presented here.

The main results are as follows:

- The proportion of FSIs for slope-related crashes was slightly lower (60.4%) compared to 61.6% for non-slope-related crashes. In terms of fatalities, 2% of crashes on slopes resulted in fatalities compared to 1.8% for non-slope-related crashes (Table B.1). There is no real differences between the values.
- There was an increasing trend in the proportion of FSI crashes from 2014 to 2018 for both slope and non-slope-related crashes, but a gradual decrease in total casualty crashes over the period (Figure B.1).
- Analysis of the crashes by unit type indicated that (Figure B.3 and Table B2):
  - motorcycles have significantly increased risk of fatal and FSI crashes, especially for slope-related fatal crashes
  - articulated trucks have a significantly increased risk of non-slope-related fatal crashes
  - rigid trucks have increased risk of slope-related FSI crashes.
- The severity of crashes (FSI proportion) on slopes was higher on curves when the view was obscured, but lower on curves with an open, straight alignment compared to non-slope-related crashes (Figure B.5).
- The severity of crashes (FSI proportion) on slopes was lower during adverse lighting conditions (darkness and dawn/dusk) compared to non-slope-related crashes (Figure B.7).
- There were no significant differences in crash severity between slope and non-slope-related crashes (Figure B.9).
- For cut slopes, it was found that there was:
  - no consistent variations in crash severity by slope angle (grade), probably due to the poor categories for slope angle used (Figure B.10)
  - an increase in crash severity with increase in slope height (Figure B11).
- For fill slopes it was found that there was:
  - a decreasing trend in crash severity with increase in slope angle (Figure B.12)
  - an increase in crash severity by slope heights greater than 1.5 m (Figure B13).

### 4.2 Severity of Rollover Crashes on Queensland Roads

Analysis of rollover crashes on Queensland roads was undertaken, and the results are presented in Table 4.1. The result shows that 4% of Queensland casualty crashes resulted in a rollover. The proportion of FSI crashes that resulted in rollovers was slightly higher at 6%. Overall, the proportion of all Queensland casualty crashes that resulted in a rollover FSI was 3%. Approximately, 62% of rollover crashes resulted in an FSI, which was higher than the proportion of all crashes that resulted in an FSI (44%).

Table 4.1: Summary of Queensland crash data (2014–18)

Crash type	Total	Rollover crashes	Per cent rollover
All injury crashes	62841	2604	4.1%
FSI crashes	27576	1608	5.8%
Per cent FSI	43.9%	61.8%	n.a.
Proportion of total casualty crashes that resulted in a rollover FSI.			2.6%

## 5. Proposed Updates to AGRD Part 6 Related to Roadside slopes

### 5.1 Main Features of AGRD Part 6 (2020)

The AGRD Part 6 (Austroads 2020) employs a different philosophy to the previous guide (Austroads 2010). The major change is that it is based on a risk assessment process in line with Safe System principles. The assessment process involved the determination of a risk score due to a run-off-road crash based on exposure, crash likelihood and severity as defined as follows (Austroads 2020):

- **Exposure:** The frequency of vehicles leaving the traffic lane and encroaching onto the shoulder. The exposure is dependent on the carriageway annual average daily traffic (AADT), the number of lanes, the lane width, terrain type, grade and curve radii.
- **Likelihood:** The proportion of drivers that leave the traffic lane and then collide with a roadside hazard. The likelihood is dependent on the operating speed and the lateral distance to a hazard.
- **Severity:** The expected severity of a collision with a particular hazard as measured by a Trauma Index. Different hazards have different Trauma Indices. The Trauma Indices for slope are expected to be based on the probability of a rollover crash, rollover severity crash rate and speed.

Identification of a hazard for treatment is determined by comparing the hazard risk score to a pre-determined Network Roadside Risk Intervention threshold (NRRIT). The risk score is the combined total of the background risk (if applicable) and the hazard risk. Other features include:

- the use of Trauma Index instead of Severity Index to determine the risk score
- the use of a Network Roadside Risk Intervention threshold (NRRIT) as the basis for identifying hazards for which treatment is required
- slopes steeper than 6:1 classified as hazards; treatment required if the risk score, including background risk score, if any, is above the NRRIT
- the use of graphical techniques to evaluate roadside risk, including the NRRIT
- the use of jurisdictional policies and corridor safety visions to define appropriate roadside treatments
- crash cost and benefit-cost ratio are not considered.

Each of these three components (exposure, likelihood, and Trauma Index) could be improved based on new research findings and learnings from the application of the model to real cases over time.

### 5.2 Trauma Index for Roadside Slopes and Barriers

The Trauma Index associated with an object is the proportion (as a percentage) of light passenger vehicle crashes with that object that are expected to result in a fatal or serious injury outcome. So a TI of 2.0 means that 2% of crashes are expected to have an FSI outcome. The Trauma Indices reported in the Guide are shown in Table 5.1. The data in the Table suggests that a flexible barrier with a lower Trauma Index is recommended for implementation on all slopes if the computed risk score at the site, including the background risk, if any, is greater than the NRRIT, noting that a 6:1 slope is not treated as a hazard in the Guide. Other barrier types, (such as w-beams and concrete barriers) have lower Trauma Indices than 4:1 slopes or steeper, except for a 4:1 slope with height less than 2 m.

**Table 5.1: Trauma Indices by slope (converted from Severity Indices)**

Slope	Slope height					Barriers	
	0 to 2 m	2 to 5 m	5 to 10 m	10 to 20 m	> 20 m	Flexible barrier	Other barrier types
6:1	0.63	0.63	0.63	0.63	0.63	0.48	0.84
4:1	0.69	0.89	0.89	0.89	0.89	0.48	0.84
3:1	0.83	1.4	1.5	1.5	2.1	0.48	0.84
2:1	1.3	3.5	4.5	6.7	9.9	0.48	0.84
1.5:1	1.7	7	14	27	39	0.48	0.84

Source: Austroads (2020).

Computed risk scores for vehicles travelling at 110 km/h for various road configurations are presented in Appendix C. The results show that the risk score for a flexible barrier would always be lower than any slope. For other barrier types, the risk score is lower for 4:1 slope or steeper, except for slopes less than 2 m high and a 4:1 slope.

## 5.3 Update of Trauma Index for Roadside Slopes

The Trauma Index for a rollover crash may be estimated based on the rollover severity rating and its probability of occurrence (Ray et al. 2012). The Trauma Indices for slopes are based on the severity indices in the 2010 Guide (Austroads 2010). Given that these severity indices are not based on well-founded research, they need to be updated based on recent research. Available information on rollover severity and rollover probability levels based on reported literature and Queensland crash data are reported below.

### 5.3.1 Severity of Rollover Crashes

A summary of the proportion of crashes that resulted in a rollover identified from the literature and Queensland crash data are provided in Table 5.2. There is a wide variation in the proportions from the various sources. This may be due to the variations in the way serious injury crashes are determined. It is noted that Queensland does not record non-injury crashes i.e. property damage only crashes (PDOs). Furthermore, some crashes are not reported which may not be PDOs.

Carrigan and Sheikh (2017) analysed crashes in the US states of Washington and Ohio and found that 15% of rollover crashes resulted in an FSI. When PDOs are excluded, 23% of rollover crashes resulted in an FSI, which is less than the 62% reported on Queensland roads. Carrigan & Sheikh (2017) also found that the crash severity was twice as high in a run-off-road event when the vehicle rolled over compared to not rolling over.

In an earlier study, DeLeys and Parada (1986) reported that 18% of rollover crashes resulted in an FSI for all crashes, or 32% when PDOs were excluded. The rollover severity rate of 15.2% reported by Carrigan and Sheikh was used in estimating the Trauma Index as it is the latest research that addresses all crash severities for the current vehicle fleet with improved vehicle safety features and driving conditions as reported in Section 5.3.3.

**Table 5.2: Summary of rollover crashes**

Source	Per cent crashes (incl. PDO) that resulted in a rollover FSI	Per cent injury crashes (incl. PDO) that resulted in a rollover FSI	Per cent rollover crashes (incl. PDO) that resulted in an FSI	Per cent rollover crashes (excl. PDO) that resulted in an FSI
Queensland crash data	n.a.	2.6%	n.a.	61.8%
Carrigan & Sheikh, 2017	3.1%	7.4%	15.19%	23.2%
National Center for Statistics & Analysis (NCSA) 2003	n.a.	n.a.	n.a.	10.0%
DeLeys & Parada (1986) <sup>1</sup>	n.a.	n.a.	27.3%	32.2%
DeLeys & Parada (1986) <sup>2</sup>	n.a.	n.a.	18.0%	25.4%
Average/suggested value	3.1%	5%	15.2%	

1. These are based on casualties and have not been considered in the average.

2. These results are based on 1970 research and have been excluded from the average due to changes in vehicle technology. It is assumed current vehicle fleet has a higher safety benefit.

### 5.3.2 Probability of a Rollover Crash

Table 5.3 provides a summary of the probability of a rollover crash and slope taken from the literature. The probability of a rollover crash increases with slope steepness, ranging from 4% to 36% across the three sources provided. The rollover probability levels reported in Sheikh et al. (2019) for 4:1 slopes or flatter were higher than those reported in the earlier studies. Their findings also indicated that rollover probability peaked at about a 5 m slope width and reduced for wider slope widths, especially for steeper slopes (Appendix D). Intuitively, rollover probability increases with slope width, so any decrease in probability after reaching its

peak levels has been excluded. This approach is similar to how the modified equations for computing the base exposure level were developed for use in Austroads (2020).

The rollover probabilities reported by Sheikh et al. (2019) and Carrigan & Sheikh (2017) were averaged across all speeds.

**Table 5.3: Probability of rollover crashes by slope**

Slope	Sheikh et al. (2019) (NCHRP 911)				Carrigan and Sheikh (2017)	Ray et al. (2012) (RSAP v3.0)
	0 to 2 m	2 to 5 m	5 to 10 m	10 to 20 m	All heights	All heights
10:1	11%	11%	11%	11%	4%	5.03%
6:1	14%	14%	14%	14%	8%	5.8%
4:1	17%	20%	20%	20%	15%	6.8%
3:1	20%	25%	25%	25%	22%	12.2%
2:1	31%	42%	42%	42%	36%	18.5%

### 5.3.3 Trauma Index of a Rollover Crash

Using a rollover FSI rate of 15.2% from Table 5.2, the Trauma Indices from the various sources, computed as the product of rollover FSI rate and rollover probability, are shown in Table 5.4.

The Trauma Indices from the three sources are much higher than those published in Austroads (2020), reproduced in Table 5.1. These values are also much higher than Trauma Indices for barriers. Therefore, if exposure and likelihood are kept the same, then the installation of a barrier will be warranted for all slopes including a 10:1 slope if the risk score is higher than the NRRIT. Care should be taken when setting the NRRIT, to avoid such a scenario.

**Table 5.4: Estimated Trauma Indices<sup>1</sup> by slope by source**

Slope	Sheikh et al. (2019), (NCHRP 911)				Carrigan and Sheikh (2017)	Ray et al. (2012) (RSAP v3.0)
	0 to 2 m	2 to 5 m	5 to 10 m	10 to 20 m	All heights	All heights
10:1	1.67	1.67	1.67	1.67	0.61	0.76
6:1	2.13	2.13	2.13	2.13	1.22	0.88
4:1	2.58	3.04	3.04	3.04	2.28	1.03
3:1	3.04	3.80	3.80	3.80	3.34	1.82
2:1	4.71	6.38	6.38	6.38	5.47	2.81
1.5:1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

1. TI computed as the product of probability of rollover and FSI rollover severity rate of 15.19% (from Carrigan and Sheikh 2017).

Computed Trauma Indices based on those reported in Sheikh et al. (2019) are shown in Table 5.5 together with the values reported in Austroads (2020). These Indices could be considered as updates to AGRD Part 6. This is because this is the latest comprehensive information available and provides Trauma Indices according to slope and slope height. However, the FSI rollover severity differs from that in Queensland, so further investigation is required.

**Table 5.5: Suggested updated Trauma Indices (72 to 121 km/h) vs AGRD Part 6 Trauma Indices for 110 km/h**

Slope	Recommended TI (Sheikh et al. 2019 (NCHRP 911))*						AGRD Part 6 (2020)					
	0 to 2 m	2 to 5 m	5 to 10 m	10 to 20 m	10 to 20 m	> 20 m	0 to 2 m	2 to 5 m	5 to 10 m	10 to 20 m	> 20 m	
10:1	1.67	1.67	1.67	1.67	1.67	1.67	n.a.	n.a.	n.a.	n.a.	n.a.	
6:1	2.13	2.13	2.13	2.13	2.13	2.13	0.63	0.63	0.63	0.63	0.63	
4:1	2.58	3.04	3.04	3.04	3.04	3.04	0.69	0.89	0.89	0.89	0.89	
3:1	3.04	3.80	3.80	3.80	3.80	3.80	0.83	1.4	1.5	1.5	2.1	
2:1	4.71	6.38	6.38	6.38	6.38	6.38	1.3	3.5	4.5	6.7	9.9	
1.5:1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.7	7.0	14	27	39	

Note: TI computed as the product of probability of rollover (Sheikh et al. 2019) and FSI rollover severity rate of 15.19% (Carrigan & Sheikh 2017).

## 5.4 Other Consideration

### 5.4.1 Exposure

Exposure is computed as the number of vehicle encroachments per km per year. It is based on AADT and various road features namely, lane width, number of lanes, terrain, curvature, and grade.

Shoulder rumble strips are a low-cost treatment with documented safety benefits. They have the effect of reducing the likelihood of run-off-road crashes. Over the past few years, TMR has invested in the installation of shoulder rumble strips to help reduce the number of run-off-road crashes by reducing the number of vehicle encroachments into the roadside.

To account for this investment and the safety benefit of shoulder rumble strips, a correction factor for the presence of shoulder rumble strip should be applied to the base exposure. This will account for the expected reduction in the number of vehicles that will run off the road. The suggested correction factor has been computed based on the risk score used in AusRAP (iRAP 2010) as shown in Table 5.6. The value of 0.8 implies that the presence of rumble strips will reduce the number of encroachments. This is not inconsistent with the crash reduction factor of 25% identified for ATLM in NACOE R87

**Table 5.6: AusRAP risk score and estimated correction factor for shoulder rumble strip**

Shoulder rumble strip	AuRAP Risk score	Correction factor for use in AGRD Part 6
Not present	1.25	1
Present	1.00	0.8

Source: Compiled from iRAP (2010).

## 6. Conclusions

This report provides a review of current practice/existing guidelines and the literature on the impacts of roadside slope on the likelihood and severity of crashes. Before the publication of the updated AGRD Part 6 (Austroads 2020), the processes for slope design and treatment in Australia and internationally are largely the same; however, there are variations in the technical specifications used by other countries. For example, the 'area of interest'/clear zone concept is generally adopted, but there are some differences in the variables used to determine the clear zone width. The criteria used to classify embankments as aggressive (hazardous) also vary between countries, with criteria for classifying a slope as an aggressive object (hazard) ranging from 1:1 to 3:1.

Austroads (2020) employs a different philosophy to the previous Guide (Austroads 2010). It is risk based and was developed in line with Safe System principles. The process involves the calculation of a hazard risk score, which is the product of exposure, likelihood, and severity (expressed as the Trauma Index). The identification of a hazard requiring treatment is determined by comparing the hazard risk score to a pre-determined Network Roadside Risk Intervention threshold (NRRIT). The risk score is the combined total of the background risk (if applicable) and the hazard risk.

Accurate and reliable data on roadside slope where single vehicle roadway departure (no object hit) crashes had occurred could not be determined. In addition, there is also a lack of information available to enable rollover severity to be accurately determined, due partly to variations in data collection and severity classification methods. Queensland does not collect information of property damage crashes; hence it is not possible to determine the actual proportion of rollover crashes that resulted in an FSI.

AGRD Part 6 (Austroads 2020) provides a quantitative and consistent way to identify when a barrier should be used compared to a slope. However, the Trauma Indices for slopes are based on the severity indices in the 2010 version of AGRD Part 6. Given that these severity indices are not based on well-founded research, they will need to be updated. Recent research by Sheikh et al. (2019) indicates that vehicle rollover events can occur at all slopes and that the probability of rollover increases with slope steepness, from 10% (10:1 slope) to 31% (2:1 slope).

Trauma Indices have been estimated based on the research reported by Sheikh et al. (2019). However, due to the different FSI rollover rates in Queensland, further research based on local conditions is required before these findings can be used to update the Trauma Indices in AGRD Part 6.

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# Appendix A Literature Review

## A.1 Review of Current Practice

All Australian jurisdictions use the Austroads Guide to Road Design (AGRD) for all road design-related issues, with guide supplements applicable in each state and territory. The Austroads guides that deal with roadside slope design and treatments are the Austroads *Guide to road design part 3: geometric design* (Austroads 2016) and the *Guide to road design part 6: roadside design, safety and barriers* (Austroads 2010). Part 3 covers slope design and Part 6 covers evaluation and treatment selection. The Australian practice as reported in the AGRD is generally based on AASHTO (2003) *Road Design Guide*.

### A.1.1 Slope Design

As per AGRD Part 3: Geometric design, Section 4.5, the selection of roadside slopes should be based on the following factors:

- geotechnical investigation
- batter slope stability
- batter slope safety
- future maintenance costs
- appearance and environmental effects
- earthworks balance
- available width of road reserve
- landscaping requirements.

According to the Guide, the selection of safe roadside slope treatments is based on whether vehicles can recover or traverse safely down the slope. Slopes are classified as recoverable, non-recoverable, or critical as follows:

- A recoverable slope – an embankment where a driver will usually be able to regain control of the vehicle and return to the roadway or safely stop.
- A non-recoverable slope – an embankment where the driver is unlikely to be able to return to the roadway but can safely stop at the bottom of the slope.
- A critical slope – an embankment that is likely to cause the vehicle to overturn

Table A.1 shows the effect of batter slope on vehicle recovery according to vehicle type. Generally, for passenger cars, 4:1 or flatter slopes are considered as recoverable, 4:1 or steeper slopes as non-recoverable and the slopes that are steeper than 3:1 are identified as critical slopes (Austroads 2016). For trucks, slopes 4:1 or steeper are considered critical.

The *AGRD Part 6: Roadside design, safety and barriers* (2010), Section 5.4.7, defines recoverable, non-recoverable and critical fill batter slopes, in terms of the likelihood of a vehicle overturning, as shown in Table A.3:

**Table A.1: Effect of fill batter slopes on vehicle recovery**

Slope (V:H)	10:1 of flatter	6:1	4:1	4:1 to 3:1	3:1 or steeper
Cars	Recoverable	Recoverable	Recoverable	Traversable	Critical/hazardous
Trucks	Recoverable	Traversable	Critical/hazardous	Critical/hazardous	Critical/hazardous

AGRD Part 3 (Austroads 2016) recommends desirable and maximum slopes based on the slope type as shown in Table A.2 (Austroads 2016). A slope of 4:1 is specified as the maximum for fill slopes, i.e. any slope steeper than this is considered aggressive and requires treatment. The TMR supplement to AGRD Part 3 provides some guidance on selecting slopes based on embankment height and soil type as shown in Table A.3.

**Table A.2: Typical design batter slopes**

Material type	Cut		Fill	
	Desirable maximum	Maximum	Desirable minimum	Minimum
Earth batter	3:1	2:1	6:1	4:1
Rock batter	0.5:1	0.25:1	–	–

Source Austroads (2016).

**Table A.3: TMR Supplement to Planning Guidance on batter slope design**

Material	Soil type	Height	Slope
Stable material/rock	Cut	≤ 1 m	≤ 3:1
		> 1 m	≤ 2:1
	Fill	≤ 1 m	≤ 4:1 (6:1 preferred)
		> 1 m	≤ 2:1
Soils with high erosion potential (e.g. sodic soils)	Cut	Any	2:1 with surface treatment and diversion drains above the slope
Sandy soils (lacking cohesion)	Cut	≤ 2 m	≤ 4:1
		> 2 m	≤ 3:1
	Fill	Any	4:1 to 10:1

Source TMR (2020).

Austroads (2010) indicated that run-off-road crashes may be reduced if the batter slopes are designed to be sufficiently flat for the driver to regain control of the vehicle; 6:1 or flatter slopes are desirable when the per cent heavy vehicles is 10% or more (AGRD, Part 6 Section 5.4.7).

Austroads (2010) generally suggested that the embankment slopes with the following characteristics require treatments (Table A.4).

**Table A.4: Suggested criteria for treatment of slopes**

Slope (V:H)	10:1 or flatter
Steeper than 4:1	<ul style="list-style-type: none"> <li>• Errant vehicles are likely to overturn</li> <li>• Batter slopes between 4:1 and 3:1 are traversable but too steep for a driver to recover</li> <li>• Reduced chance for a driver to control or safely stop the vehicle after encroaching onto the slope</li> </ul>
Embankment height over 1.5 m	The likelihood of vehicle rollover with a high severity outcome increases significantly.
Ground conditions	Increased probability of vehicle rollover if there is a likelihood that the vehicle tyres will dig into the ground or the vehicle will strike a surface irregularity (e.g. large rocks, sharp mounds or depressions) which could trip the vehicle
Absence of rounding at gradient changes of roadside terrain	Rounding should be applied at gradient changes (hinge points) as it provides drivers with a greater opportunity to maintain or regain control of the vehicle and decreases the likelihood of rollover by preventing the vehicle from achieving large values of angular momentum about the longitudinal roll axis.

Source Austroads (2010).

## A.1.2 Review of RISC Model

The RISC application was developed by TMR based on the methodology established by AASHTO's (1996) *Roadside Design Guide* and their ROADSIDE software. The RISC is intended to be used in conjunction with TMR's (2014) *Supplement to Austroads GRD Part 6*.

The application aims to allow users to numerically model roadside hazards and proposed treatments on a road section and then perform a quantitative economic evaluation by calculating the benefit-cost ratio (BCR) for treatment options (TMR 2014). This process is intended to help the user to determine the most cost-effective treatment option. The process of the RISC model is broken into four main steps. These are the calculations of the:

- the encroachment frequency (i.e. how many vehicles will leave the roadway)

- the impact frequency of the object: based on the number of encroachments (i.e. how many errant vehicles will hit an object) and road conditions
- the Severity Index (SI) related to different types of roadside hazards
- crash cost.

## Step 1: Calculate encroachment frequency

The first step in the RISC model is to determine the encroachment frequency of a road segment. The encroachment frequency is an estimate of how many vehicles will leave the roadway per kilometre per year, considering road and traffic conditions.

The encroachment frequency (measured in run-off-road events/year/km) is calculated using the method shown in AGRD Part 6 (Austroads 2010) (see Equation A1). It is based on the following parameters:

- base encroachment frequency (default 0.0003 value)
- AADT
- horizontal curve correction factor
- grade correction factor
- user factor.

$$EF = BER \times AADT \times EF_c \times EF_g \times EF_u \quad A1$$

where

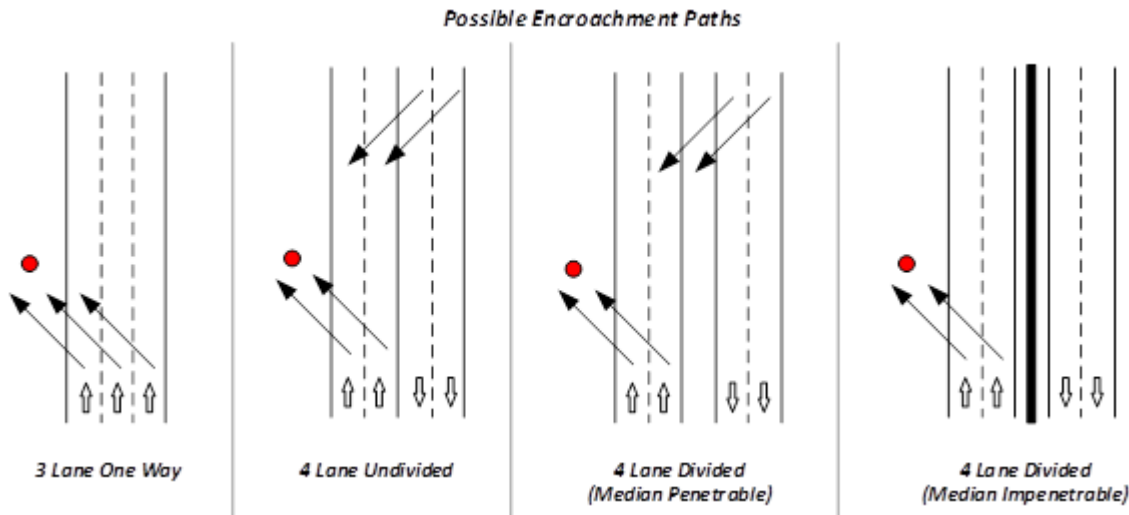
$BER$	=	Base encroachment frequency – default is 0.0003 (enc/km/year/veh/day)
$AADT$	=	Annual Average Daily Traffic
$EF_c$	=	Curvature factor to account for the influence of horizontal curves on vehicles leaving the roadway
$EF_g$	=	Grade factor to account for the influence of longitudinal grade on vehicles leaving the roadway
$EF_u$	=	A user factor adopted at the discretion of the engineer to accommodate special circumstances

## Step 2: Calculate impact frequency of the object

The next step is to determine the impact frequency of the hazard. Within the RISC model, parallel slopes are considered as an object which can be collided with. In the case of a parallel slope, the impact frequency would be almost 100% (depending on the offset distance from the travel lane). The impact frequency is an estimation of how many of the vehicles that leave the roadway will impact with the roadside hazard per year based on road conditions, and the location and dimensions of roadside hazards.

The total impact frequency is determined by first identifying the likely paths of run-off road events (see Figure A.1) which may include both directions of travel if undivided. The collision frequency is then calculated (see Equations A2 – A5) for each impact zone of the object, which are the face (zone 1), corner (zone 2) and parallel face (zone 3). The collision frequencies for all likely paths are then summed to determine the object impacts per year.

Figure A.1: Roadway types and possible encroachment paths



Source: TMR (2017).

## Equations

$$\frac{\text{Impacts}}{\text{year}} = CFUS + CFUC + CFFA \quad A2$$

$$CFUS = EF \times \frac{1}{\tan \phi} \times \frac{\sum_{i=1}^W LEP(A + SW \times \phi + |i - 1|)}{1000} \quad A3$$

$$CFUC = EF \times \frac{1}{\sin \phi} \times \frac{\sum_{i=1}^{SW} LEP(A + |i - 1| \times \cos \phi)}{1000} \quad A4$$

$$CFFA = \frac{EF \times L \times LEP(A)}{1000} \quad A5$$

where

- $\frac{\text{Impacts}}{\text{year}}$  = Summed impacts per year for likely path of travel
- $CFUS$  = Collision frequency for side
- $CFUC$  = Collision frequency for corner
- $CFFA$  = Collision frequency for parallel face
- $LEP$  = Lateral Extent Probability
- $\phi$  = Encroachment angle (degrees)
- $SW$  = Swath Width (default = 3.6 m)
- $EF$  = Encroachment Frequency (enc/km/y)
- $A$  = Lateral offset of object (m)
- $W$  = Width of object (m)
- $L$  = Length of object (m)

## Step 3: Determine Severity Index (SI)

A severity index (SI) is assigned to an object using a range of 0 to 10. An SI of 0 indicates that a crash involves no significant property damage or injury, while 10 indicates a crash with a 100% probability of fatality (TMR 2014).

The RISC model uses the suggested Severity Indices (extract shown in Table A.5) from the AGRD Part 6, which was sourced from AASHTO's (1996) *Roadside Design Guide*. While these tables may not

accurately reflect some systems used in Australia and New Zealand, they are considered acceptable estimates (Austroads 2010). These indices are used to determine the expected severity of a crash based on the object type and characteristics, object surface, and road design speed.

**Table A.5: Severity Index for slopes**

Slope	Height (m)	Road surface	50 km/h	60 km/h	70 km/h	80 km/h	90 km/h	100 km/h	110 km/h	120 km/h
10:1	0.15	A	0.2	0.3	0.5	0.6	0.7	0.9	1.1	1.2
	>= 0.3	A	0.4	0.5	0.7	0.8	1.0	1.2	1.4	1.5
6:1	0.15	A	0.5	0.8	1.0	1.3	1.5	1.7	1.9	2.0
	>= 0.3	A	0.5	0.8	1.0	1.3	1.6	1.9	2.1	2.2
4:1	0.15	A	0.5	0.7	0.9	1.1	1.3	1.5	1.7	2.0
	0.3	A	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.5
	>= 2.0	A	1.3	1.6	1.8	2.1	2.3	2.5	2.7	2.8
3:1	0.15	A	0.7	0.9	1.1	1.3	1.5	1.8	2.0	2.3
	0.3	A	1.6	1.8	2.0	2.2	2.4	2.6	2.8	2.9
	2.0	A	2.0	2.3	2.5	2.8	3.0	3.3	3.5	3.6
	4.0	A	2.0	2.3	2.6	2.9	3.1	3.4	3.6	3.9
	6.0	A	2.0	2.3	2.6	2.9	3.1	3.5	3.7	4.0
	8.0	A	2.0	2.3	2.6	2.9	3.2	3.5	3.8	4.1
	>=10.0	A	2.0	2.3	2.6	2.9	3.2	3.5	3.9	4.3
2:1	0.15	A	0.9	1.2	1.5	1.8	2.0	2.3	2.6	2.9
	0.3	A	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.6
	2.0	A	2.9	3.2	3.5	3.8	4.0	4.3	4.5	4.8
	4.0	A	3.1	3.4	3.8	4.2	4.4	4.6	4.8	5.1
	6.0	A	3.3	3.6	3.9	4.3	4.5	4.7	4.9	5.2
	8.0	A	3.6	3.9	4.1	4.4	4.6	4.8	5.0	5.3
	10.0	A	4.1	4.3	4.5	4.7	4.9	5.2	5.4	5.5
	14.0	A	4.5	4.7	4.9	5.1	5.3	5.5	5.7	6.0
	18.0	A	4.8	5.0	5.2	5.4	5.6	5.8	6.0	6.3
	22.0	A	4.9	5.1	5.3	5.5	5.7	5.9	6.1	6.4
	26.0	A	4.8	5.1	5.3	5.6	5.8	6.1	6.3	6.4
	30.0	A	4.8	5.1	5.3	5.6	5.9	6.2	6.4	6.5
	>= 34.0	A	4.8	5.1	5.3	5.6	5.9	6.2	6.4	6.7

Source: Austroads (2010) (Extract from Table E1).

## Step 4: Determine crash cost

The final step in the RISC model is to determine the crash cost of a roadside object. The estimated annual crash cost can be determined using the following relationship:

$$\text{Annual crash costs per year (\$)} = (\text{impacts per year}) \times (\text{SI crash cost per impact})$$

The severity index crash cost used in the RISC application is a function of the severity index, the probabilities of different crash severity outcomes (e.g. fatality, hospitalisation, etc.), and the cost of crash severity outcomes as shown in Table A.6. TMR developed this matrix based on the relationship between AASHTO's (1996) crash severity probabilities and TMR's (2017) cost of crash severity outcomes based on 'willingness to pay' (WTP). The model indicates that the SI matrices provided are considered as a guide and the values could vary based on engineering judgement and particular scenarios.

**Table A.6: Summary table for crash cost related to severity index**

Severity Index (SI)	Property Damage	Minor injury	Moderate injury	Hospitalisation	Fatal	Cost (in 2016 WTP\$)
0	0%	0%	0%	0%	0%	\$-
0.5	100%	0%	0%	0%	0%	\$9,775
1	90%	7%	2%	0%	0%	\$14,709
2	71%	22%	7%	0%	0%	\$24,723
3	43%	34%	21%	1%	1%	\$141,558
4	30%	30%	32%	5%	3%	\$359,318
5	15%	22%	45%	10%	8%	\$856,405
6	7%	16%	39%	20%	18%	\$1,816,695
7	2%	10%	28%	30%	30%	\$2,952,553
8	0%	4%	19%	27%	50%	\$4,735,073
9	0%	0%	7%	18%	75%	\$6,930,714
10	0%	0%	0%	0%	100%	\$9,077,270

Source: Based on TMR (2017) and AASHTO (1996).

Once the annual crash costs per year have been determined for both the hazard and the proposed treatment options, a benefit-cost ratio (BCR) for the initial year can then be calculated (see Equation A6). This BCR calculation looks at the ratio between crash and repair costs (for hazard and treatment), and the installation and maintenance costs (for hazard and treatment) to determine if the treatment option provides a net economic benefit. This can then be expanded upon to determine the BCR across the project life.

$$BCR_{initial} = \frac{(\$Crash_{Hazard} + \$Repair_{Hazard}) - (\$Crash_{Treatment} + \$Repair_{Treatment})}{(\$Installation_{Treatment} + \$Maintenance_{Treatment}) - (\$Installation_{Hazard} + \$Maintenance_{Hazard})} \quad A6$$

where

- $\$Crash_{Hazard}$  = Hazard annual accident crash costs for the initial year
- $\$Crash_{Treatment}$  = Treatment annual accident crash costs for the initial year
- $\$Repair_{Hazard}$  = Hazard repair costs per accident in the initial year
- $\$Repair_{Treatment}$  = Treatment repair costs per accident in the initial year
- $\$Installation_{Hazard}$  = Hazard installation costs in the initial year
- $\$Installation_{Treatment}$  = Treatment installation costs in the initial year
- $\$Maintenance_{Hazard}$  = Hazard maintenance costs per year (initial year dollars)
- $\$Maintenance_{Treatment}$  = Treatment maintenance costs per year (initial year dollars)

## Comparison of RISC vs. RSAP models

Another software package recommended by Austroads for evaluating the cost-effectiveness of roadside safety is the National Cooperative Highway Research Program's (NCHRP) Roadside Safety Analysis Program (RSAP) (Ray et al. (2012)).

A comparison between the RISC and RSAP models (shown in Table A.7) was used to determine any deficiencies/limitations of the RISC model. The comparison suggested that the parameters incorporated in the RISC model were mostly based on hypothetical functions, whereas the RSAP applied the parameters based on real-world crash data. Fewer manual calculations were required to achieve a more accurate analytical result.

**Table A.7: Severity Index and associated crash cost (Table 3.1, TMR (2014) based on ASHTO (1996))**

Parameter	RISC	RSAP
<b>Encroachment Frequency</b>		
Encroachment frequency	Calculates overall encroachment frequency using base encroachment rate, AADT and adjustment factors (3 factors)	Calculates overall encroachment frequency by multiplying base encroachment rate by adjustment factors (8 factors)
Base encroachment rate	Uses a default base encroachment rate constant of 0.0003 (enc/km/year/veh/day). Can be changed if data is available	Uses the Cooper encroachment table <sup>1</sup> for base encroachment rate (enc/million VKT). This is based on specific base conditions. It is a function of AADT and highway type.
Traffic volume (AADT)	TMR uses AADT in the calculation of encroachment frequency	RSAP uses AADT in the calculation of encroachment frequency. Typically uses a range rather than direct input.
Horizontal curve factor	Uses graphs to determine adjustment factor based on curve radius and direction of curve (left or right)	Uses the Wright-Robertson horizontal curve adjustment factor. However, has investigated and recommends a more robust method <sup>2</sup> .
Vertical grade factor	Uses graphs to determine adjustment factor based on the grade in direction of traffic (down grade or upgrade)	Uses the Wright & Robertson (1976) study values for adjustment factors. It is noted that the study uses old data so statistical reliability has been questioned (Ray et al. 2012).
Crash multiplier	Uses a crash multiplier that can be used at the discretion of the user to accommodate special circumstances	Provides the opportunity for users to add adjustment factors at the discretion of the user to accommodate special circumstances
Multilane adjustment factor	None	Uses a table of adjustment factors based on number of lanes and road type (undivided or divided). Table was generated during a review of median-related traffic crashes from 52 Texas counties Miaou et al. (2005).
Posted speed limit adjustment factor	None	Provides adjustment factor to alter the base encroachment frequency for speeds other than the base speed of 65 mph. Provides a table of adjustment factors based on speed and road type (undivided or divided).
Access density adjustment factor	None	Provides a table of adjustment factors for Access Density (number of major road and highway access points per mile in any segment) as the BCR is calculated using zero access points/mile <sup>3</sup> . The table is based on number of access points/mile and the road type (undivided or divided).
Terrain adjustment factor	None	Provides adjustment factors based on terrain (flat, rolling, and mountainous) and road type (undivided, divided, and one-way)
Lane width adjustment factor	None	Uses adjustment factors based on AASHTO's (2010) Highway Safety Manual Crash Modification Factors for lane width adjustment. This leads to the use of a table assuming a volume of 2000 vehicles per day. Factor is based on lane width and road type (undivided or divided) (AASHTO 2010).
<b>Object impact frequency</b>		
Lateral extent of Encroachment	Assumes 3.7 m/s/s (0.4 g) deceleration rate and sine curve density function for steer back	Cooper encroachment data, adjusted for encroachments with lateral extent less than 4 m
Encroachment angle	Average angle based on point-mass model.	Derived from real-world crash data
Encroachment speed	Hypothetical function of design speed.	Derived from real-world crash data
Swath width	Uses default 3.6 m swath width. Intended to represent a non-tracking passenger car that is skidding towards the roadside object	Based on real-world crash data
Impact speed	= Encroachment speed – speed loss with 3.7 m/s/s (0.4 g) deceleration rate	Derived from real-world crash data
Impact angle	Same as encroachment angle	Derived from real-world crash data

<sup>1</sup> Cooper encroachment tables are based on a study of real-world encroachment rates (Ray et al. 2012).

<sup>2</sup> Discussed the use of AASHTO's (2010) *Highway Safety Manual* method; however, this does not differentiate between left and right curves.

<sup>3</sup> RSAP manual, high magnitude of increase. Access density of 0 = 1, Access density of 7 = 10.99.

Parameter	RISC	RSAP
Vehicle orientation	None	Based on real-world crash data
Shielding of one hazard by another	None	Can handle various hazards with algorithm to account for shielding of one hazard by another and multiple impacts
Multiple hazards	Each hazard is to be analysed individually and the crash costs summed manually	Yes, takes into account multiple hazards and redirection from striking a hazard
Multiple hazards	All impacts with hazard shielded by barrier eliminated, regardless of barrier length	Vehicles encroaching upstream of barrier could impact hazard shielded by barrier
<b>Severity and Crash cost</b>		
Vehicle type	Single vehicle type	12 vehicle types, based on nominal percent truck
Severity (SI)	Average values only	Severity is measured as a function of impact speed through the dimensionless value of Equivalent Fatal Crash Cost Ratio. This is essentially the average crash cost divided by the cost of a fatal crash. The average crash cost was determined from real-world crash data.
Incremental BCR for multiple alternatives	Required to be calculated manually	Yes
Solution method	Deterministic	Stochastic, using the Monte Carlo simulation technique

Source: Based on Mak & Sicking (2003) and findings from comparison.

## Limitations of the RISC model

Through a comparison of the RISC and RSAP models, and a review of the literature, the following limitations to parameters of the RISC model were identified:

- The numerous factors used in the calculation of both encroachment frequency and object impact frequency are based on hypothetical functions adopted from AASHTO (1996). This could result in under/overestimated encroachment and object impact frequencies. More robust methods have been implemented into the RSAP which use real-world crash data as the basis for assessment.
- The current version of RISC is not able to combine two or more treatments and calculate a resulting BCR. Users are required to calculate BCRs separately and manually calculate the combined BCR.
- The current version of RISC considers passenger vehicles only.
- The current SI based on AASTHO's (1996) *Roadside Design Guide* was based on surveys of experienced engineers and may not provide an accurate estimate of severity for passenger vehicles or other vehicle types. The crash severities based on default SIs are reported to be over-estimated (Carrigan & Sheikh 2017). Alternative measures of SI have been proposed in Jurewicz et al. (2012 & 2014). A summary of crash modifications factors is shown in in Table A.8.

Table A.8: Summary of crash reductions factors

Variable	Category	CMF to the left	CMF to the right
<b>Road design/standard related</b>			
Mean speed	120	1.34	
	110	1.16	
	100	1.00	
	90	0.84	
	80	0.70	
	70	0.57	
	60	0.44	
	50	0.33	
Traffic lane + LHS sealed shoulder (m) LHS unsealed shoulder (undivided roads only) (m)	< 3.0, ≤ 0.5	8.06	5.78
	< 3.0, 0.6–1.0	3.19	2.54
	< 3.0, 1.1–2.0	2.48	1.39
	< 3.0, > 2.0	1.20	0.67
	3.0–3.5, ≤ 0.5	1.99*	1.90*
	3.0–3.5, 0.6–1.0	1.38	1.42
	3.0–3.5, 1.1–2.0	1.00	1.00
	3.0–3.5, > 2.0	1.17	0.70
	3.6–4.0, ≤ 0.5	1.72	1.65
	3.6–4.0, 0.6–1.0	1.15	0.66
	3.6–4.0, 1.1–2.0	0.61	0.80
	3.6–4.0, > 2.0	n/a	n/a
	4.1–4.5, ≤ 0.5	1.04	0.86
	4.1–4.5, 0.6–1.0	0.61	0.54
	4.1–4.5, 1.1–2.0	0.40	0.47
	4.1–4.5, > 2.0	n/a	n/a
		4.6–5.0, ≤ 0.5	1.46
4.6–5.0, 0.6–1.0		0.63	0.47
4.6–5.0, 1.1–2.0		0.56	0.36
	4.6–5.0, > 2.0	n/a	n/a
<b>Hazard removal/relocation/modification</b>			
Clear zone LHS (undivided roads only) (m)	0–2	2.79	n/a
	2–4	1.78	n/a
	4–8	1.21	n/a
	> 8	1.00	n/a
Clear zone RHS (undivided roads only) (m)	0–2	n/a	1.57
	2–4	n/a	1.56
	4–8	n/a	1.03
	> 8	n/a	1.00
LHS batter slope	< 1:6 (flat)	1.00	n/a
	1:6–1:3.5	1.67	n/a
	1:3.5–1:2	1.97	n/a
	> 1:2	3.35	n/a
RHS batter slope	< 1:6 (flat)	n/a	1.00
	1:6–1:3.5	n/a	1.40
	1:3.5–1:2	n/a	1.81
	> 1:2	n/a	2.45
Density of hazards (per 100 m of roadside)	< 10	1.00	1.00
	10 to 25	0.98	0.98
	25 to 50	1.08	1.08
	> 50 or continuous	1.57	1.57
Frangibility: change hazard from rigid to frangible	–	0.60	0.60

Hazard shielding			
Barriers	Change from rigid to more flexible along embankment	0.68	0.68
	New semi-rigid barrier	0.65	0.65
	Flexible centreline barrier, rural undivided roads	0.30	0.30
	Flexible (rural freeway)	0.21	0.21
	Flexible (urban freeway)	0.14	0.14
	Impact attenuator (fixed object crashes)	0.31	0.31
Barrier offset factor**	≤ 0.5	5.60	5.60
	1.0	2.19	2.19
	≥ 1.5	1.00	1.00

\* Values extrapolated in line with other trends due to lack of data.

\*\* Based on semi-rigid barriers only.

Source: Austroads (2014).

## A.2 Jurisdiction Supplements to Austroads Guides

All jurisdictions have adopted the Austroads guides. However, in order to address state-specific issues, each jurisdiction has produced a range of mandatory Supplements to the Austroads Guides. These supplements cover specific local variations/additions and have been developed to be used in conjunction with AGRD. Generally, the contents in the supplement take precedence over Austroads guides, unless specifically stated otherwise.

The Supplements have the same structure as the equivalent Austroads guide and only additional requirements, clarifications, or practices different from Austroads are documented. Where appropriate, the Supplements may also contain additional sections and figures not covered by Austroads; however, the numbering sequence found in the Austroads Guide remains. Figures and tables in the Supplement replace those with the same figure or table number in the equivalent Austroads guide. A comparative summary of the guidelines on roadside slope design by Jurisdictions is provided in Table A.9.

**Table A.9: Comparison between slope design parameters between jurisdictions**

Parameters	Austroads	TMR	NSW RMS	VicRoads	MRWA
Critical slope	See Table A.1	Same as Austroads	Same as Austroads	Same as Austroads	Supplement
• cars	3:1	✓	✓	✓	4:1
• trucks	4:1	✓	✓	✓	10:1
Fill slope (batter)	See Table A.2	Same as Austroads	Same as Austroads	Same as Austroads	Based on slope height:
• maximum slope	4:1	✓	✓	✓	6:1 for height 0.3–1 m,
• slope height	> 1.5 m	✓	✓	✓	4:1 for height > 1 m
• offset to roadway	✓	✓	✓	✓	All slopes > 3 m high
Cut slope	See Table A.2	Same as Austroads	Same as Austroads	Same as Austroads	Cut slopes to be
• maximum slope	2:1	✓	✓	✓	constructed flatter than
• slope height	X	X	X	X	1:1
• presence of ditch	✓	✓	✓	✓	
Rock slope (batter)	See Table A.2	Same as Austroads	Same as Austroads	Same as Austroads	Same as Austroads
• maximum	0.25:1	✓	✓	✓	✓
• slope height	X	X	X	X	X
• offset to roadway	✓	✓	✓	✓	✓
• presence of ditch	X	X	X	X	X
Area of interest/Clear zone	✓	✓	✓	✓	✓
<b>Clear zone parameters</b>					
• Road type	X	X	X	X	X
• Traffic volume	✓	✓	✓	X	✓

Parameters	Austrroads	TMR	NSW RMS	VicRoads	MRWA
• Design speed	✓	✓	✓	✓	✓
• Embankment slope	✓	✓	✓	X	✓
• Horizontal alignment	✓	✓	✓	X	✓
• Lane width	X	X	X	X	X
• Per cent heavy vehicles	X	X	X	X	X
Quantitative evaluation methods	Simple manual	X	X <sup>2</sup>	✓	✓
	Detailed manual	X	X <sup>2</sup>	✓	X
	RISC	✓	X <sup>2</sup>	✓	✓ (recommended)
	RSAP	X	X <sup>2</sup>	✓ (recommended) <sup>3</sup>	✓ (for info only) <sup>4</sup>
	Hazard risk assessment	X	✓	✓	X
Severity Index	See Appendix D Based on AASHTO (1996)	✓ modified	✓	✓	✓
Treatments selection process	Embankment warrant for high speed roads <sup>5</sup>	Generalised hazard assessment <sup>7</sup>	✓	Only used as general guidance.	✓ <sup>8</sup>
	Embankment assessment process <sup>6</sup>		✓	✓	✓
Treatment types	<ul style="list-style-type: none"> <li>• Flatten to 4:1 slope or flatter (preferred)</li> <li>• Barriers</li> </ul>	Barriers preferred on 2:1 fill slopes with height > 2 m.	<ul style="list-style-type: none"> <li>• Flatten to 4:1 slope or flatter</li> <li>• Barriers</li> </ul>	Barriers for ≥ 80 km/h Flattening for < 80 km/h	Determined via evaluation by RISC

Sources: Austrroads (2010), RTA (2008), TMR (2014, 2017, 2020), VicRoads (2019a, 2019b), Main Roads WA (2019a, 2019b).

### A.3 Guides from European Countries

Dupre et al. (2006) reviewed the guidelines adopted by some European countries. They found that the general methodology used to improve roadside safety was largely the same among the seven countries reviewed; however, the technical specifications varied. All seven countries make use of the clear zone concept. However, there are variations in the variables considered in determining the clear zone width as are shown in Table A.10. It is noted that five European countries consider road type as one of the criteria to determine clear zone, a variable which is not used in Australia.

Table A.10: Parameters to determine clear zone in European countries and Australia

Parameters	Finland	France	Germany	Netherlands	Spain	Sweden	UK	Australia
Road type		✓	✓	✓	✓		✓	
Traffic volume	✓	✓	✓	✓	✓	✓		✓
Design speed	✓	✓	✓	✓	✓	✓	✓	✓
Embankment slope gradient	✓	✓	✓	✓	✓	✓		✓
Horizontal alignment	✓		✓	✓	✓			✓
Driving lane width					✓	✓		
Percentage of heavy vehicles	✓							
Evaluation of personal and third-party risks				✓				

Source: Dupre et al. (2006).

The criteria used by the various European countries to classify embankments as aggressive (hazardous) vary between countries as shown in Table A.11. In the UK, safety barriers are recommended to be installed to protect all hazards within 4.5 m from the road on high-speed roads.

**Table A.11: Alternative guidelines in various European countries**

Slope type	Parameters	Finland	France	Germany	Netherlands	UK
Cut	Gradient	–	> 1.5:1	> 3:1	> 3:1	–
	Height	–	> 0.5 m	–	–	–
	Ditch or hazard at foot of slope	–	–	–	–	–
Fill	Gradient		> 1:1	> 3:1	> 3:1	$\geq 1:1$ & height $\geq 0.75$ m
	Height	> 2 m	> 4 m	–	–	> 6 m
	Offset to roadway	–	–	–	–	Less than 4.5 m on high-speed roads (> 80 km/h)
Rockface cuttings	Gradient	Generally, 7:1	–	–	–	2:1 or steeper side slope
	Height	All unshielded rock cuttings	–	–	–	< 1.5 m above carriageway level
	Offset to roadway	2–3 m from roadway edge	–	–	–	< 4.5 m

Source: Dupre et al. (2006).

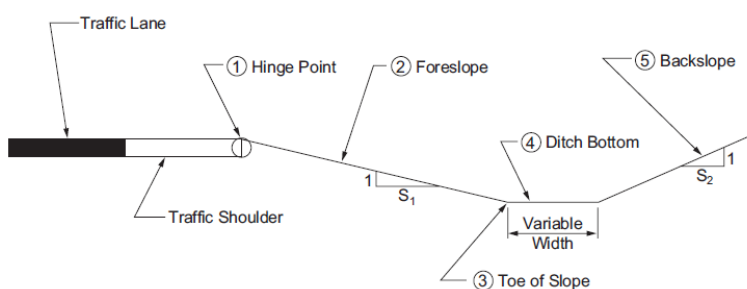
## A.4 Review of Slope Parameters

### A.4.1 Roadside Slope Sections and Options to Reduce Crash Outcomes

The US *Roadside Design Guide* (AASHTO 2011) specifies three roadside regions that are important to reducing the potential for loss of control for vehicles running off the road. These are (Figure A.2):

- the hinge point (top of the slope)
- foreslope
- toe of the slope (intersection of the foreslope with level ground or with a backslope, forming a ditch).

**Figure A.2: Main roadside regions that impact of run-off-road crashes**



Source: Sheikh (2019).

Some of the options provided to reduce the severity of crashes due to roadside slopes include (AASHTO 2011):

- Provide a flatter slope between the shoulder edge and the ditch bottom.
- Locate ditch farther from the roadway.
- Backslopes should be 3:1 or flatter to accommodate maintenance equipment.
- Backslopes steeper than 3:1 should be evaluated with regard to soil stability and potential crash severity.
- Retaining walls should be considered where there would be a slope steeper than 2:1.
- Rate of 6:1 or flatter on embankments should be provided where practical.
- For moderate heights with good rounding, steeper slopes up to about 3:1 can also be traversable but are not always recoverable.

## A.4.2 Effects of Slope Gradient on Crashes

### Impacts on the control of errant vehicles

Prior to 1960, run-off-road crashes were commonly perceived as the fault of careless drivers until Stonex (1960) reported otherwise. Based on the crash data analysis and full-scale crash tests, Stonex (1960) found that vehicles could potentially lose contact with the ground on 4:1 slopes (becoming airborne) at 64 km/h and that 6:1 or flatter slopes were preferable. In 1967 AASHTO incorporated the findings from this research in the 'Highway Safety and Operational Practices' commonly known as the 'Yellow Book' (AASHTO 1996).

Schoon (1997) conducted mathematical simulations and concluded that vehicles could stay in good contact with the ground on 4:1 slopes but steering manoeuvres would be compromised to regain control. The minimum gradient to allow for vehicles to regain control was 5:1 on high slopes (e.g. 5 m). For slope height lower than 2 m approximately, at least 6:1 would be required.

Lynam & Kennedy (2005) identified that fill slopes greater than 3:1 could lead to a high likelihood of rollover and the scope for the driver to control over short distances would be limited, even on slopes of 4:1.

### Impacts on crash rate

Graham and Harwood (1982) investigated the safety effectiveness of clear recovery zones and suggested that the crash rate on 4:1 slopes was generally doubled compared to 6:1 slopes (Table A.12). The authors also stated that the USA generally built 4:1 slopes before the 1960s and only started to build 6:1 or flatter slopes after AASHTO published the 1967 "Yellow Book".

**Table A.12: Crash rate (number of crashes per million vehicle mile)**

Slope	Two-lane freeway	Four-lane freeway	Four-lane divided non-freeway
1.4	0.4	0.29	0.32
1.6	0.25	0.18	0.16

Source: Graham & Harwood (1982).

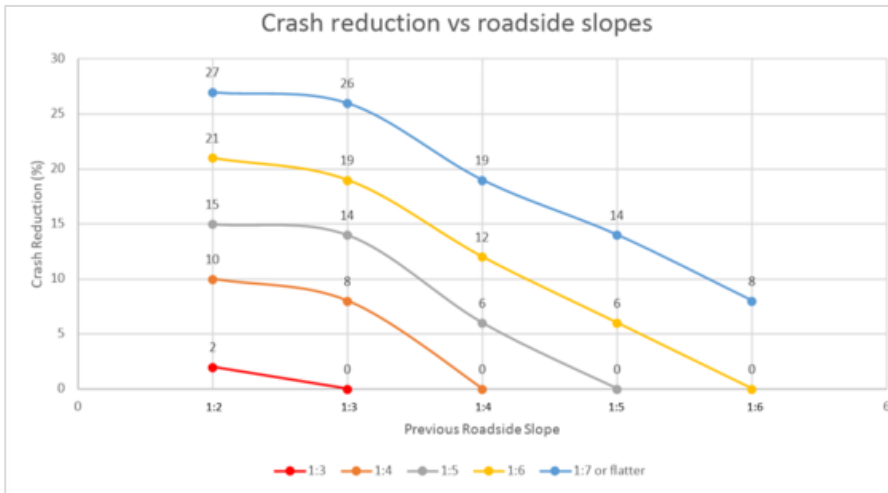
In 1988, Zeeger et al. conducted a study using data on rural roadway sections in the USA. They found a relationship between crash rate and roadside slope as shown in Table A.13 and Figure A.3. The expected reductions in single-vehicle crashes due to slope flattening ranged from 2 to 27%, depending on the slope in the before-and-after scenarios. The crash reduction by flattening a 2:1 slope or steeper to 3:1 was very small; only a 2% reduction in single-vehicle crashes was reported for this treatment.

**Table A.13: Expected reduction (%) in single-vehicle crashes by flattening roadside slopes**

Roadside slopes in Previous condition	Roadside slopes in after condition				
	3:1	4:1	5:1	6:1	7:1 or flatter
2:1	2	10	15	21	27
3:1	0	8	14	19	26
4:1	–	0	6	12	19
5:1	–	–	0	6	14
6:1	–	–	–	0	8

Source: Zeeger et al. (1988).

**Figure A.3: Expected crash reduction (%) in single-vehicle crashes by flattening roadside slopes**



Source: Based on Zeeger et al. (1988).

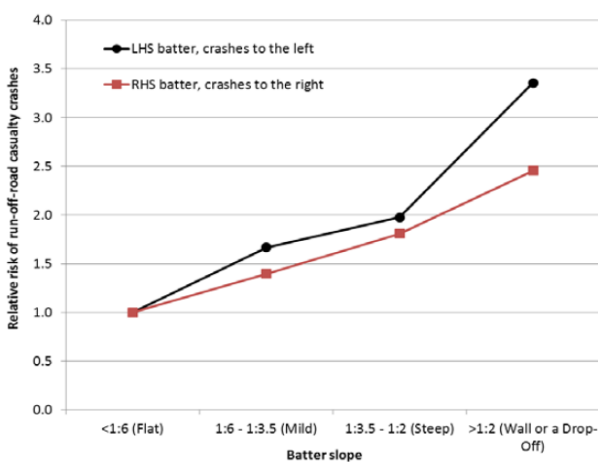
Allaire et al. (1996), in their review and further investigation of previous research, reported that slope flattening from 2:1 and 3:1 to 6:1 resulted in crash rate reductions of 15% and 14% reduction respectively, a doubling of the reduction potential by flattening 2:1 or 3:1 slopes to 4:1 (7% and 6% respectively).

Elvik et al. (2009) reviewed three US studies conducted by Dotson (1974), Missouri Department of Transportation (1980) and Graham and Harwood (1982). They concluded that flattening side slopes reduced both the number and severity of crashes. They reported that flattening a 3:1 slope to a 4:1 slope reduced the number of injury crashes by around 40% and flattening from 4:1 to 6:1 reduced the number of injury crashes by a further 20%.

Bergh and Petersson (2010) conducted a review and full-scale tests to validate the existing Swedish designs based on real-world crash data. They found no difference in the assessment of 3:1 and 1:4 slopes at on a fill that was 4 m deep, i.e. a 3:1 slope was a competitive design to a 4:1 slope. They also reported that, based on experience gained over time, 6:1 slopes did not have any safety advantages compared to 4:1 slopes. They further reported that, in most cases, a guard-rail treatment was superior to any other roadside design, the only exceptions being where there was an infinite clear zone at a low embankment and a well-designed soil cut.

Austrroads (2014) reported an increase in run-off-road casualty crashes with slope steepness. The relative risk of run-off-road crashes on a 2:1 slope or steeper was 2.5 and 3.4 times higher than on flatter slopes (less than 6:1) (Figure A.4)

**Figure A.4: Relative risk of run-off-road crashes by slope**



Source: Austrroads (2014).

## Impacts on rollover crash rate

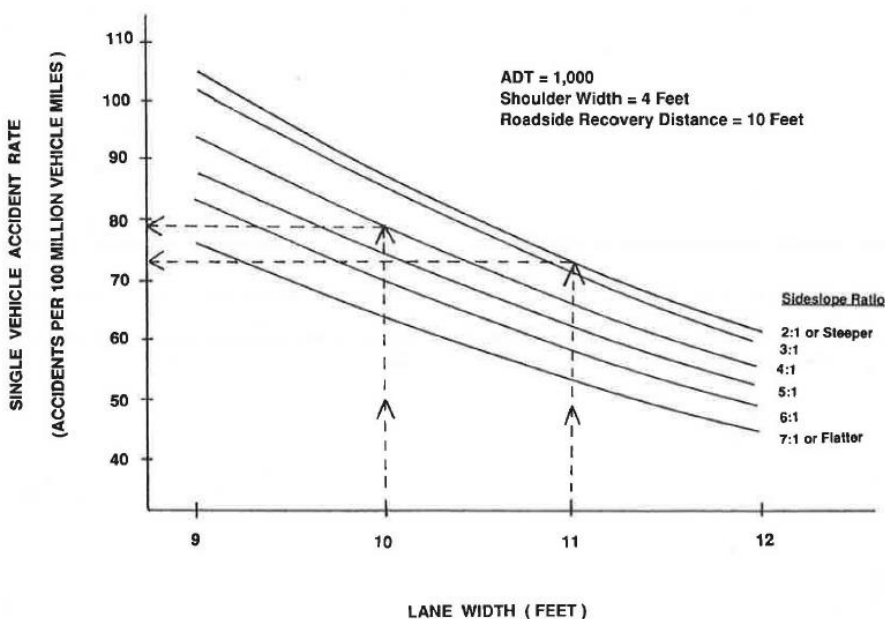
Based on full-scale tests and computer simulations, DeLeys and Parada (1986) reported that the likelihood of rollover increases with increasing slope steepness and height. They suggested that fill slopes should not be designed steeper than 3:1, and preferably flatter, for fill heights greater than 0.9 m to reduce the likelihood of rollovers involving small cars. Available data indicated that rollover frequency increased sharply for fill/ditch heights/depths greater than 3 ft (0.9 m).

Rollover crashes are severe in terms of their frequency and the severity of injuries to the vehicle occupants. They reported that fatality rates of occupants in rollover vehicles were approximately twice that for occupants in non-rollover impacts. They also reported that ejection was the leading cause of serious and fatal injuries, accounting for more than half of the fatalities occurring in rollover crashes. This implies that an increased use of vehicle restraints and improved in-vehicle safety features would help reduce the number of serious and fatal crashes.

### A.4.3 Effects of Lane Width on Rollover Crash Rate

Zeeger et al. (1988) developed a predictive model to assess the relationship between lane width and six categories of roadside slopes on single-vehicle crash rates (Figure A.5). They found that the crash rate reduced with an increase in lane width. They also reported that the crash rate on 3:1 slopes was similar to 2:1 or steeper slopes (difference very small). In addition, the study results showed that crash rates were significantly higher on 3:1 or steeper slopes compared to those on 4:1 or flatter slopes.

Figure A.5: Single-vehicle crash rates for various lane widths and roadside slopes



Source: Zeeger et al. (1988).

### A.4.4 Effects of Slope Width on Rollover Crashes

Based on real-world crash data and mathematical simulations, Carrigan and Sheikh (2017) reported a doubling in the probability of rollover crashes from an increase in slope width from 8 ft (2.4 m) to 16 ft (4.8 m) on a 2:1 slope. Beyond 4.8 m, the probability of rollover crashes reduced. As the relationship was found to be insignificant on other slopes, it was suggested that further research was required to provide guidance on limiting slope width, particularly on steep slopes.

### A.4.5 Effects of Slope Height on Crash Rate

Pardillo-Mayora et al. (2010) conducted cluster analysis based on crash data on two-lane rural roads in Spain. The study results suggested that the crash rates on 3:1 slopes started to increase significantly when the slope height was greater than 1 m, compared with less than 1 m high slopes. The FSI crash rates for slopes greater than 1 m high was about four times higher. Details of the study results are provided in Table A.14.

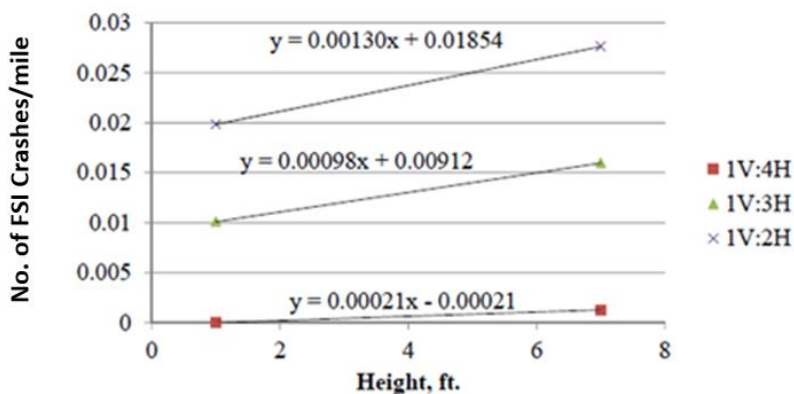
Reid et al. (2014) reported that crash rates generally increased with slope height. However, the increase in crash rate with increasing slope height was relatively small on 4:1 slopes compared to 2:1 and 3:1 slopes as shown in Figure A.6. The severity indices for different slopes and heights from this study are shown in Table A.15. The results showed relatively little variation in SI values on 4:1 or flatter roadside slopes except on local roads (as shown in Figure A.7), indicating 4:1 and flatter slopes are relatively safe in terms of crash severity outcomes.

**Table A.14: Crash rates on different slopes by height by road alignment**

	Slope	Injuries	FSIs	Comments	Conditions
No barriers	6:1 or flatter	0-0.21	0.00	Clear zone for at least 5 m, both curved and tangent roads	Ideal slope conditions for vehicle control recovery
	4:1 or flatter	2.0-2.7	0.29-0.32	On tangent alignment and no hazards within 3 m (i.e. clear zone at least 3 m)	This type of slopes leads to a relatively significant increase in injury crashes and FSI crashes starts to occur
		2.1-3.4	0.7-1.1	On curved alignment and clear zone at least 3 m	Curve alignment leads to relatively slight increase in injury crashes but more than doubles FSI crash rates
No or inappropriate barriers	4:1 – 6:1	4.8	2.1	On tangent alignment and hazards present with 3 m	Curve alignment more than doubles the crash rates for both injury and FSI crashes
		11.3	5.2	On curved alignment and hazards present within 3 m	
	3:1 with less than 1 m height	3.8-7.5	2.0-2.2	Clear zone of at least 3 m	Reduced probability of vehicle control recovery for this slope type
	3:1 with more than 1 m height	15.8	7.9	Clear zone of at least 3 m	Low probability of vehicle control recovery for this slope type and high rollover risk
	2:1 or steeper	19.9	9.3	On curved alignment and hazards within 3–5 m	No possibility of vehicle control recovery, the highest crash rates recorded
Barriers	All slopes	3.97	0.54	Both curved and tangent road alignments, distance of barrier from roadway not specified	Crash rates lower except on 4:1 slope with at least 3 m clear zone on straight roads, and on 6:1 slopes or lower

Source: Pardillo-Mayora et al. (2010).

**Figure A.6: Crashes per mile v. slope height**



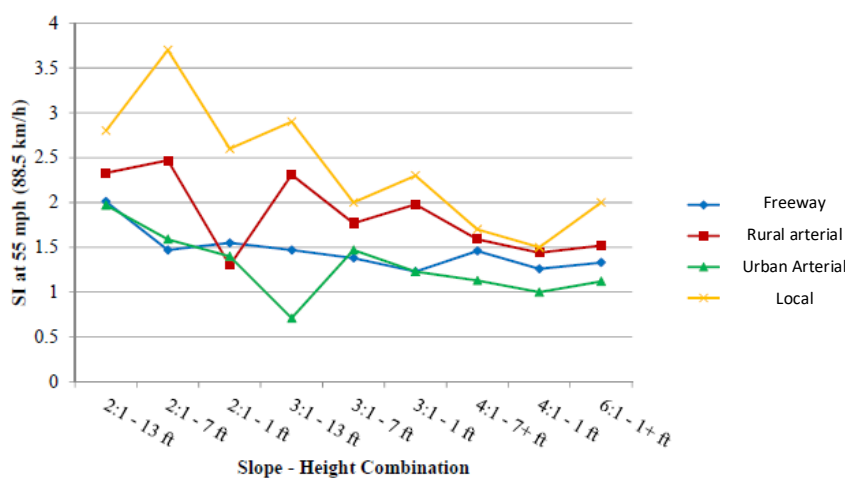
Source: Schrum et al. (2014).

**Table A.15: Severity indices and FSI crashes related to slope gradient and height**

Slope	Height (ft)	Severity index	FSI crashes per mile
6:1	Any	0.98	0
4:1	0.3	1	0
	2.1 & 4	1.31	0.0013
3:1	0.3	1.97	0.0102
	2.1	2.17	0.0157
	4.0	2.37	0.0218
2:1	0.3	2.30	0.0197
	2.1	2.51	0.0268
	4.0	2.66	0.0355

Source: Schrum et al. (2014).

**Figure A.7: Comparison of SI according to road functions, slope and height<sup>4</sup>**



Source: Schrum et al. (2014).

#### A.4.6 Effects of Slope on Probability of Vehicle Rollover

DeLays and Parada (1986) reported that the likelihood of rollover increases with the steepness and height of slopes and that the highest proportion of rollover occurred on a 3:1 slope. In their study on the effect of slope on rollover probability Carrigan and Sheikh (2017) reported that a vehicle is approximately nine times more likely to rollover on a 2:1 slope than a 10:1 slope.

In a recent study to develop guidelines for slope traversability, Sheikh et al. (2019), investigated the influence of shoulder width, slope width and slope on vehicle rollover probability. Their results included the following:

- As the slope increases, the probability of a recoverable encroachment decreases (Figure A.8).
- There is a significant probability of any of the three crash outcomes (rollover, recoverable and traversable non-recoverable) occurring on all slopes (Figure A.8). This implies that all slopes have a risk of rollover associated with them, and so it could be misleading for current guidelines to assign one particular outcome type to a specific slope.
- The probability of rollover crashes increases with steeper slopes (Figure A.8 and Figure A.9).
- The rollover probability on roads with a shoulder width less than 1.2 m is higher than the rollover probability on roads with a shoulder width greater than 1.2 m (Figure A.9).
- For a 10:1 slope or flatter, the probability of rollover does not vary much, with slope width varying between 10% and 13% for all slope widths (Figure A.9).

<sup>4</sup> Lack of available crash data on 2:1 slopes could result in discrepancy in results (Reid et al. 2014).

- An increase in slope width above 16 ft (4.9 m) resulted in a decrease in rollover probability, except for flatter slopes, which remained at nearly the same rollover probability as the 4.9 m slope width.

Sheikh et al. (2019) recommended that slope design guidelines should be based on rollover probability as a function of slope gradient, slope width and shoulder width as shown in Figure A.9.

Figure A.8: Probability of crash outcomes for vehicles encroaching on different slopes

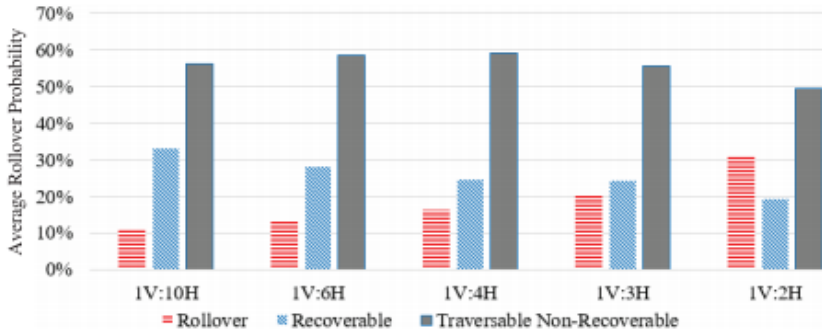
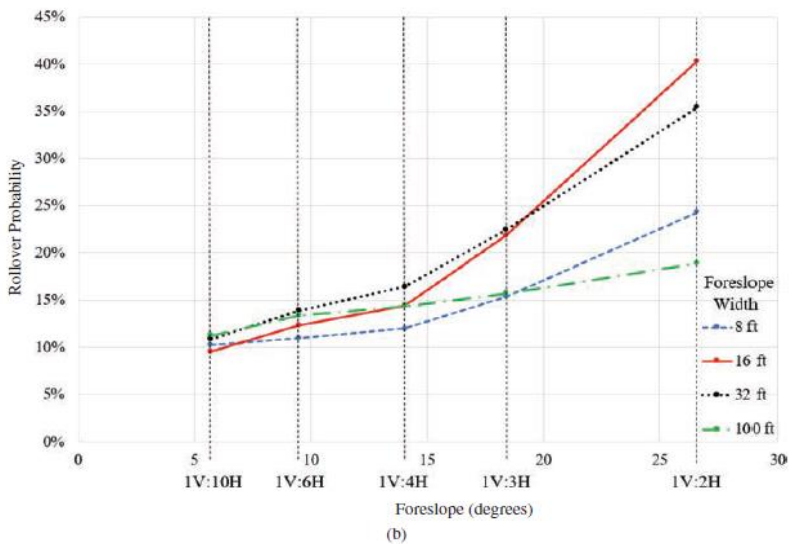
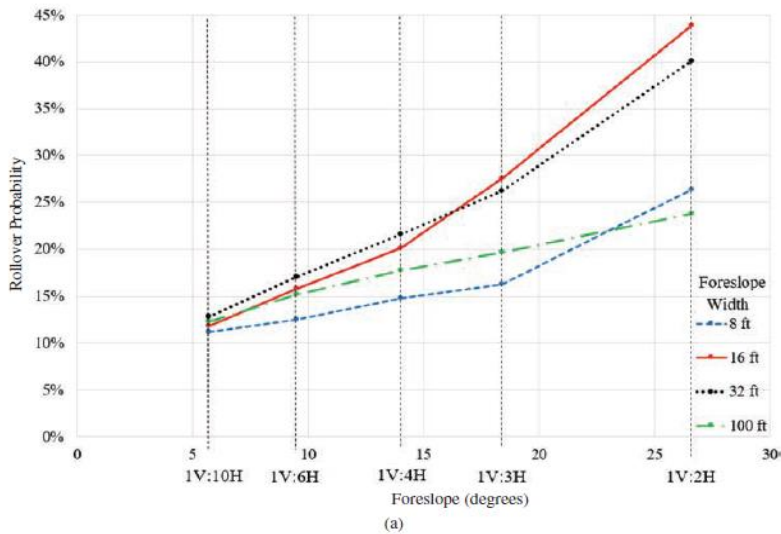


Figure 7.11. Probability of outcome for vehicles encroaching on slopes.

Source: Sheikh et al. (2019).

Figure A.9: Influence of slope on probability of vehicle rollover for: (a) a narrow shoulder widths of 1.2 m or less; (b) full shoulder widths greater than 1.2 m

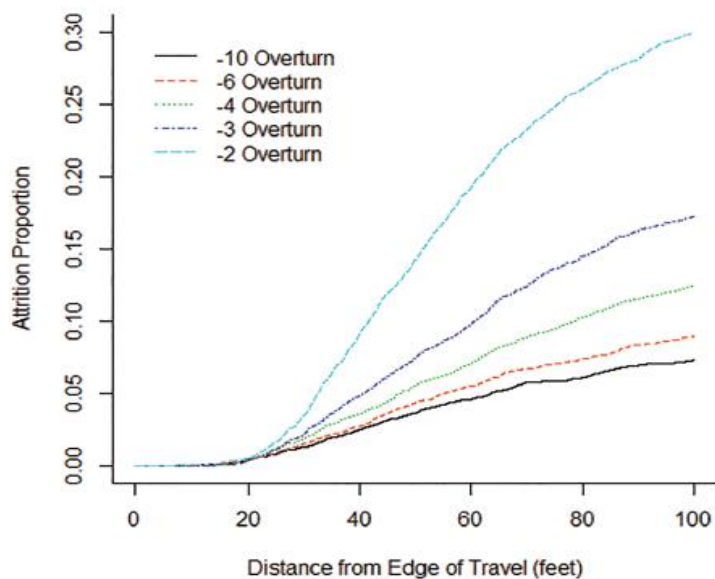


Source: Sheikh et al. (2019).

#### A.4.7 Effects of Encroachment Distance on Rollover Crash Rate

Based on several US datasets and simulation results, Carrigan and Ray (2019) investigated the effects of encroachment speed and angle, vehicle type, and slope on lateral extent and rollover risk. The probability of rollover crashes for passenger vehicles, expressed as attrition rate based on slope gradient and encroachment distance, is shown in Figure A.10. It can be seen that, a vehicle is unlikely to rollover within the first 20 ft (6.1 m) of the maximum lateral extent, regardless of the slope. The steeper the slope, the higher the rate of attrition. The risk of a rollover also increases with encroachment distance, and the risk of a vehicle overturning is highest on a 2:1 slope.

Figure A.10: Estimated risk v. distance from edge of travel by different slopes



Source: Carrigan and Ray (2019).

It was reported in Austroads (2011) that the proportion of rollover crashes increases with encroachment distance (clearway zone) whilst the proportion of run-off-road, hit-object crashes reduces with encroachment distance.

#### A.4.8 Departure Angle and Speed

Carrigan and Ray (2019) reported that median departure angles based on four US datasets range from 14° to 20° (Table A.16).

Table A.16: Comparison of departure speed and angle for specific crash databases

Reference	Number of cases	50 <sup>th</sup> percentile of data set	
		Departure speed	Departure angle
NCHRP Project 17-11	485		19.9°
NCHRP Project 17-11 <sup>a</sup>	485	48.9 mph	16.9°
NCHRP Project 17-22	392	49.7 mph	17.2°
NCHRP Report 665	877 <sup>b</sup>	49.3 mph	16.9°
NCHRP Project 17-43 (Gabler, 2018)	1124	48.6 mph	13.8°

<sup>a</sup>After reconstructed and manual reviews by the 17-22 group.

<sup>b</sup>Combination of 17-11 reconstructed data set and 17-22 data set.

Source: Carrigan and Ray (2019).

In an earlier study, DeLeys and Parada (1986) reported that about half of all crash departures from the roadway occurred at path angles greater than 15 degrees, and the majority of vehicles were estimated to have been traveling at speeds less than 40 to 50 mi/h (64 to 80 km/h). The reported mean angle was 13.9 degrees.

#### A.4.9 Rollover Crashes by Vehicle Type

DeLeys and Parada (1986) reported distinct differences in rollover crash rates according to vehicle type and size as follows:

- Utility vehicles had the highest rollover frequency (40 to 60% rollover rate) and were about three to five times more likely to overturn than passenger cars. This was due primarily to the centre of gravity for a utility vehicle being higher than that of a passenger car.

- The rollover rate for passenger cars decreased with increasing car size; the weight, wheelbase length, and tyre tread width appeared to be equally appropriate as classificatory variables, since they were all highly interrelated.

In a recent USA study, Carrigan and Sheikh (2017) found that the variation in the probability of rollover crashes by vehicle type was statistically insignificant, i.e. there was statistically no difference in the probability of rollover crashes by vehicle type, leading them to recommend the use of the same crash modification factors (CMFs) cross the vehicle fleet. They did, however, report evidence of variation in crash severity as the rollover frequency increased.

#### A.4.10 Effects of Slope Rounding on the Control of Errant Vehicles

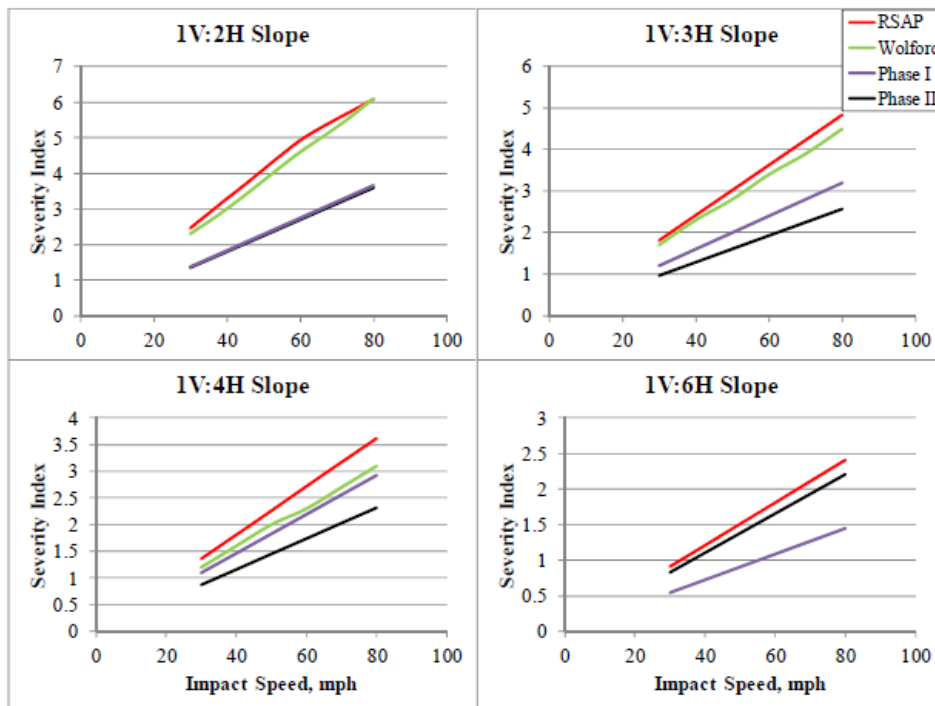
Through a series of models validated by full-scale tests, Weaver, Marquis & Olson (1975) found that rounding the top of the slope could reduce the tendency of errant vehicles to become airborne. From the study results, it was reported that return manoeuvres were achieved on 3:1 or flatter at a speed of 129 km/h.

Schoon (1997) also suggested that the radius of curvature of the slope top contributed significantly to preventing vehicles from becoming airborne. Therefore, he suggested that the radius of curvature of the cut slopes should be higher than 9 m (preferably 12 m).

#### A.4.11 Severity Indices/Crash Modification Factors

The severity index in the US RSAP program used for the qualitative evaluation by other jurisdictions is a functional relationship based on impact speed. Reid et al. (2014) compared the severity indices from their research with those in the US RSAP program. They found that the severity indices in the RSAP program were over-estimated compared to their results (phase 1 and II) as shown in Figure A.11. They reported that the estimated slope severities from the RSAP program could be reduced by as much as 50% for the steeper embankments and 10 to 15% for 6:1 slope conditions.

Figure A.11: Estimated risk vs speed of travel by different slopes



Source: Schrum et al. (2014).

More recent crash modification factors were developed by Carrigan & Sheikh (2017). Their results, shown in Table A.17, are disaggregated by crash severity and slope only. Their study found no difference in the

probability of rollover according to vehicle type; hence they recommended that the CMFs developed should be applied across the vehicle fleet.

Table A.17: Carrigan and Sheikh (2017) proposed slope CMF

**Table 10 Proposed Slope CMF and TAF**

$xH:1V$	$CMF_{KABC0U}$ and TAF	$CMF_{KABC}$	$CMF_{KAB}$	$CMF_{KA}$
-10	1.00	0.65	0.52	0.15
-6	1.98	1.30	1.04	0.30
-4	3.83	2.51	2.00	0.58
-3	5.68	3.71	2.96	0.86
-2	9.21	6.02	4.81	1.40

Note: K – fatal; A – serious injury, B – Injury; C – minor injury; O – property damage only.

Source: Carrigan and Sheikh (2017).

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# Appendix B Crash Analysis

The results of the analysis of the 2471 run-off-road crashes that satisfied the selection criteria are provided in this Appendix.

## B.1 Crash Severity

The proportion of crashes that resulted in fatalities on slopes was 2% compared to 1.8% for non-slope-related crashes. However, the proportion of FSIs for slope-related crashes was slightly lower (60.4%) compared to 61.6% for non-slope-related crashes. There is no real differences between the values.

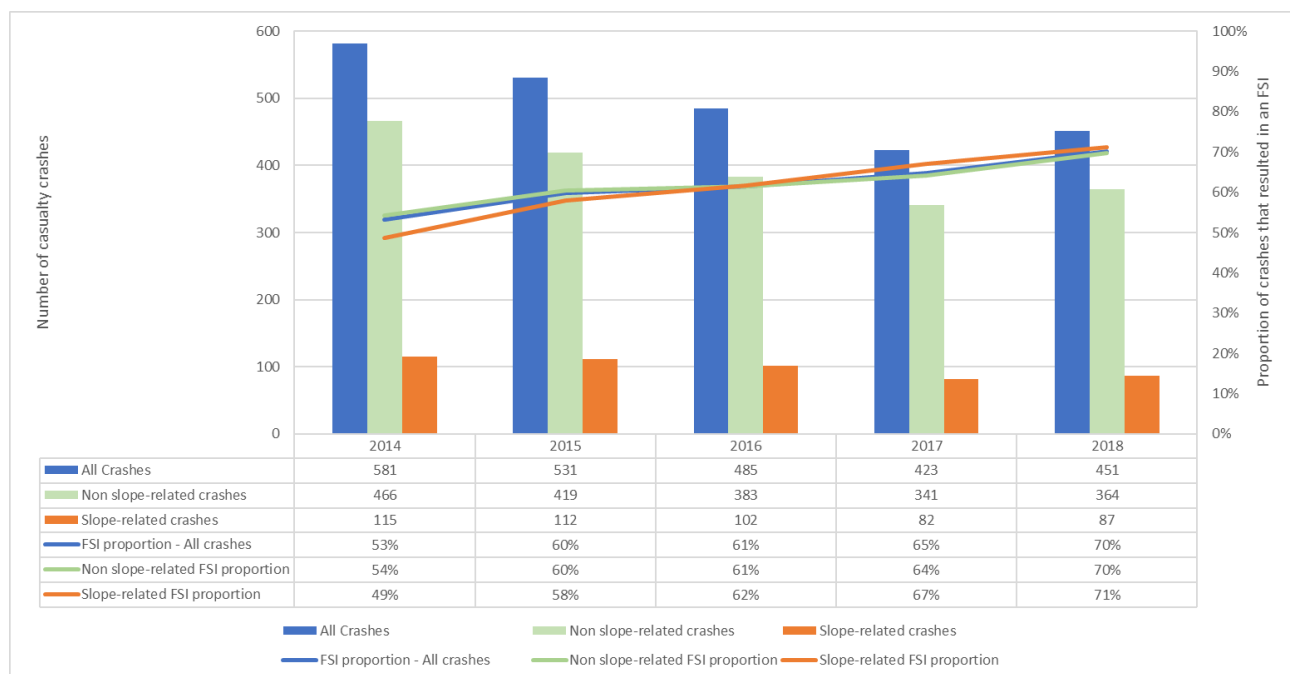
Table B.1: Slope parameters and likelihood of crashes

Severity	Non-slope crashes		Slope crashes		Total crashes	
Fatal	35	1.8%	10	2.0%	45	1.8%
Hospitalised	1179	59.8%	291	58.4%	1470	59.5%
Other injury crashes	759	38.4%	197	39.6%	956	38.7%
Total	1973	100%	498	100%	2471	100.0%

## B.2 Annual Crashes

There was an increasing trend in the proportion of FSI crashes from 2014 to 2018 for both slope and non-slope-related crashes (Figure B.1). Overall, there has been a gradual decrease in the number of crashes over the period.

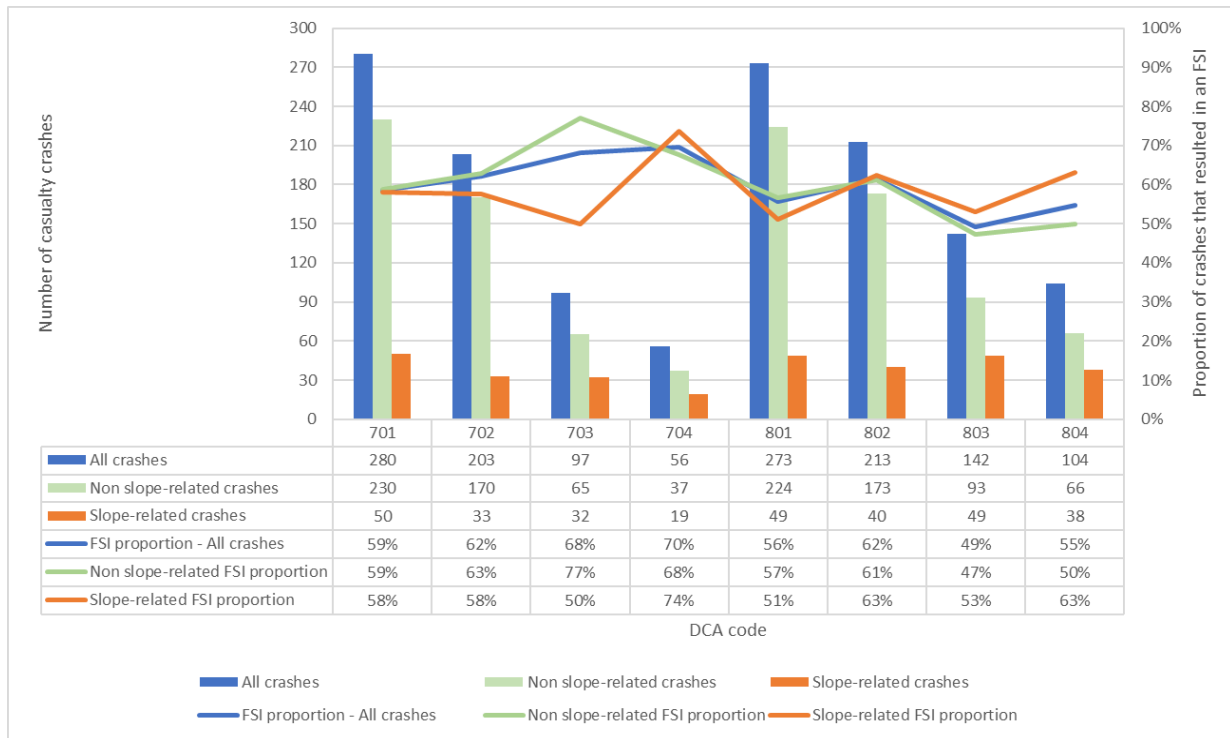
Figure B.1: Annual crashes



## B.3 Crash types (DCA Code)

The distribution of crashes by DCA code is shown in Figure B.1: . Overall, there is no variation between slope-related and non-slope-related crashes.

Figure B.2: Crashes by DCA code



## B.4 Unit Type

Analysis of the crashes by unit type indicates that (Figure B.3 and Table B.1):

- Motorcycles have a significantly increased risk of fatal and FSI crashes, especially for slope-related fatal crashes.
- Articulated trucks have a significantly increased risk of non-slope-related fatal crashes.
- Rigid trucks have an increased risk of slope-related FSI crashes.
- There was a slight increase in FSI slope-related crashes for buses/coaches.

Figure B.3: Crashes by unit type



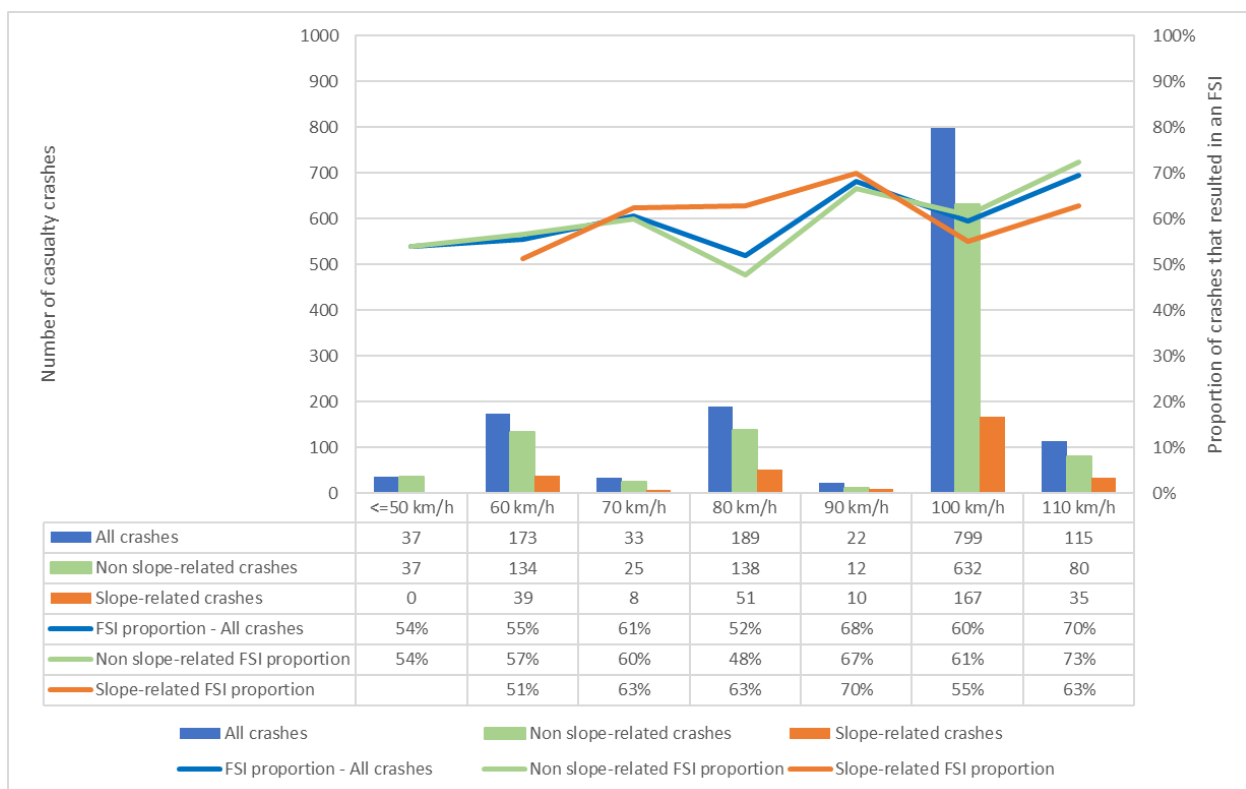
**Table B.2: Crash rates on different slopes**

Unit type	All crashes			Fatal crashes			FSI crashes		
	Non-slope	Slope-related	Total crashes	Non slope	Slope-related	Total fatal	Non slope	Slope-related	Total FSIs
Articulated truck	3.8%	2.3%	3.4%	25.0%	0.0%	22.7%	4.6%	1.7%	4.0%
Bus/Coach	0.8%	0.3%	0.7%	0.0%	0.0%	0.0%	0.8%	0.6%	0.7%
Car/Station wagon	55.8%	64.2%	57.7%	35.0%	50.0%	36.4%	53.6%	60.7%	55.2%
Rigid truck	4.3%	3.9%	4.2%	0.0%	0.0%	0.0%	4.1%	5.6%	4.5%
Road train/B-double/Triple	2.6%	1.6%	2.4%	0.0%	0.0%	0.0%	3.5%	2.2%	3.2%
Special Purpose Vehicle	0.7%	0.6%	0.7%	0.0%	0.0%	0.0%	0.8%	0.6%	0.7%
Utility/Panel van	32.1%	27.1%	31.0%	40.0%	50.0%	40.9%	32.5%	28.7%	31.7%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Total crashes	1058	310	1368	20	2	22	627	178	805

## B.5 Speed Limit

Figure B.4 shows the distribution of crashes by posted speed limit. The proportion of FSI for slope-related crashes was higher on 80 km/h zone sections and slightly lower on 60, 100 and 110 km/h sections compared to non-slope crashes (Figure B.4).

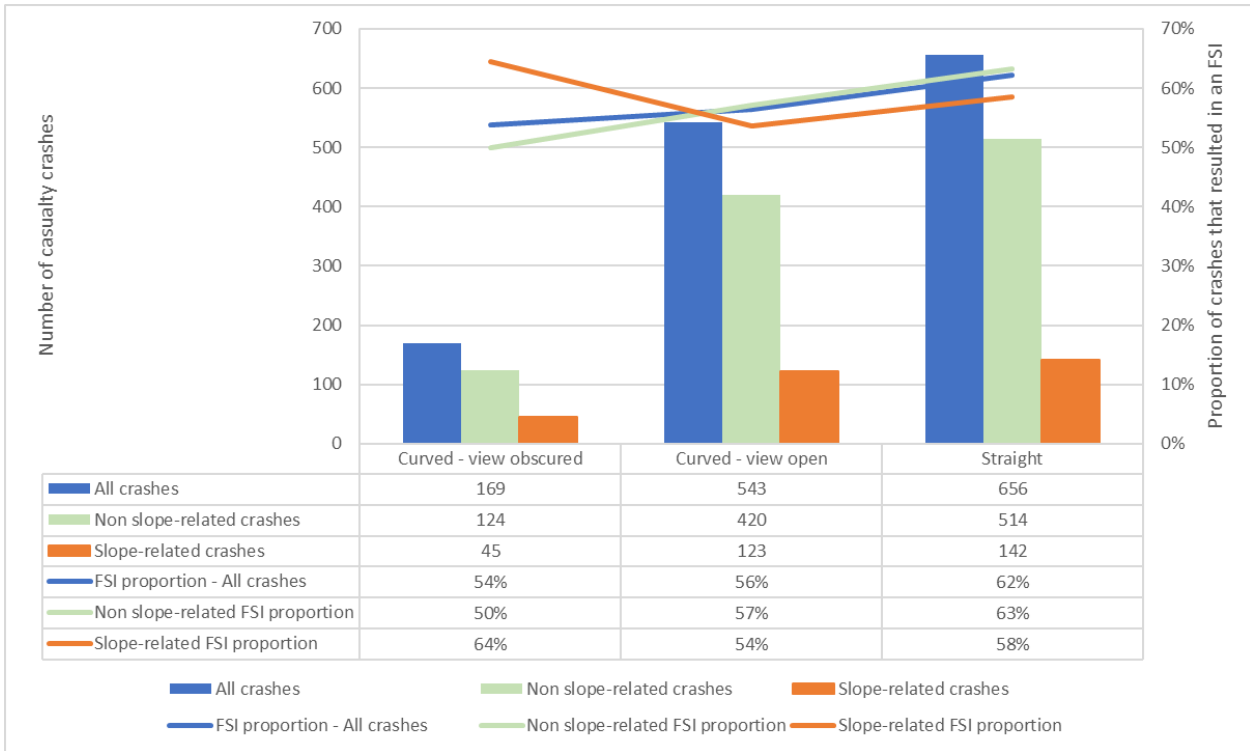
**Figure B.4: Crashes by speed limit**



## B.6 Horizontal Alignment

The severity of crashes (FSI proportion) on slopes was higher on curves when the view was obscured, but lower on curves with an open view, straight alignment compared to non-slope-related crashes (Figure B.5).

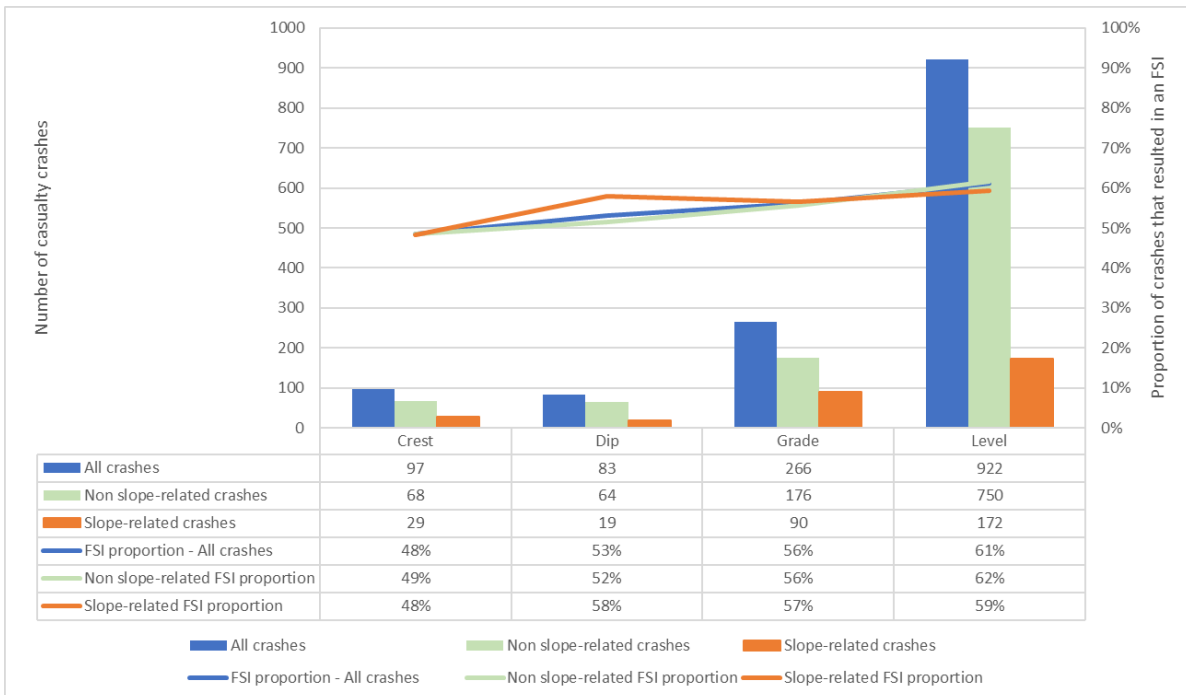
Figure B.5: Crashes by horizontal alignment



## B.7 Vertical Alignment

The severity of crashes (FSI proportion) on slopes was slightly higher on dips, but the same elsewhere compared to non-slope related crashes (Figure B.5).

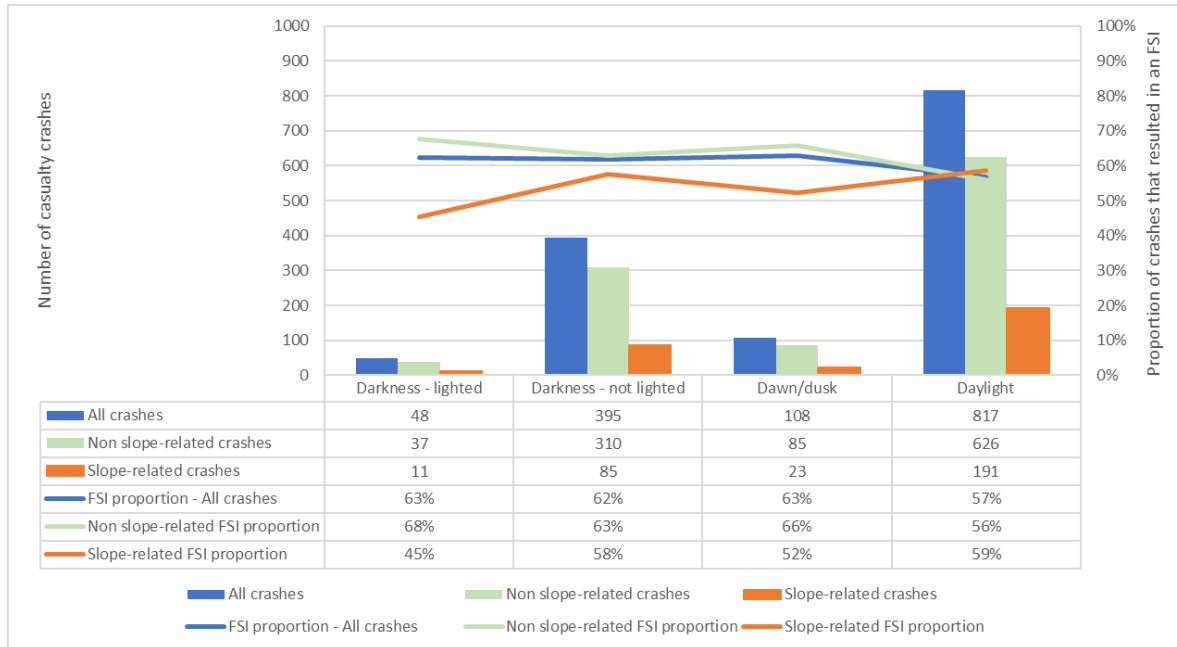
Figure B.6: Crashes by Vertical alignment



## B.8 Lighting Condition

The severity of crashes (FSI proportion) on slopes was lower during adverse lighting conditions (darkness and dawn/dusk) compared to non-slope-related crashes (Figure B.7). There was no difference in crash severity during the daylight period.

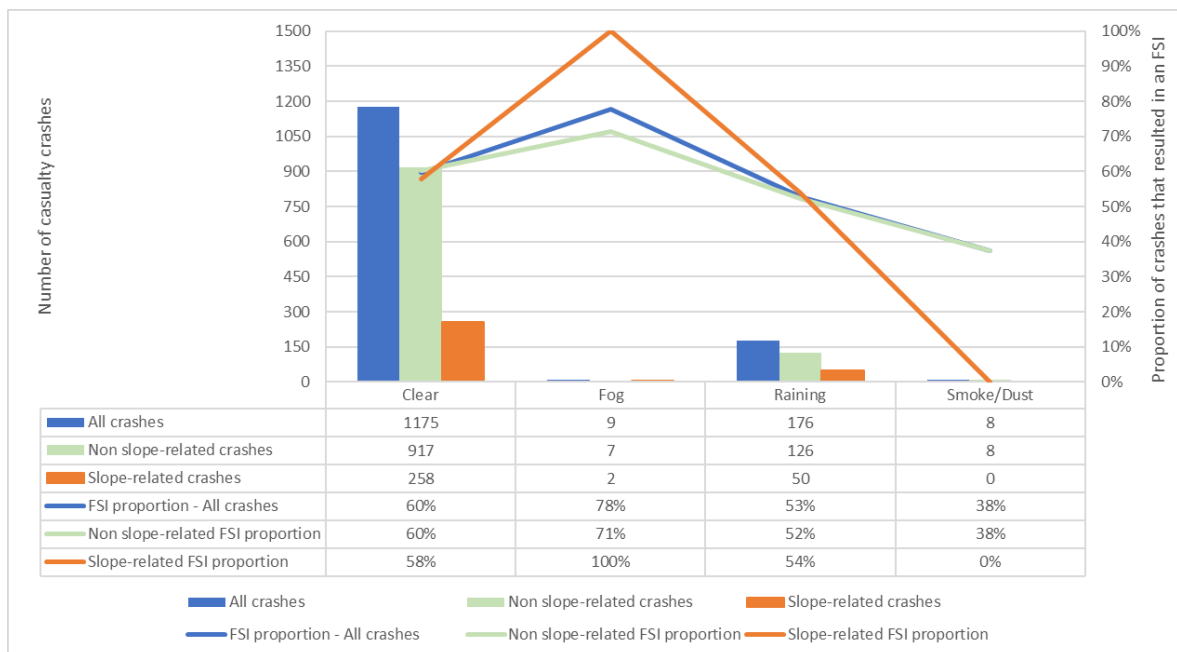
Figure B.7: Crashes by lighting conditions



## B.9 Weather Condition

The severity of crashes (FSI proportion) on slopes in foggy weather was higher compared to non-slope-related crashes; however, the number of crashes was small (Figure B.7). There was no difference in crash severity during other weather conditions.

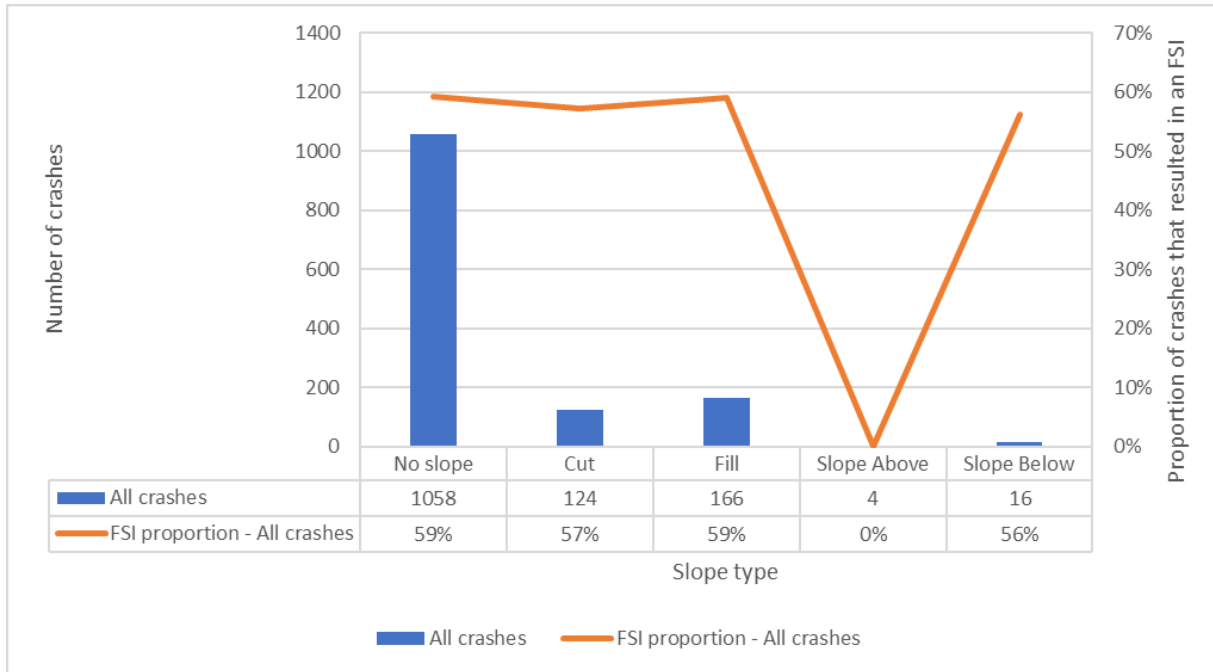
Figure B.8: Crashes by weather condition



## B.10 Slope Type

Approximately 55% of all slope-related crashes occurred on fill slopes and 40% on cut slopes (Figure B.9). There was no significant difference in crash severity between slope and non-slope-related crashes.

Figure B.9: Crashes by slope type



## B.11 Cut Slope Crashes

There were no consistent variations in crash severity by slope angle (grade), probably due to the poor categories used (Figure B.10). However, there is an increasing trend in crash severity by slope height (Figure B.11).

Figure B.10: Cut slope crashes by slope angle

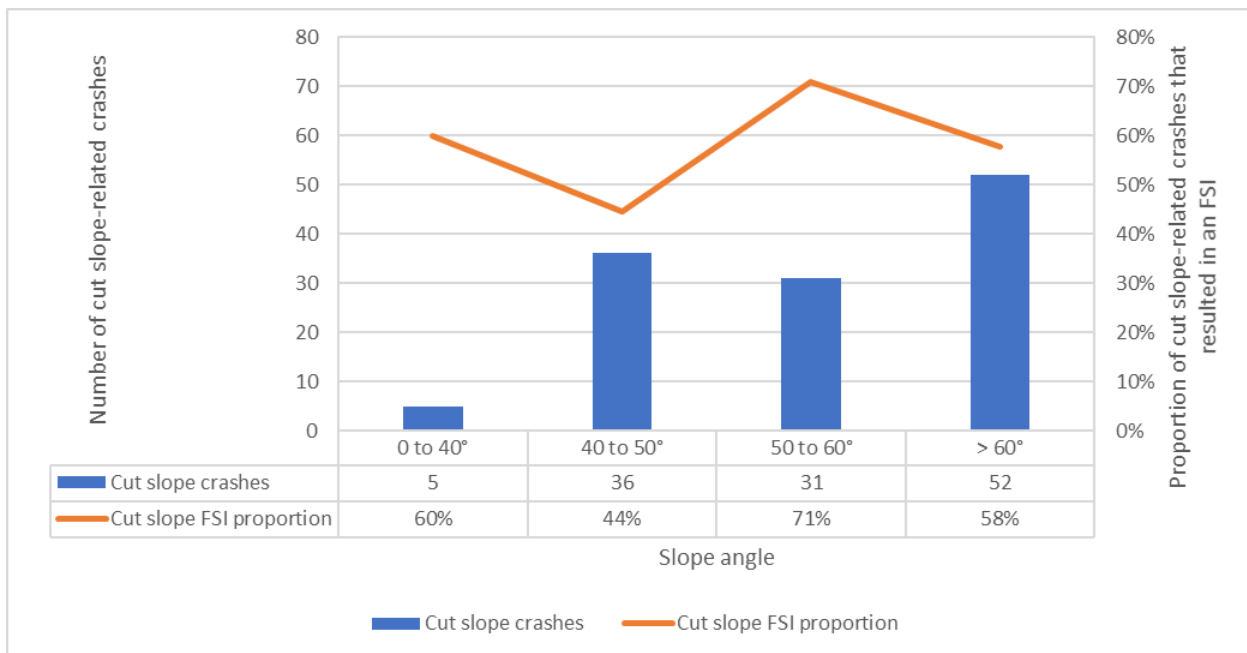
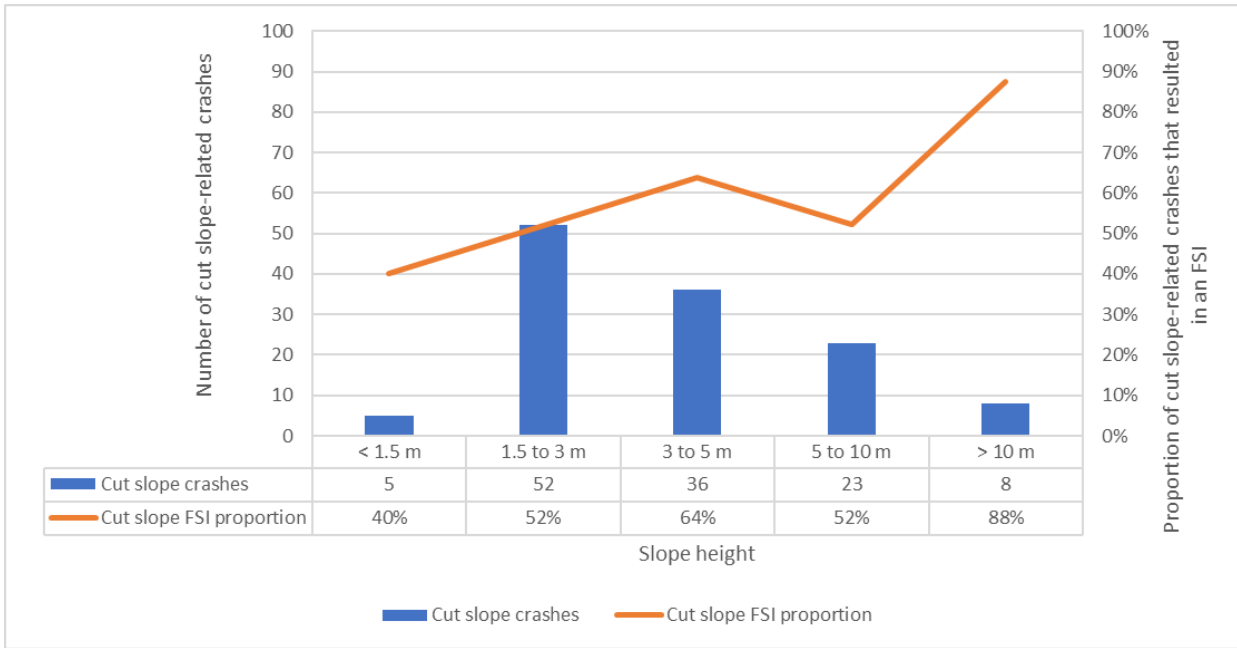


Figure B.11: Cut slope crashes by slope height



## B.12 Fill Slope Crashes

The analysis of crashes on fill slopes found:

- a decreasing trend in crash severity with increase in slope angle (Figure B.12)
- an increase in crash severity when the slope heights were greater than 1.5 m (Figure B.13).

Figure B.12: Fill slope crashes by slope angle

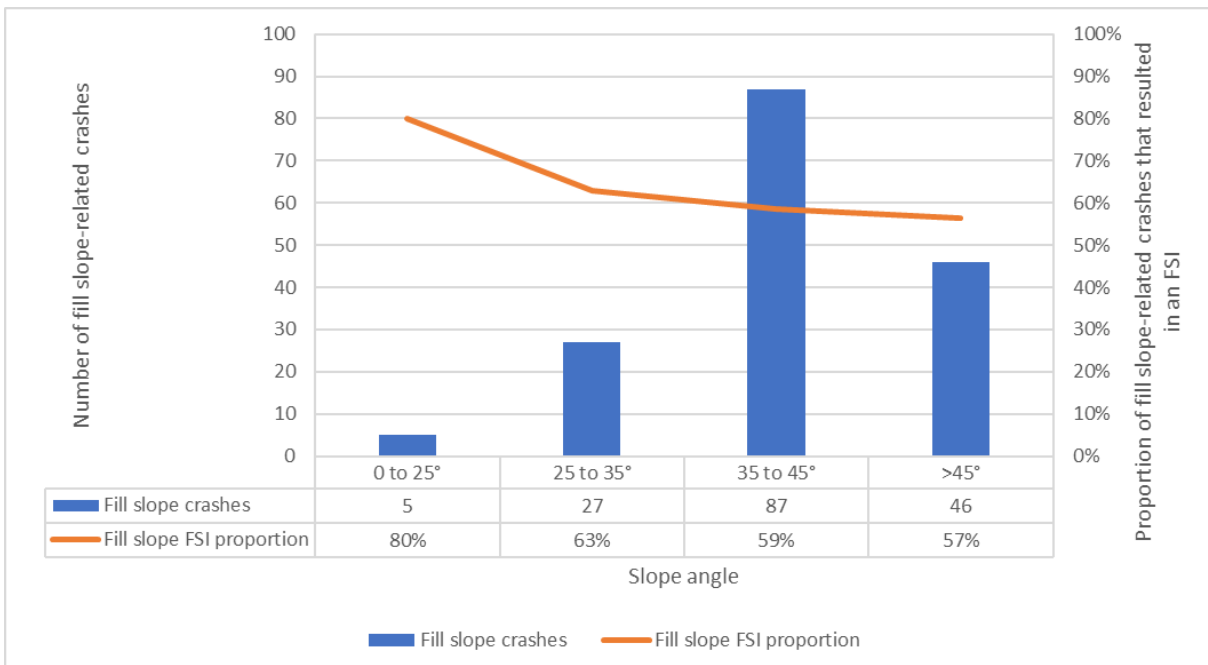
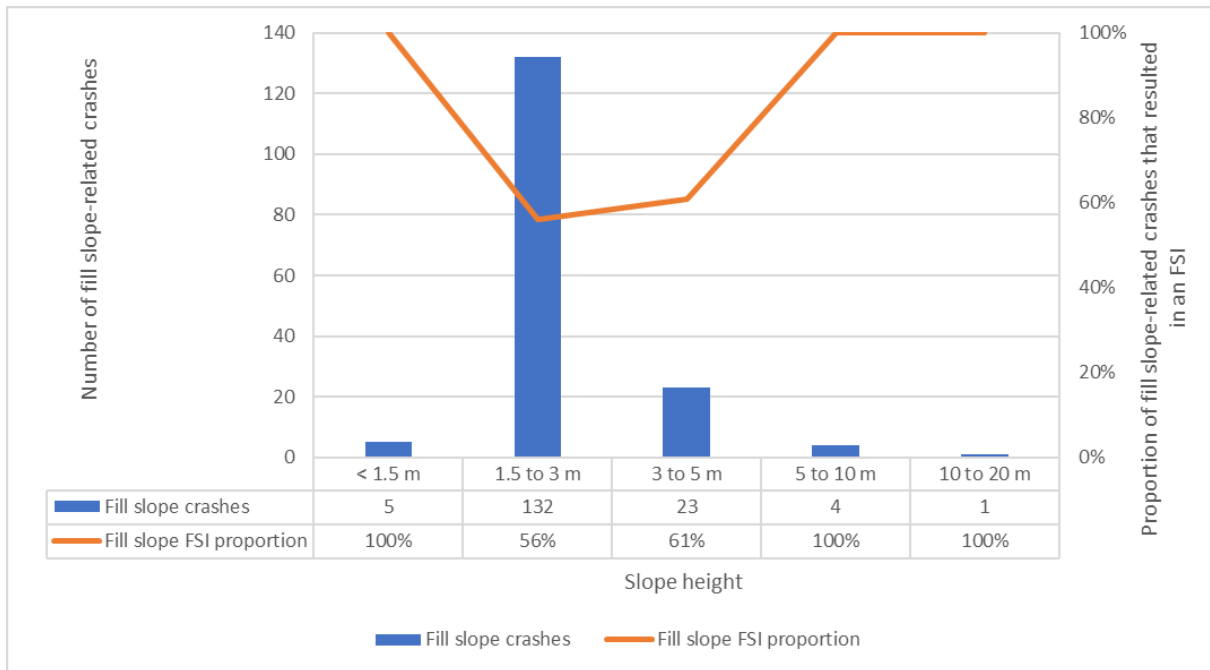


Figure B.13: Fill slope crashes by slope height



## Appendix C Risk Scores for 110 km/h

Table C.1 shows sample results of risk scores when a vehicle is travelling at 110 km/h for different slopes and the following road conditions: rural one-lane undivided road with straight alignment (curve radius of 2000 m), zero grade, AADT = 2000 and 3.3 m lane width.

Table C.2: Risk scores for 110 km/h

Hazard	Terrain	Section length (m)	Lateral distance (m)	Slope height					Safety Barrier
				0–2 m	2–5 m	5–10 m	10–20 m	20 m+	
Slope 2:1	Flat	100	1	0.72	1.94	2.49	3.71	5.48	0.51
Slope 2:1	Flat	100	1	0.72	1.94	2.49	3.71	5.48	0.51
Slope 2:1	Flat	100	3	0.52	1.40	1.80	2.67	3.95	0.40
Slope 2:1	Flat	100	3	0.52	1.40	1.80	2.67	3.95	0.40
Slope 2:1	Flat	100	5	0.38	1.01	1.30	1.93	2.84	0.34
Slope 2:1	Flat	100	5	0.38	1.01	1.30	1.93	2.84	0.34
Slope 2:1	Flat	100	7	0.28	0.73	0.94	1.39	2.05	0.34
Slope 2:1	Flat	100	7	0.28	0.73	0.94	1.39	2.05	0.34
Slope 2:1	Flat	100	9	0.20	0.53	0.68	1.00	1.48	0.34
Slope 2:1	Flat	100	9	0.20	0.53	0.68	1.00	1.48	0.34
Slope 2:1	Rolling	100	1	1.86	5.00	6.42	9.56	14.13	1.30
Slope 2:1	Rolling	100	1	1.86	5.00	6.42	9.56	14.13	1.30
Slope 2:1	Rolling	100	3	1.35	3.61	4.63	6.89	10.18	1.03
Slope 2:1	Rolling	100	3	1.35	3.61	4.63	6.89	10.18	1.03
Slope 2:1	Rolling	100	5	0.98	2.61	3.34	4.97	7.34	0.88
Slope 2:1	Rolling	100	5	0.98	2.61	3.34	4.97	7.34	0.88
Slope 2:1	Rolling	100	7	0.71	1.88	2.41	3.58	5.28	0.88
Slope 2:1	Rolling	100	7	0.71	1.88	2.41	3.58	5.28	0.88
Slope 2:1	Rolling	100	9	0.52	1.36	1.74	2.58	3.81	0.88
Slope 2:1	Rolling	100	9	0.52	1.36	1.74	2.58	3.81	0.88
Slope 2:1	Mountainous	100	1	1.63	4.40	5.65	8.41	12.43	1.15
Slope 2:1	Mountainous	100	1	1.63	4.40	5.65	8.41	12.43	1.15
Slope 2:1	Mountainous	100	3	1.19	3.17	4.08	6.06	8.96	0.91
Slope 2:1	Mountainous	100	3	1.19	3.17	4.08	6.06	8.96	0.91
Slope 2:1	Mountainous	100	5	0.86	2.29	2.94	4.37	6.45	0.78
Slope 2:1	Mountainous	100	5	0.86	2.29	2.94	4.37	6.45	0.78
Slope 2:1	Mountainous	100	7	0.62	1.65	2.12	3.15	4.65	0.78
Slope 2:1	Mountainous	100	7	0.62	1.65	2.12	3.15	4.65	0.78
Slope 2:1	Mountainous	100	9	0.45	1.20	1.53	2.27	3.35	0.78
Slope 2:1	Mountainous	100	9	0.45	1.20	1.53	2.27	3.35	0.78
Slope 3:1	Flat	100	1	0.46	0.78	0.83	0.83	1.16	0.51
Slope 3:1	Flat	100	1	0.46	0.78	0.83	0.83	1.16	0.51
Slope 3:1	Flat	100	3	0.34	0.56	0.60	0.60	0.84	0.40
Slope 3:1	Flat	100	3	0.34	0.56	0.60	0.60	0.84	0.40
Slope 3:1	Flat	100	5	0.25	0.41	0.44	0.44	0.61	0.34
Slope 3:1	Flat	100	5	0.25	0.41	0.44	0.44	0.61	0.34
Slope 3:1	Flat	100	7	0.18	0.30	0.32	0.32	0.44	0.34
Slope 3:1	Flat	100	7	0.18	0.30	0.32	0.32	0.44	0.34

		Section length	Lateral distance	Slope height					Safety
Slope 3:1	Flat	100	9	0.13	0.22	0.23	0.23	0.32	0.34
Slope 3:1	Flat	100	9	0.13	0.22	0.23	0.23	0.32	0.34
Slope 3:1	Rolling	100	1	1.19	2.00	2.14	2.14	3.00	1.30
Slope 3:1	Rolling	100	1	1.19	2.00	2.14	2.14	3.00	1.30
Slope 3:1	Rolling	100	3	0.86	1.45	1.55	1.55	2.17	1.03
Slope 3:1	Rolling	100	3	0.86	1.45	1.55	1.55	2.17	1.03
Slope 3:1	Rolling	100	5	0.63	1.05	1.13	1.13	1.57	0.88
Slope 3:1	Rolling	100	5	0.63	1.05	1.13	1.13	1.57	0.88
Slope 3:1	Rolling	100	7	0.46	0.76	0.82	0.82	1.14	0.88
Slope 3:1	Rolling	100	7	0.46	0.76	0.82	0.82	1.14	0.88
Slope 3:1	Rolling	100	9	0.34	0.55	0.59	0.59	0.82	0.88
Slope 3:1	Rolling	100	9	0.34	0.55	0.59	0.59	0.82	0.88
Slope 3:1	Mountainous	100	1	1.04	1.76	1.89	1.89	2.64	1.15
Slope 3:1	Mountainous	100	1	1.04	1.76	1.89	1.89	2.64	1.15
Slope 3:1	Mountainous	100	3	0.76	1.28	1.37	1.37	1.91	0.91
Slope 3:1	Mountainous	100	3	0.76	1.28	1.37	1.37	1.91	0.91
Slope 3:1	Mountainous	100	5	0.56	0.93	0.99	0.99	1.38	0.78
Slope 3:1	Mountainous	100	5	0.56	0.93	0.99	0.99	1.38	0.78
Slope 3:1	Mountainous	100	7	0.41	0.67	0.72	0.72	1.00	0.78
Slope 3:1	Mountainous	100	7	0.41	0.67	0.72	0.72	1.00	0.78
Slope 3:1	Mountainous	100	9	0.30	0.49	0.52	0.52	0.72	0.78
Slope 3:1	Mountainous	100	9	0.30	0.49	0.52	0.52	0.72	0.78
Slope 4:1	Flat	100	1	0.38	0.49	0.49	0.49	0.49	0.51
Slope 4:1	Flat	100	1	0.38	0.49	0.49	0.49	0.49	0.51
Slope 4:1	Flat	100	3	0.28	0.36	0.36	0.36	0.36	0.40
Slope 4:1	Flat	100	3	0.28	0.36	0.36	0.36	0.36	0.40
Slope 4:1	Flat	100	5	0.20	0.26	0.26	0.26	0.26	0.34
Slope 4:1	Flat	100	5	0.20	0.26	0.26	0.26	0.26	0.34
Slope 4:1	Flat	100	7	0.15	0.19	0.19	0.19	0.19	0.34
Slope 4:1	Flat	100	7	0.15	0.19	0.19	0.19	0.19	0.34
Slope 4:1	Flat	100	9	0.11	0.14	0.14	0.14	0.14	0.34
Slope 4:1	Flat	100	9	0.11	0.14	0.14	0.14	0.14	0.34
Slope 4:1	Rolling	100	1	0.99	1.27	1.27	1.27	1.27	1.30
Slope 4:1	Rolling	100	1	0.99	1.27	1.27	1.27	1.27	1.30
Slope 4:1	Rolling	100	3	0.72	0.93	0.93	0.93	0.93	1.03
Slope 4:1	Rolling	100	3	0.72	0.93	0.93	0.93	0.93	1.03
Slope 4:1	Rolling	100	5	0.53	0.68	0.68	0.68	0.68	0.88
Slope 4:1	Rolling	100	5	0.53	0.68	0.68	0.68	0.68	0.88
Slope 4:1	Rolling	100	7	0.39	0.49	0.49	0.49	0.49	0.88
Slope 4:1	Rolling	100	7	0.39	0.49	0.49	0.49	0.49	0.88
Slope 4:1	Rolling	100	9	0.28	0.36	0.36	0.36	0.36	0.88
Slope 4:1	Rolling	100	9	0.28	0.36	0.36	0.36	0.36	0.88
Slope 4:1	Mountainous	100	1	0.87	1.12	1.12	1.12	1.12	1.15
Slope 4:1	Mountainous	100	1	0.87	1.12	1.12	1.12	1.12	1.15
Slope 4:1	Mountainous	100	3	0.63	0.82	0.82	0.82	0.82	0.91
Slope 4:1	Mountainous	100	3	0.63	0.82	0.82	0.82	0.82	0.91

		Section length	Lateral distance	Slope height					Safety
Slope 4:1	Mountainous	100	5	0.47	0.60	0.60	0.60	0.60	0.78
Slope 4:1	Mountainous	100	5	0.47	0.60	0.60	0.60	0.60	0.78
Slope 4:1	Mountainous	100	7	0.34	0.43	0.43	0.43	0.43	0.78
Slope 4:1	Mountainous	100	7	0.34	0.43	0.43	0.43	0.43	0.78
Slope 4:1	Mountainous	100	9	0.25	0.32	0.32	0.32	0.32	0.78
Slope 4:1	Mountainous	100	9	0.25	0.32	0.32	0.32	0.32	0.78
Slope 6:1	Flat	100	1	0.35	0.35	0.35	0.35	0.35	0.51
Slope 6:1	Flat	100	1	0.35	0.35	0.35	0.35	0.35	0.51
Slope 6:1	Flat	100	3	0.26	0.26	0.26	0.26	0.26	0.40
Slope 6:1	Flat	100	3	0.26	0.26	0.26	0.26	0.26	0.40
Slope 6:1	Flat	100	5	0.19	0.19	0.19	0.19	0.19	0.34
Slope 6:1	Flat	100	5	0.19	0.19	0.19	0.19	0.19	0.34
Slope 6:1	Flat	100	7	0.14	0.14	0.14	0.14	0.14	0.34
Slope 6:1	Flat	100	7	0.14	0.14	0.14	0.14	0.14	0.34
Slope 6:1	Flat	100	9	0.10	0.10	0.10	0.10	0.10	0.34
Slope 6:1	Flat	100	9	0.10	0.10	0.10	0.10	0.10	0.34
Slope 6:1	Rolling	100	1	0.90	0.90	0.90	0.90	0.90	1.30
Slope 6:1	Rolling	100	1	0.90	0.90	0.90	0.90	0.90	1.30
Slope 6:1	Rolling	100	3	0.66	0.66	0.66	0.66	0.66	1.03
Slope 6:1	Rolling	100	3	0.66	0.66	0.66	0.66	0.66	1.03
Slope 6:1	Rolling	100	5	0.48	0.48	0.48	0.48	0.48	0.88
Slope 6:1	Rolling	100	5	0.48	0.48	0.48	0.48	0.48	0.88
Slope 6:1	Rolling	100	7	0.35	0.35	0.35	0.35	0.35	0.88
Slope 6:1	Rolling	100	7	0.35	0.35	0.35	0.35	0.35	0.88
Slope 6:1	Rolling	100	9	0.26	0.26	0.26	0.26	0.26	0.88
Slope 6:1	Rolling	100	9	0.26	0.26	0.26	0.26	0.26	0.88
Slope 6:1	Mountainous	100	1	0.79	0.79	0.79	0.79	0.79	1.15
Slope 6:1	Mountainous	100	1	0.79	0.79	0.79	0.79	0.79	1.15
Slope 6:1	Mountainous	100	3	0.58	0.58	0.58	0.58	0.58	0.91
Slope 6:1	Mountainous	100	3	0.58	0.58	0.58	0.58	0.58	0.91
Slope 6:1	Mountainous	100	5	0.43	0.43	0.43	0.43	0.43	0.78
Slope 6:1	Mountainous	100	5	0.43	0.43	0.43	0.43	0.43	0.78
Slope 6:1	Mountainous	100	7	0.31	0.31	0.31	0.31	0.31	0.78
Slope 6:1	Mountainous	100	7	0.31	0.31	0.31	0.31	0.31	0.78
Slope 6:1	Mountainous	100	9	0.23	0.23	0.23	0.23	0.23	0.78
Slope 6:1	Mountainous	100	9	0.23	0.23	0.23	0.23	0.23	0.78

# Appendix D NCHRP 911 Rollover Probability

Rollover probabilities reported by Sheikh et al. (2019) are shown in Figure D.1, Figure D.2 and Figure D.3.

Figure D.4: Rollover probabilities by slope width for shoulder width < 1.2 m on the left; reproduced in metres on the right (Sheikh et al. 2019)

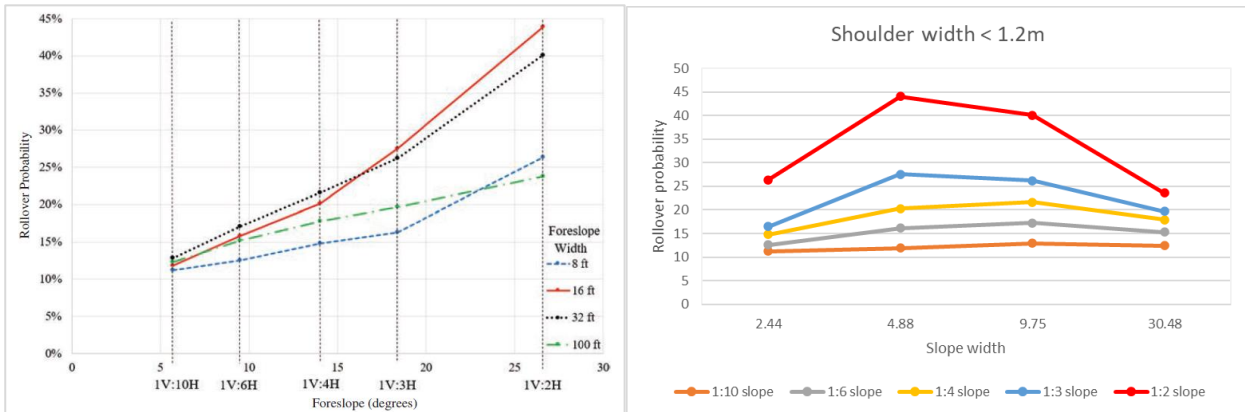


Figure D.5: Rollover probabilities by slope width for shoulder width > 1.2 m on the left; reproduced in metres on the right (Sheikh et al. 2019)

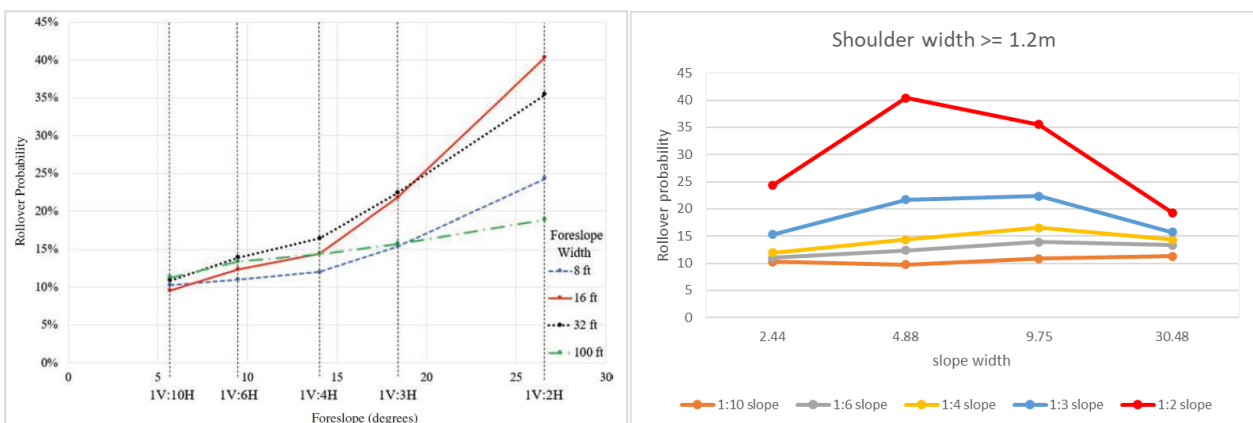


Figure D.6: Revised rollover probabilities by slope width (for shoulder width < 1.2 m on the left; and shoulder width >= 1.2 m on the right)

