Rollover Crashes: Road Design Risk Factors and Infrastructure Solutions

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2 authors:

Chris Jurewicz
SafeMobility

Farhana Ahmed
Monash University (Australia)

Austroads

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Rollover Crashes: Road Design Risk Factors and Infrastructure Solutions

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Prepared by

Chris Jurewicz and Farhana Ahmed

Project Manager

Peter Ellis

Publisher

Austroads Ltd.
Level 9, 287 Elizabeth Street
Sydney NSW 2000 Australia
Phone: +61 2 8265 3300
austroads@austroads.com.au
www.austroads.com.au

Abstract

Rollover crashes are an undesirable outcome in a substantial proportion of casualty crashes on high-speed roads. Rollovers are especially over-represented in run-off-road crashes due to their direct interaction with the roadside geometry.

This project sought to identify and quantify road and roadside design factors associated with rollover events in run-off-road crashes on high-speed rural roads and with high-severity outcomes. However, the data analysis provided largely non-statistically significant results, and few conclusive factors can be drawn from this work due to data limitations. Therefore, expected inputs to the update of the *Guide to Road Design Part 6* are not available from this work. The update to the *Guide to Road Design Part 6* will therefore use an alternative or theoretical method for estimating rollover crash risk as input to run-off-road crash mitigation. The literature review did reconfirm known contributing factors including sharp curvature, lack of sealed shoulders, roadside slopes and ditches, hitting unforgiving roadside objects (high-severity risk) and vehicle factors.

Keywords

Rollover, AusRAP, run-off-road crashes, roadside

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About Austroads

Austroads is the peak organisation of Australasian road transport and traffic agencies.

Austroads' purpose is to support our member organisations to deliver an improved Australasian road transport network. To succeed in this task, we undertake leading-edge road and transport research which underpins our input to policy development and published guidance on the design, construction and management of the road network and its associated infrastructure.

Austroads provides a collective approach that delivers value for money, encourages shared knowledge and drives consistency for road users.

Austroads is governed by a Board consisting of senior executive representatives from each of its eleven-member organisations:

- Transport for NSW
- Roads Corporation Victoria
- Queensland Department of Transport and Main Roads
- Main Roads Western Australia
- Department of Planning, Transport and Infrastructure South Australia
- Department of State Growth Tasmania
- Department of Infrastructure, Planning and Logistics Northern Territory
- Transport Canberra and City Services Directorate, Australian Capital Territory
- Department of Infrastructure, Transport, Cities and Regional Development
- Australian Local Government Association
- New Zealand Transport Agency.

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Summary

Rollover crashes are an undesirable outcome in approximately one third of run-off-road casualty crashes on high-speed roads. The project aimed to quantify roadside design factors associated with rollover outcomes in run-off-road crashes on high-speed roads. It then sought to suggest roadside management techniques to reduce such risk.

AusRAP and crash data from Victoria were used to develop statistical models, quantifying significant road, roadside and vehicle design attributes associated with the occurrence of run-off-road casualty crashes, probability of a rollover, and the probability of fatal and serious injury outcomes in such a crash. The models were able to measure the effect of the significant road design attributes on these outcomes indicated by crash modification factors, or CMFs.

A literature review was also undertaken as a complement to the modelling task to help determine the extent and severity of rollover crashes and to identify crash contributing factors and measures that may be implemented to reduce crash occurrence and severity. Key findings from the literature review can be found within this report.

The data analysis provided largely non-statistically significant results, and few conclusive factors can be drawn from this work due to data limitations. Therefore, expected inputs to the update of the *Guide to Road Design Part 6* are not available from this work. The update to the *Guide to Road Design Part 6* will therefore utilise an alternative or theoretical method for estimating rollover crash risk as input to run-off-road crash mitigation.

Indicative results from the modelling showed that run-off-road casualty crash risk was increased, in descending order of influence, by:

- tight curvature
- the presence of an intersection
- high traffic volumes
- lack of audio-tactile linemarkings (ATLMs)
- moderate pavement condition (vs good)
- lack of sealed shoulders.

Rollover risk was very low when a roadside object was hit and higher when no object was hit. The risk of severe outcomes was high for impacts into non-forgiving roadside objects such as trees, poles and drainage structures, compared to not hitting an object. This result was generally true regardless of a rollover event.

Motorcyclists were the least prone to rollover in a run-off-road casualty crash, but the outcomes were most likely to be severe. Vehicles most prone to rollover were light commercial vehicles and large heavy vehicles (no meaningful change in severe outcome probability).

These findings will be considered as background to roadside design, crash-predictive modelling, and management guidance. Road safety measures were also suggested for targeted crashes which confirms existing Austroads guidance. Also, note that while the term ‘clear zone’ has been used in this research to align to the 2010 version of the *Guide to Road Design Part 6*, this approach is being replaced by other project work to move to a considered risk approach.

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1. Introduction

1.1 Background

Rollover crashes (rollovers) are an undesirable outcome in a substantial proportion of casualty crashes on high-speed roads. Rollovers are represented in run-off-road crashes due to their direct interaction with the roadside geometry. The accepted knowledge is that these crashes result in high-severity outcomes due to the mix of speed, gravity and human vulnerability to head injuries during rollover.

This project sought to identify and quantify roadside design factors associated with rollover outcomes in run-off-road crashes, and their severity, on high-speed roads and, if possible, suggest roadside design and management techniques to reduce such risk.

Improved understanding of the roadside features which contribute to vehicle rollovers and their severity will be used to inform future Austroads design practices and cross-sectional guidance, and practical applications suitable for implementation on a network-wide basis through upgrade programs. This should lead to a reduction in vehicle rollover and run-off-road crashes and a consequential decrease in fatal and serious injuries.

1.2 Objectives

The key objectives of this project were to:

- Identify the factors that may contribute to the occurence and severity of rollover crashes.
- Determine the level of risk associated with road and roadside factors that may contribute to rollover crashes.
- Investigate the
  - application of statistical models that estimate the risk of a rollover crash that are associated with road and roadside risk factors
  - collation of available Australian National Risk Assessment (ANRAM) or AusRAP data as a means by which a data set can be created for safety analysis of relevant road design factors.
- Identify best practice measures that will reduce the risk and severity of rollover crashes.
- Identify areas of current practice, as provided in the Austroads guides that may be revised in light of the project outcomes.

1.3 Scope

The scope of this project was to:

- review current best practice in relation to the prevention of vehicle rollover
- analyse currently available rollover crash data involving all vehicle types; i.e. motorcycles, cars, heavy vehicles (HVs)
- identify all crash statistical data, if possible, including run-off-road crashes where a rollover potentially should have occurred but did not occur

- identify practical applications suitable for implementation on a network-wide basis, including indicative costings (i.e. assist in the network-wide decision-making process, which includes self-explaining roads, consistent corridor treatment, factors to be considered for run-off-road (ROR) crashes and therefore the need for targeted approaches)
- identify those areas within the parts of the Austroads Guides where revision/rewording may be required
- identify direct linkages that will be required to be made with the ‘Philosophy of Road Design’ within the *Guide to Road Design* (Austroads 2016), the *Guide to Road Safety Part 9* (Austroads 2008) and the *Guide to Traffic Management Part 13* (Austroads 2017a).

2. Methodology

The tasks and methods applied in delivery of this project are outlined in this section.

2.1 Literature Review

A literature review was undertaken to examine recent research relevant to the role of road design in rollover crashes. The review sought to identify factors that may contribute to the occurrence and severity of rollover crashes, and to identify measures that may be applied to address them.

The review focussed on road safety and design literature, rather than vehicle dynamics or design sources.

The M.G. Lay library, Australia's leading transport library, located at ARRB, was used to identify and access references for the literature review. The library has access to the international TRID database, which includes material in the Australian Transport Index, TRB proceedings, NCHRP, Accident Analysis and Prevention, and other academic journals.

2.2 AusRAP and Crash Data

Nearly 87 000 km of AusRAP carriageway data (compatible with ANRAM) and the associated crash data was provided in-kind by the participating jurisdictions. This enabled a national-level analysis of relevant road design factors affecting rollovers in run-off-road crashes. Most of the data was related to state-controlled roads in rural areas of Victoria, Queensland, New South Wales and South Australia.

Table 2.1 outlines the data that was collected. Some of the datasets lacked traffic volumes (annual average daily traffic (AADT) that is necessary for further analysis.

Table 2.1: AusRAP data

State	Crash data	AusRAP/ANRAM	Comments
New South Wales	Obtained	Obtained	20 500 km of data was provided but 15 200 km lacked AADT data
Victoria	Obtained	Obtained	20 200 km of data was provided, but 4 200 km lacked AADT data
Queensland	Obtained	Obtained	34 800 km of data was provided
South Australia	Obtained	Obtained	11 200 km of data was provided but 9 500 km lacked AADT data

Following consultation with Austroads, only the Victorian AusRAP data was used in further analysis. This was dictated by the available budget, the completeness of AusRAP data, and the suitability of crash data for the project objectives. Section 5 provides additional discussion of the data issues.

The Victorian AusRAP data was collected during 2014–15 financial year, with some fields requiring an update. The speed limit data was replaced to provide a more accurate dataset, and some duplication of road segments in the data was removed. The missing AusRAP Victorian AADT data was sourced from VicRoads. All other AADT data was also updated.

Victorian casualty crash data for the study period of five years (2012–16) was then linked to AusRAP data at 100 m segment intervals using latitude and longitude as the link. Crash data was categorised into run-off-road and other crash data types, and by severity. Rollover status was established for each crash based on the sub-DCA (Definition for Coding Accidents) coding in the crash data. The run-off-road crashes were then categorised by their direction to mark the specific roadside into which the vehicle crashed. This relational database was then used to construct datasets for statistical modelling and analysis.

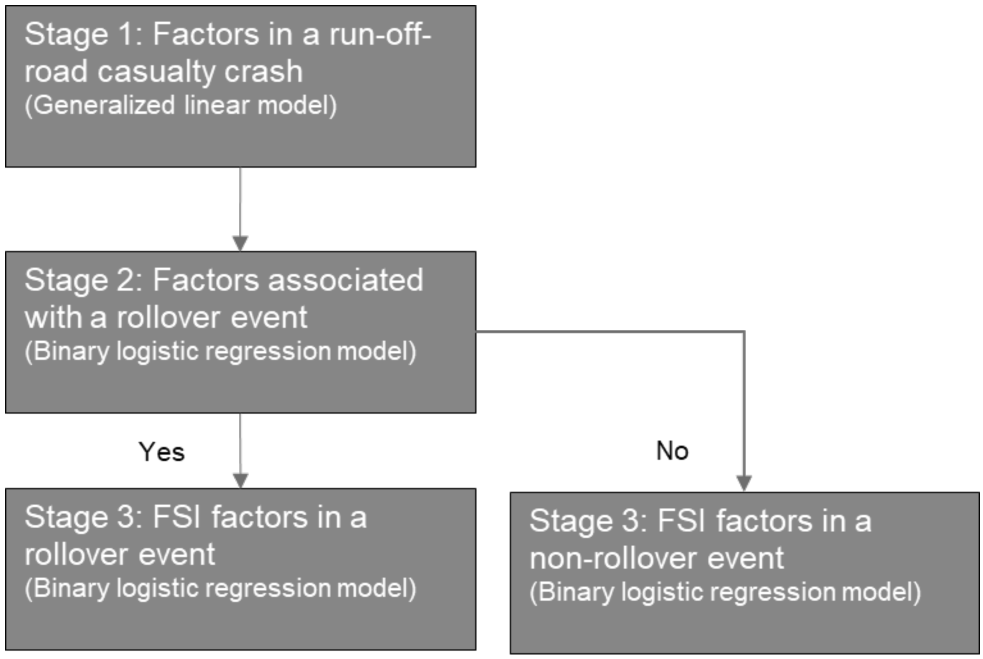
2.3 Modelling Methods

Initially, a univariate descriptive trend analysis of run-off-road rollover casualty crash attributes was conducted. This preliminary analysis of road, traffic and vehicle attributes helped to determine the potential variables for the modelling approach.

Figure 2.1 shows the statistical modelling approach adopted to identify and quantify the factors associated with a rollover in run-off-road casualty crashes and their severity. As suggested by the univariate analysis results, the modelling was based on data from rural undivided highways in Victoria, with speed limits between 80 km/h and 110 km/h, i.e. the road environment most prone to the target crash type.

The rollover event is one of the outcomes of a run-off-road casualty crash. The outcome may or may not be severe, hence the following three-stage modelling approach was necessary to better understand the risk of rollover occurrence.

Figure 2.1: Modelling approach to identify and quantify fatal and serious injury (FSI) factors



Stage 1

A run-off-road casualty crash was a precursor to a rollover event that may occur in a roadside. Thus, it was important to identify and quantify the significant risk factors affecting the number of run-off-road casualty crashes over a given period (a crash frequency model).

Crash count is a non-negative, discrete variable. As counts may not follow the normal distribution, it is appropriate to use generalised linear models such as Poisson regression and Negative Binomial regression (Cameron & Trivedi 1998). Both the Poisson regression model and Negative Binomial regression model were tested to identify which one was more appropriate. In addition, a zero-augmented model was also applied to address the zero inflation in the database. The Akaike information criterion, the ratio of the 'residual deviance and residual degrees of freedom' and the overall model p-values were used to assess the model fit (Fridstrøm et al. 1995).

The basic model for run-off-road casualty crash frequency took the following underlying structure (Equation 1). This structure was suggested as optimal to the task of crash frequency modelling through application of many alternative techniques by many authors (e.g. as reviewed by Roque & Cardoso 2014). The model form accounts for logical and observed differences in the way that independent variables affect the dependant variable.

$$ROR = exp\ (\beta_0) \times AADT^{\beta_i} \times \exp\ (\sum_{i=2}^{n} \beta_i \times x_i) \qquad 1$$

where

ROR = the predicted number of casualty run-off-road crashes per 100 m segment over a five-year period

AADT = the average annual daily traffic applicable to the section

β_i x x_i = model parameters for independent explanatory variable categories related to road infrastructure and operation present in the road segment (e.g. sealed shoulder width 1.0–2.4 m)

Model data was used to relate roadside design information to the same side of the road into which the run-off-road crash occurred.

Variables were checked for mutual correlations, and those highly correlated were excluded. The model was constructed and run in R[1] statistical software.

Stage 2

Given a run-off-road casualty crash occurred, this binary logistic model identified and quantified significant risk factors affecting the probability of a rollover event. The model took the underlying mathematical structure shown in Equation 2 (Tabachnick & Fidell 2001, Freedman 2009).

$$\text{Pr (Rollover)} = \frac{1}{1+\exp\ (\sum_{i=1}^{n} \beta_i \times y_i)} \qquad 2$$

where

Pr (Rollover) = a probability that a run-off-road casualty crash will contain a rollover

β_i x y_i = model parameters for independent explanatory variable categories, related to road infrastructure and vehicle involved in the crash

[1] R is a programming language and software environment for statistical computing.

The second form of model (stage 2) aimed to identify and quantify the factors contributing to the probability of a rollover event once a run-off-road casualty crash occurred. The model was based on run-off-road casualty crash dataset for the high-speed roads, enriched with available AusRAP road design features applicable to the 100 m segment where the crash occurred.

Stage 3

Given that a run-off-road casualty crash occurred, it was then necessary to identify and quantify the risk factors that such crash resulted in severe injury outcomes (fatal and serious injuries (FSIs)). Another binary logistic regression was constructed, based on the same crash data associated with AusRAP data for the relevant crash segment.

Two FSI models were created, taking the same logistic form as shown in Equation 2 – one for a scenario with a rollover, and one for a scenario without a rollover. The second model was intended as a check against suggesting design recommendations with unintended consequences, such as those leading to higher severity in case of non-rollover crash.

The focus of the modelling approach was to maximise the number of statistically significant risk factors (i.e. meaningful for guidance), rather than maximising predictive accuracy of the model (i.e. useful for prioritisation of road sections). The method adopted for this project was developed by the ARRB project team in consultation with Prof Denny Meyer, Professor Statistics, Department of Statistics, Data Science and Epidemiology, Swinburne University of Technology from Swinburne University.

2.4 Suggested Guide Amendments

The project modelling and literature findings were used to systematically identify locations in selected Austroads guides to suggest updates in guidance to reduce rollover occurrence and severity. The following guides were reviewed:

- *Guide to Road Design Part 3: Geometric Design* (Austroads 2016)
- *Guide to Road Design Part 6: Roadside Design, Safety and Barriers* (Austroads 2019)
- *Guide to Road Safety Part 9: Roadside Hazard Management* (Austroads 2008)
- *Guide to Traffic Management Part 13: Road Environment Safety* (Austroads 2017a).

3. Literature Review

A literature review was conducted to identify:

- factors that may contribute to rollover occurrence
- the level of risk associated with factors that contribute to rollover occurrence and severity
- countermeasures to reduce the risk of rollover occurrence and severity.

The magnitude of the risk factors that contributed to crash occurrence and severity was not well-documented. Some of the potential countermeasure to reduce rollover risk which were identified in the review included installing barriers, straightening sharp curves and improving lighting conditions. The following section documents the outcomes of the literature review in more detail.

3.1 Risk Factors for Occurrence and Severity of Vehicle Rollover Crashes

Vehicle rollover crashes may occur in two manners, tripped and non-tripped, and occur most often when a vehicle runs off the road (Austroads 2014a, 2014b). Tripped rollover crashes occur as a result of external forces when a vehicle strikes an object, such as a curb (Plaxico et al. 2005) or a tree/pole (Austroads 2014a, 2015), while a non-tripped rollover crash may occur as a result of abrupt steering and speed, and surface friction (Phanomchoeng & Rajamani 2012).

Austroads (2010, 2014b) investigated run-off-road crashes in rural and urban areas across Australia and New Zealand. Key findings of these studies, which in part cited the outcomes of research that investigated rollover crashes, were that:

- On the basis of crash data from Victoria, NSW, South Australia and the ACT (2006 to 2010), 12.8% of urban run-off-road casualty crashes were of the rollover type.
- Based on 2005 Australian crash data, one in every three vehicle fatalities (on any road type) involved a vehicle rollover (Fréchède et al. 2009).
- In North Carolina, USA, Hummer et al. (2010) found that, though vehicle rollovers amount to 6% of collisions occurring on two-lane urban roads, they amount to 16% of crashes resulting in serious or fatal injuries.
- About 3 in every 100 collisions with fixed roadside objects in urban areas resulted in a rollover crash. The object most commonly struck was a guardrail, which contributed to 5.7% of all rollover crashes in urban environments (Viner 1995).
- Roadside run-off areas or clear zones should be traversable and be free of holes or ‘snags’ that may result in a vehicle losing control and overturning (Austroads 2010).
- Johnston et al. (2006) found that run-off-road casualty crashes involving roadside hazards or rollovers were the largest contributor to serious injury and death crashes, which accounted to 40% of all road fatalities in Victoria.
- Rollover collisions and partial overlap collisions (e.g. up to 25% offset) are more severe than other types of run-off-road crashes and head-on collisions Austroads (2014b).

It was also reported that the likelihood of a rollover would be affected by the roadside slope and the density of the soil (less dense soil would allow tyres to plough into the soil according to Viner (1995)). Viner (1995) also indicated that slopes and ditches were the major causes of rollovers crashes in rural (83%) and urban (73%) road environments and that on two-lane rural roads:

- 78% of slope rollover fatalities occurred on roads where the speed limit was greater than 55 mph (i.e. 90 km/h)
- 53% of slope rollover fatalities occurred on curves, and 37% on grades.

Kordani and Tavassoli (2015) undertook dynamic vehicle simulations to analyse the effects of shoulder width and edge drop-off on vehicle rollovers. The shoulder width showed a modest negative relationship with the rate of rollover. The results showed that increasing width from 1m to 2.6m decreased the rate of rollover by 2%.

Cruz et al. (2017) investigated the rollover potential of heavy vehicles using reliability analysis. The study specifically investigated horizontal curve design in relation to heavy vehicle rollover risk. Different design scenarios and heavy vehicle types were modelled. This analysis showed that higher speed and tighter horizontal curve radius affects the probability of heavy vehicle rollover. For heavy vehicles with high centre of gravity, e.g. a double decker bus, the minimum radius should be between 40 m and 170 m for speeds between 40 km/h and 80 km/h respectively. For vehicles with lower centre of gravity travelling at the same speed range, the minimum radius should be between 60m and 100m.

Graham et al. (2014) indicated that for divided roads with traversable medians in the USA, the median down slope ratio had a negative relationship with rollover crash frequency. A flatter slope, i.e. an increase in the H:V slope ratio, was correlated with a decrease in the number of all casualty rollover crashes in the median, all other factors being equal.

Graham also indicated that:

- The provision of a median shoulder also reduced the rollover risk. For each 0.3 m of shoulder, the FSIs were expected to reduce by 13% in median rollover crashes (four-lane freeways). The effect was even stronger (22% reduction) for medians with median barriers.
- The presence of a curve in a road section increased the risk of injury rollover crashes by 30% on traversable medians in four-lane freeways.

Carrigan and Sheikh (2017) analysed changes in rollover probability due to vehicle type. Their conclusions were not statistically significant despite a large crash dataset, but the following was indicated:

- Passenger vehicles may have the lowest rollover probability.
- Pickup trucks and semi-trailers may be 50% more likely to rollover than passenger vehicles.
- Rigid trucks may be twice as likely to rollover as passenger vehicles.
- Motorcycles could be as much as four times more likely to rollover than passenger vehicles.

McLean et al. (2005) analysed rollover crashes in South Australia in each of two ways. Firstly, from data collected by South Australian police crash reports (1999 to 2003 inclusive), and secondly from an in-depth study of rural crashes, which collected in-depth information associated with rollover crashes on rural roads within 100 km of Adelaide, South Australia between March 1998 and February 2000. Key findings from each of their two-part investigations are discussed in the following sections.

South Australian police rollover crash reports

- While 4.5% of all casualty crashes were of the rollover type, these types of crashes resulted in 10% of all fatal and serious injury crashes.
- 41% of all rollover crashes resulted in a fatality or a serious injury, compared to 16.9% for other types crashes.

- Rollover casualty crashes were almost 2.4 times more likely to result in a fatality or serious injury crash than all other combined types of crashes.
- 92.3% of rollover casualty crashes resulted in a fatality, hospitalisation or treatment in a hospital, compared to 63.4% for all other crash types.
- 42.1% of rollover casualty crashes occurred along curved sections of road compared to 14.7% of other types of crashes; three times more likely to occur along a curve than other types of crashes.
- 26.8% of rollover casualty crashes occurred on roads at grade or on a crest or at the bottom of a hill, compared to 18% for other types of crashes.
- 82% of rollover casualty crashes occurred on roads speed zoned at 100 or 110 km/h compared to 16% of other types of crashes. Furthermore, 90% of rollover crashes occurred on roads speed zoned at 80+ km/h or more, compared to 25% for all other types of crashes.
- 25% of all casualty crashes on roads speed zoned at 100 or 110 km/h were of the rollover type.
- Utility/4WD vehicles were involved in 15% of all rollover casualty crashes, compared to 5% for other types of crashes; three times more likely to be involved in a rollover crash than other types of crashes. The data also revealed that trucks were involved in 9% of rollover casualty crashes, compared to 4% of other crash types.

South Australian in-depth rollover crash investigations

- 64 of 236 rural crashes investigated involved a vehicle rollover.
- 19 (30%) of the rollover crashes occurred without a prior collision, 24 (37%) occurred when the vehicle struck a tree or embankment, while the remaining 21 (33%) rollover crashes occurred when a vehicle struck another vehicle.
- Of the rollover crashes that did not involve the hitting of another vehicle (i.e. 43 of 64)
  - 22 (50%) occurred on a curve
  - 15 (35%) involved a 4WD, light van or heavy vehicle
  - 11 (58%) of 19 rollover crashes that occurred without a prior collision involved a 4WD, light van or heavy vehicle.

Hosseinpour et al. (2016) investigated the contributary impact of road characteristics to the occurrence of rollover crashes. Their study applied crash prediction models to estimate the number of rollover crashes as a function of road geometry, the roadside environment and traffic conditions.

Once the models were developed their outputs were compared with crash data collected along 448 sections of Malaysian federal road to determine the model best fit for rollover crash frequency. Road design variables including sharp horizontal curvature, high speed limit, number of access points and the presence of a median, increased the frequency of rollover events.

High speed limit and presence of curves were also found to contribute to rollover occurrence in North Carolina (Dabbour 2017). However, Dabbour did not indicate any quantitative value to show the extent of risks associated with these road design factors impacting rollover occurrence.

Anarkooli, Hosseinpout & Karfar (2017) investigated the factors affecting severity of single vehicle rollover crashes on federal roads in the Malaysia Peninsular. The results suggested that a combination of roadway conditions and vehicle attributes impacted the severity of rollover crashes. The significant roadway conditions included presence of a horizontal curve, poor road lighting, presence of median barriers and narrow shoulder width.

Carrigan and Sheikh (2017) investigated the run-off-road rollover crash severity in high-speed free-flowing roads in the USA. Results indicated that the probability of an FSI outcome was doubled if a rollover occurred, resulting in approximately 52% chance of severe casualty outcome. Overall, there was a 65% probability of a risk of an injury outcome in a rollover event.

A study by the National Highway Traffic Safety Administration (NHTSA), US Department of Transportation (Deutermann 2002), which investigated the characteristics of fatal rollover crashes (1995 to 2000) concluded that:

- Most fatal rollover crashes are single vehicle.
- Rollover crashes are more likely to result in fatalities than other crash types.
- Rollover crashes make up about 20% of all fatal crashes.
- Fatal light truck rollover crashes were seen to increase, particularly among SUVs and vans.
- Fatal SUV rollovers more than doubled since 1991, increasing faster than any other type of light trucks.
- Increases in fatal light truck fatalities, generally involving SUVs, have been offsetting the decreases in fatal passenger car rollover crashes.
- Increases in fatal light truck rollovers may be considered a result of their growing proportion of the vehicle mix instead of the degradation in the design and construction of the vehicles involved.
- Speed was an important factor in fatal rollovers, with most crashes occurring on roads with a speed limit of 55 mph (approx. 90 km/h) or more.

3.2 Summary of Rollover Risk Factors

The findings from the literature review suggest that there were several road and roadside design considerations that are likely to contribute to vehicle rollover occurrence. These factors included curve radius, centreline medians, and road lighting conditions. Table 3.1 summarises the identified rollover risk factors and provides quantification of rollover likelihood and severity where available.

Table 3.1: Summary of rollover risk factors in reviewed literature

Factors contributing to rollover events	Effect on rollover likelihood or severity (quantified where available)	References
High speed (limit)	Likelihood increased	Hosseinpour et al. (2016)
	Likelihood increased	Dabbour (2017)
	Likelihood of a rollover in run-off-road event increased by 6% for each 5 mph (8 km/h) increase in departure speed	Carrigan and Sheikh (2017)
	Likelihood increased on tight curves for HVs	Cruz, Echaveguren and Gonzalez (2017)
	Associated with FSI crashes	McLean et al. (2005)
	Associated with fatalities	Viner (1995)
Roadside soil softness	Likelihood increased	Viner (1995)
Curves (presence)	Curves over-represented compared to comparison sites	Viner (1995)
	Likelihood increased	Dabbour (2017)
	Likelihood of median rollover increased by 30% on four-lane freeways with traversable medians. No change for non-traversable medians	Graham et al. (2014)
	Severity increased	Anarkooli, Hosseinpour and Karfar (2017)
Sharp curves	Likelihood increased	Hosseinpour et al. (2016)
	Likelihood increased for HVs	Cruz, Echaveguren and Gonzalez (2017)

Factors contributing to rollover events	Effect on rollover likelihood or severity (quantified where available)	References
Shoulder width	Likelihood of FSI crash associated with unsealed shoulders	McLean et al. (2005)
	Likelihood increased by 13% for each 0.3 m narrowing of traversable median shoulder (four-lane freeways) Likelihood increased by 22% where sealed shoulder was not present, if median had barriers	Graham et al. (2014)
	Likelihood of rollover event increased by 2% for 1.0 m shoulder compared with a 2.6 m shoulder, if drop-off was present (i.e. drop-off was the controlling risk factor)	Kordani and Tavassoli (2015)
	Severity increased when the shoulder was narrow	Anarkooli, Hosseinpour and Karfar (2017)
Ditches	Identified as a risk factor	Viner (1995)
Number of access points	Likelihood increased with number	Hosseinpour et al. (2016)
Poor lighting conditions	Likelihood increased	Hosseinpour et al. (2016)
	Severity increased	Anarkooli, Hosseinpour and Karfar (2017)
Presence of median	Likelihood increased	Hosseinpour et al. (2016)
	Severity increased	Anarkooli, Hosseinpour and Karfar (2017)
Median width	Likelihood increased by 7% for each added metre on four-lane freeways with traversable median. Similar result for non-traversable medians	Graham et al. (2014)
Median barriers	Severity increased	Anarkooli, Hosseinpour and Karfar (2017)
Presence of curbs	Potential risk due to vehicle dynamics	Plaxico et al. (2005)
Batter slopes (medians)	Change in crash frequency per unit change in median slope ratio: –3 (freeway), –22% (non-freeway) on four-lane roads with traversable medians –12% to –38% on four-lane roads with median barriers (barrier-dependent) Likelihood increased by 14% on six-lane roads with traversable medians	Graham et al. (2014)
	Associated with fatalities	Viner (1995)
Median batter down-slopes only (foreslopes)	Likelihood of rollover event in run-off-road event increased with steeper down slope X(H):1(V) — Relative rollover risk –10 — 1.0 –6 — 2.0 –5 — 2.7 –4 — 3.8 –3 — 5.7 –2 — 9.2	Carrigan and Sheikh (2017)
Batter down-slope width	Likelihood of rollover in run-off-road event was 2.6 higher for 16 ft (4.9 m) width than that of 8 ft width (2.4 m)	Carrigan and Sheikh (2017)

The literature review revealed that rollover crashes:

- represent a relatively low proportion of crashes that occur, although they result in a substantial proportion of fatal and serious crashes
- result in high-severity outcomes
- are mainly caused by roadside slopes and ditches
- are at greater risk of occurring on curved and non-level sections of road than other crash types
- most often occur on high speed zoned roads (i.e. 80 km/h or greater)
- are a greater risk for SUVs and trucks than for cars.

3.3 Measures to Reduce the Risk of Vehicle Rollovers

Table 3.2 provides an overview of the countermeasures suggested by the previous studies to reduce or minimise the occurrence or severity of rollover crashes. These are based on the observed relationships by the studies and do not imply causality.

Table 3.2: Summary of countermeasures to reduce the risk of vehicle rollovers

Countermeasures	References
Increasing sealed shoulder width	McLean et al. (2005)
	Hosseinpour et al. (2016)
	Kordani and Tavassoli (2015)
	Anarkooli, Hosseinpour and Karfar (2017)
	Austroads (2014b)
Reducing speed limit	Hosseinpour et al. (2016)
	Austroads (2014b)
	McLean et al. (2005)
Adding audio-tactile edge lines	Hosseinpour et al. (2016)
	McLean et al. (2005)
	Austroads (2014b)
Guardrail installation	Hosseinpour et al. (2016)
	Anarkooli, Hosseinpour and Karfar (2017)
	Graham et al. (2014)
Guardrail installation with curb configuration	Plaxico et al. (2005)
Increasing curve radius	Hosseinpour et al. (2016)
	Austroads (2014b)
Reducing median slope steepness	Graham et al. (2014)
	Carrigan and Sheikh (2017)
Road delineation improvement	Austroads (2014b)
Removal of objects obstructing sight at curves and intersections	Austroads (2014b)
Speed cameras	Hosseinpour et al. (2016)

In summary, the measures to reduce or minimise rollover crashes are as follows:

- roadside run-off areas or clear zones should be traversable and be free of holes or ‘snags’ that may result in a vehicle losing control and overturning
- flatten batters providing hazard-free uniform surfacing to reflect current guidance
- minimise curves and maximise curve radius

- ensure roads are delineated to current practice (i.e. audio-tactile edge lines and guideposts)
- ensure that curves are delineated with guideposts and chevron alignment markers (CAMS), and have advanced curve warning signs provided in accordance with current standards
- provide road grades that are as flat as practicable
- provide speed limits that are compatible with road cross-section, and vertical and horizontal alignments on rural roads
- provide roadside infrastructure that minimises the likelihood of vehicles (particularly light trucks and heavy vehicles) tripping on a fixed object.

4. Modelling

Sections 4.1 to 4.4 present the summary of analytical results and their interpretations.

4.1 Analysis of Rollover Crashes

A preliminary univariate analysis was carried out on Victorian crash data covering the period 2006–16 for time-trend and 2012–16 for the rest of the analysis. This provided an overview and descriptive trends relating to the rollover problem to inform further analysis. Extension of these findings to other jurisdictions should be subjected to separate testing.

Table 4.1 provides a summary of the key findings of the rollover casualty crashes analysis presented in Appendix A. Initially, this univariate analysis was limited to high-speed roads in rural and urban environments.

Univariate analysis of crash data showed that most rollover crashes occurred on high-speed undivided rural roads (≥ 80 km/h). Accordingly, the project direction focussed on this road network subset.

Further, the analysis showed that run-off-road casualty crashes involving single vehicles were the most common rollover crash type. The second most common crash type was loss-of-control on-carriageway crashes, mainly by motorcycles. This crash type was out of scope for the project.

Table 4.1: Key findings of rollover casualty crashes

Key findings	Appendix figure/table
• Rollover casualty crashes are predominately as a result of loss-of-control (LoC) types of crashes: on- and off-road.	Figure A 1
• Over one-third of LoC casualty crashes involved a rollover event.	Figure A 2
• LoC crashes on the curves appear to be a smaller problem than on straights. However, since less than 10% of rural roads are curves, the number of LoC crashes on curves are over-represented compared to LoC crashes on straights. • Rollover events seem to be over-represented in run-off-road to the left/right crashes where no object was hit. This applies on straights and curves. • Rollover events also appear to be over-represented in LoC crashes where a vehicle did not leave the carriageway (i.e. not run-off-road).	Figure A 3
• 95% of LoC casualty crashes involve single vehicles (the investigation can focus on these crashes only and remain relevant).	Figure A 4
• A large number of LoC 'on-carriageway' crashes involved motorcycles. • There was no run-off-road crash – vehicle stayed on the road. The most likely road user to be injured in this scenario (rollover or not) was the vulnerable one. • Run-off-road to the left and right without hitting a hazard and without rolling over, had substantial proportion of motorcycle involvement. • Run-off-road crashes on curves had a higher proportion of crashes involving motorcycles (rollover or not).	Figure A 5 Figure A 6
• Time series analysis: While the overall occurrence of run-off-road crashes was steady across the years (r with a slight down-trend), the number and overall proportion of run-off-road crashes resulting in rollover crashes has been increasing since 2013, especially for motorcycles and utilities.	Figure A 7, Figure A 8, Figure A 9

Key findings	Appendix figure/table
• Trees and poles account for the most numerous types of hazards hit, and the most severe crashes. Rollover was much less likely in these crashes (6–11%) and did not add to average crash severity (where sufficient data is available) • While run-off-road crashes where no hazards were hit were the second most types of crashes, they were most prone to a rollover event (78%). The rollover event did not add substantially to the average crash severity. • Safety barriers (guardrail) involvement represented a smaller but significant group in run-off-road crashes. Rollover risk is comparatively low to moderate (18%) but results in higher average crash severity. • Embankments are also struck in a significant number of run-off-road crashes, that the rollover risk is moderate (38%), but the severity appears to be somewhat lower.	Figure A 10

These findings are indicative only. They may be influenced by internal correlations between the data, and for this reason, the findings presented in the following sections should be treated with caution.

4.2 Factors Affecting Rollover Crashes

The combined AusRAP and crash dataset (Section 2.2) was used to develop a Negative Binomial statistical regression model which identified and quantified significant factors increasing the likelihood of the occurrence of a run-off-road event – a precursor to a rollover in this project. This was Stage 1 of the modelling process (Section 2.3).

Then, a binary logistic model was developed from crash data supplemented by AusRAP data to quantify factors increasing the probability of a rollover event, should a run-off-road casualty crash occur. This was Stage 2 of the modelling.

In the Stage 3 modelling, two additional binary logistic models were developed to find factors increasing probability of severe injury outcomes (FSI) in a crash with a) rollover event and b) no rollover event. The last model was intended as a check against suggesting design amendments with unintended consequences.

The following sections present the findings and interpretation of the modelling task. A number of crash modification factors (CMFs) were developed to account for the effect of different design choices on the risk of a run-off-road casualty crash, a rollover, and an FSI crash outcome.

The model results are presented in Appendix A.2.

4.3 Risk Factors for Run-off-road Casualty Crashes

In this project, a run-off-road event was considered a precursor to a rollover. The main findings were the CMFs with different design conditions and choices affecting frequency of run-off-road crashes. A change in a CMF can be expected to change the predicted mean number of crashes.

The detailed modelling results are presented in the Appendix A.2.

The following road attributes were found to be significant factors affecting the risk of run-off-road casualty crashes:

- road curvature
- roadside object offsets
- intersection presence
- traffic volumes

- audio-tactile linemarking treatments (ATLMs)
- pavement condition
- sealed shoulders.

Road curvature was a strong and consistent predictor of run-off-road casualty crash risk. Table 4.2 shows the relationship between the road segment radius and the run-off-road casualty CMF. All CMFs reported were statistically significant at $p < 0.05$ unless otherwise indicated. This finding confirms the findings in Austroads (2014a, 2017b).

Table 4.2: Run-off-road casualty CMFs for segment radius

Road curvature(1)	CMF
Straight or gently curving (R > 900 m)(2)	1.00
Moderate (R 500–900 m)	2.60
Sharp (R 200–500 m)	6.19
Very sharp (R < 200 m)	9.42

1 Based on AusRAP coding.
2 All road segments were 100 m long, hence a single curve could comprise several segments of different radii.

Typical offset to unforgiving objects (clear zone) broadly confirmed previous findings from Austroads (2014a), although the CMF magnitude was somewhat lower. Table 4.3 shows the significant results for run-off-road casualty CMFs.

Table 4.3: Run-off-road casualty CMFs for the roadside object offset

Roadside object offset(1)	CMF
(>= 10 m)	1.00
(5 to < 10 m)	1.14
(1 to < 5 m)	1.68

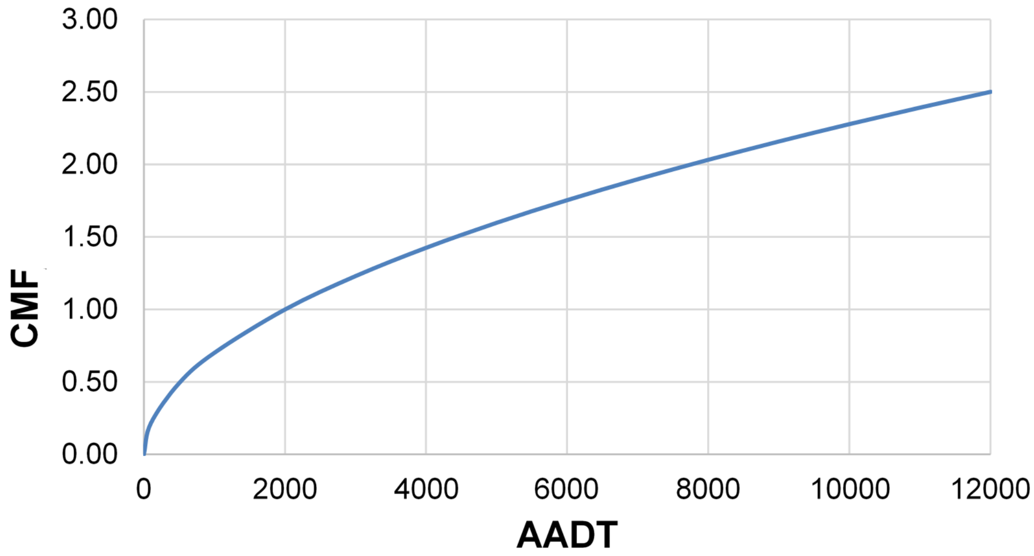
1 Based on AusRAP coding. Applies to the same side into which the crash would have occurred.

There were a few instances of object offsets in the 0–1 m range, hence the results were not significant for this group, and were omitted from the table.

The presence of an at-grade intersection, other than a roundabout, increased the crash risk estimate, CMF of 1.66 (mostly priority T- and cross-intersections in this dataset). Roundabouts were shown to also potentially increase run-off-road casualty crash risk, although this finding was not statistically significant.

Higher traffic flows increased the frequency of run-off-road casualty crashes. Doubling of AADT led to crash rate estimates increasing by a factor of 1.4. The general relationship between AADT and the frequency of run-off-road casualty crashes was as shown in Figure 4.1.

Figure 4.1: Effect of increasing AADT on likelihood of run-off-road casualty crashes



Note: CMF of 1.00 set at average AADT value of 2000 vpd.

Where there were no audio-tactile linemarking (ATLMs) or shoulder rumble strips, the crash estimate increased by a factor of 1.23.

Medium[2] rather than good pavement condition led to a higher crash risk estimate by a factor of 1.10 (p 0.05 – 0.10). As there were very few cases of poor pavement condition, this effect was not statistically significant.

Lack of a sealed shoulder increased the crash risk estimate, CMF of 1.09 (p 0.05 – 0.10).

Many other factors were evaluated via the modelling process and were shown to be non-significant contributors to run-off-road casualty crash risk as noted below:

- Speed limit (80–110 km/h), with only 90 km/h showing up as significantly high-risk compared to others. This reflects anecdotal VicRoads feedback that 90 km/h roads were initially 100 km/h roads with exceptionally high crash history.
- Lane width – too little variation in the data given the broad AusRAP categories.
- Median type (e.g. wide painted) or presence of centreline rumble strips – too little variation in the data.
- Roadside object type – previous research showed this to be related to severity outcomes, but not significant in this analysis.
- Grade – more recent research showed much lower effect of grade alone on run-off-road crashes, unless combined with sharp curves (Austroads 2017b).
- Skid resistance – AusRAP's definition did not align well with SCRIM[3].
- Delineation – too little variation in the data (mostly adequate).

[2] Pavement condition as defined by AusRAP.
[3] SCRIM – sideways-force coefficient routine investigation machine.

4.4 Risk Factors for Rollover Events and Crash Severity

The modelling results provided an indication of some FSI CMFs, as shown in Table A 2; however, due to the limited data available, most results were not considered statistically significant. The analysis indicated results that seemed counter-intuitive to what may have been expected. The FSI CMFs attributed to a rollover crash were found to be only slightly higher than a crash not involving a rollover. This outcome needs to be considered with some caution due to the data limitations (refer to Section 5.2), and so, drawing firm conclusions may not be representative of findings from a larger set of data.

The full model results are presented in Appendix A.2.

Road design factors

The significant road design CMFs influencing rollover and FSI risks are presented in Appendix A.2.

Presence of a curve increased the chance of a rollover crash by a factor of 1.56, but this did not affect FSI outcome probability.

A rollover was much more likely to occur when no object was hit in the crash, as shown in Table 4.4. This ‘no-object-hit’ crash category was likely to include roadsides containing driveable batters (up or down); however, this could not be tested from the available data. A rollover event did not contribute to the risk of FSI outcomes in these no-object-hit crashes (tested by a separate model, not statistically significant).

The stopping effect of hazardous roadside objects was clear in the case of trees. Rollover risk was only 3% compared with not hitting an object. Of the various roadside objects hit, the ‘other fixed’ category, which included culverts and other drainage structures, had the highest risk of rollover but still only 8% of that when nothing was hit.

In essence, hitting an object during a crash minimised the rollover risk. There was evidence that barriers (all types) decreased the risk of rollover compared to not hitting an object, but this risk was slightly higher than for some other roadside objects (e.g. tree or pole). This is a reasonable observation given the design of barriers. Severity CMFs for barriers were not statistically significant, i.e. not different compared to not hitting an object.

While the rollover risk was low when roadside objects were hit, the severity consequences were not. The Stage 3 group of models showed that hitting trees, poles and ‘other fixed’ objects was associated with the significantly higher probability of FSIs regardless of whether a rollover occurred. This is shown in Table 4.4 where robust findings were available.

Table 4.4: Object-hit CMFs affecting probability of rollover and FSI severity

Object hit	Rollover CMF	Rollover FSI CMF	No Rollover FSI CMF	Comments
Embankment(1)	0.08	–	–	
Fence	0.04	–	–	
Barrier	0.04	–	–	
Guide post	0.04	–	–	
Other fixed (incl. culverts and drainage structures)	0.08	2.22	–	Not likely to rollover, but twice as likely to be severe compared with not hitting anything.
Pole	0.01	-	1.87	
Tree	0.03	2.13	2.42	

Object hit	Rollover CMF	Rollover FSI CMF	No Rollover FSI CMF	Comments
Traffic sign	0.06	–	–	
Other	0.03	–	–	
Nothing	1.00	1.00	1.00	Comparison baseline

1 *Austroads (2014b) identified these to be a cutting embankment/wall in the reviewed Victorian crash data. Vehicles running off downhill a fill embankment only would not be coded as hitting an object.*

Note: Only significant results shown.

A wider offset to hazards generally increased the risk of rollover, i.e. rollover risk increased where there was more hazard-free space available. Only one hazard offset category was statistically significant, but the relationship was logically correlated with the no-object-hit category.

A higher AADT reduced the FSI risk, but only when no rollover event was present (0.89 when volume doubled from 2000 vpd to 4000 vpd).

From the road design perspective, the key risk for rollover was availability of object-free roadsides, and this translated to low-moderate FSI risk. Rollover risk was very low when non-forgiving roadside hazards were hit, but the severity of a rollover was generally much higher than when no object was hit.

Speed limit was tested for its effect on rollover and FSI probability, but it did not add to the models' ability to predict these outcomes (non-significant). Speed limits were generally strongly correlated with other variables.

Vehicle factors

Vehicle type had greater influence on the probability of a rollover event than any other variable, as shown in Table 4.5. The rollover likelihood was highest when a light commercial vehicle (rigid), a minibus or a panel van were involved in the crash.

Large heavy vehicles (rigid heavy vehicle, prime mover, B-double and prime mover only) also carried a very high risk of rollover, compared to passenger cars.

Table 4.5: Vehicle CMFs affecting probability of rollover and FSI severity

Predictors		Rollover CMF	Rollover FSI CMF	No Rollover FSI CMF
Vehicle manufacturing year	Before 2012	–	1.51[1]	–
	2012 or after		1.00	
Vehicle type	Station wagon & utility	1.42	–	
	Heavy vehicle (rigid); prime mover, prime mover B-double & prime mover only	2.79	–	
	Motorcycle, moped & motor scooter	0.26	1.54	
	Light commercial vehicle (rigid), minibus & panel van	3.35	–	
	Passenger car	1.00	1.00	
Number of persons		–	1.12	–

1 *Lower level of statistical significance, p-value in the range 0.05–0.1.*

Note: Only significant results shown.

Station wagons (SUVs) and utilities also had a 42% higher risk of a rollover compared with passenger cars.

Motorcycles were the least likely to be involved in a rollover event (tendency to slide), but the severity of their crashes was the highest.

Table 4.5 shows only statistically significant results; however Table A 2 in Appendix A.2 shows that the non-significant severity CMFs for different vehicle types were consistently higher than the baseline value of 1.00 for cars. This may be indicative of larger vehicles being associated with higher severity of run-off-road crash outcomes.

Run-off-road rollover crashes involving vehicles manufactured before 2012 had a much higher risk of resulting in severe injuries than post-2012 vehicles (CMF of 1.51 with p-value 0.05–0.10). This may be related to poorer passive safety designs in pre-2012 vehicles. These older vehicles were not actually found to be more prone to rolling over in run-off-road crashes (i.e. the variable was not significant).

Risk of a severe injury in a rollover crash increased by a factor of 1.12 with each additional vehicle occupant.

5. Discussion

The following discussion topics aid in the interpretation of the findings. Some limitations of the project are highlighted together with recommendations for further research.

5.1 Interpretation

Interpreting the findings of the project may be aided by presenting typical rollover risk scenarios. Table 5.1 shows four cases of a typical run-off-road casualty crash on a high-speed road, arranged by the probability of a rollover event in response to the provided crash and design conditions. The scenarios were selected to show a graded decrease in rollover probability.

The overall trend shown in Table 5.1 shows that FSI risk could be inversely proportional to rollover risk. This is an observation rather than a robust causal relationship, as high-severity outcomes are certainly possible where rollover is very likely.

Table 5.1 also shows that the absolute difference in FSI probability does not differ greatly between crashes with and without rollover events.

Table 5.1: Selected rollover risk scenarios

Rollover risk scenarios	Rollover probability in run-off-road casualty crash	FSI probability	
		Rollover	No rollover
High: A light commercial vehicle runs off on a curve with a wide clear zone, hits nothing	97%	40%	38%
High: A car runs off the road on straight and hits nothing in presence of a wide clear zone	82%	36%	38%
Moderate: A car loses control on a curve and hits culvert headwall located 2 m from the edge	36%	56%	48%
Low: A car runs off the road on a curve and hits a tree in a clear zone < 5 m	15%	54%	60%
Low: A motorcyclist on a new bike falls on a straight section and hits a tree	3%	68%	60%

The project demonstrated the potential for statistical modelling of big data such as AusRAP to improve understanding of the complex relationships between road infrastructure and safety outcomes. The project then showed how this knowledge can be applied to suggest changes in practice guidance.

5.2 Data Limitations

Approximately 87 000 km of AusRAP data from four states was available for the project in October 2017. For some states, AADT information was missing for large parts of the network. Crash data in some states lacked the detailed information required for this project (e.g. type of object-hit). All provided datasets required substantial quality management resources to check for missing data, make corrections, attach all-casualty crash data to AusRAP segments, and to construct relational databases needed to extract datasets for modelling.

Data from only one state could be processed in the context of the available budget and timeframe. Based on the balance of AusRAP data quality and crash data detail, Victorian data was selected with Austroads' approval. This means that caution needs to be exercised when applying the project findings to other jurisdictions.

This project focussed on run-off-road casualty crashes as the baseline level of severity. An observation was made that a no-object-was-hit crash was associated with a very high risk of rollover but relatively low risk of FSI and should be understood in this context. This relationship could be very different for run-off-road crashes which do not result in an injury of any kind. There is a valid question whether a rollover event could be a causal factor in changing non-casualty crashes (ie property damage only crashes) to casualty crashes.

It may be possible that rollover crashes are reported to police more frequently (and thus included in the analysis) than non-rollover crashes, due to the greater need for rescue and clean-up after a rollover. Potential over-reporting could reduce the average severity of rollover crashes (more of the less-severe crashes in the sample). This reporting bias was considered but could not be tested with the available data.

These limitations of casualty crash data analysis may be partially mitigated by using evidence inputs from rollover crash lab tests with dummies. Such tests would need to cover a wide range of rollover scenarios found in crash data (e.g. partial rollovers on the side, or rollover without roof compression).

5.2.1 Batter Slope

The project sought to verify slope of batters in context of their potential for rollover risk and safety outcomes. The project results were not able to inform this. The main issue was the AusRAP data, which is coded using specific logic of noting the most severe roadside object in any 100 m segment. Every roadside had potentially multiple characteristics which could influence run-off-road crash outcomes, e.g. drainage channel, batter slope, and objects within the batter. These were not recorded by the AusRAP process. AusRAP roadside batter slope categories were also not aligned with design categories.

Object-hit records in crash data were shown to be a better predictor of rollover and severity than AusRAP roadside object-type categories. The latter data was also tried in the models but produced fewer statistically significant results. A separate verification exercise showed that AusRAP roadside hazard types did not correlate well with actual object-types hit in each crash in the dataset and relate to the coding technique discussed above.

5.2.2 Barriers

The severity CMF results for barriers were not statistically significant. As a check, a different severity model was developed which ignored rollovers altogether (not included in this report). This model also did not provide a clear result about barriers (mostly guardrail). In all models the severity CMFs for barriers were close to the value of 1.00, i.e. the baseline 'hit nothing', which makes achieving statistical significance difficult, even with large datasets. Further, the result also suggests a significant error range, meaning that there could be large variability in the safety performance of barriers. This gap in knowledge was also raised in Austroads (2014a).

5.3 Safe System Relevance

This project focussed on factors responsible for FSI risk when a run-off-road casualty crash occurred. The model findings presented in Section 4.4 (detailed in Table A 2) confirmed the evidence gathered in previous Austroads studies (e.g. Austroads 2014a, 2017b). Unforgiving roadside hazards were found to be the main contributors to run-off-road crash severity.

This project also quantified additional FSI risk factors in run-off-road crashes: involvement of older vehicles (pre-2012), motorcycles, and multiple vehicle occupants, when a rollover occurred. This new knowledge may help to target road design and road safety practice to identify 'high-severity rollover' locations and propose treatments. Such locations may include rural road curves with wide offsets to hazards such as trees (i.e. rollover is more likely with a high crash severity outcome).

5.4 Knowledge Gaps and Research Opportunities

Studies based on more precise road design and crash data could be carried out in future to answer the design questions more precisely. These studies could be based on a sample of crashes with supporting road data information collected on site. Such studies would be lower in data cost than collection of data for an entire road network. Research topics could include the effect of batter slope on rollover probability, and the effect of barrier type on probability of severe crash outcome.

5.5 Summary of Findings

Findings of this project were drawn from the literature review (Section 3) and modelling results (Section 4.2 and Section 4.3), with both sources of knowledge generally providing the same findings. The following treatments could be considered for mass-action programs to reduce occurrence of high-severity run-off-road crashes with and without rollovers:

- increasing sealed shoulder and driveable verge widths (also increases offset to hazards)
- providing audio-tactile linemarking (ATLM) on edge lines
- installing barriers in roadsides and medians to shield errant vehicles from hazards (forgiving systems preferred)
- improving the forgiveness of other fixed objects, e.g. drainage structures
- minimising or removing intersections
- reducing road curvature.

The literature suggested the following additional safety measures:

- reducing speed limit
- using speed cameras
- reducing batter slope
- improving road delineation
- removing objects obstructing sight lines at curves and intersections.

The suggested amendments to the Austroads guides are contained in Section 6.1.

Other observations and suggestions in the reviewed guides where omissions and inconsistencies were observed with respect to recent Austroads research were passed on to Austroads for future consideration.

6. Conclusions and Suggested Amendments

This project aimed, through the application of big data (linked AusRAP and crash databases) and crash-predictive modelling, to quantify significant road, roadside and vehicle design factors associated with rollover events and severe injury outcomes in run-off-road casualty crashes on high-speed roads.

The literature review revealed that rollover crashes are a relatively low proportion of crashes but result in a substantial proportion of FSIs. It was also identified that there is a greater risk of a rollover crash occurring on curved sections of road, in high speed zones (90 km/h or greater), and with SUVs and/or trucks being at greater risk of rolling over when compared to cars.

The data analysis also revealed that a rollover casualty crash was more likely to occur on a horizontal curve, involve a light commercial vehicle, minibus or panel van and occur when no object was hit, largely confirming the findings in the literature review.

The project outlined measures that could be implemented on a network-wide basis, but was unable to quantify design-related changes, e.g. batter slopes, to minimise the likelihood and FSI outcome of a rollover crash.

Several possible amendments to Austroads guides were identified and these are contained in Section 6.1.

6.1 Suggested Guide Amendments

Table 6.1 – Table 6.4 outline measures and suggested guide amendments which may be considered to reduce occurrence and severity of rollover events in run-off-road casualty crashes on high-speed rural roads. Any suggested wording amendments are shown in ***bold italics***.

Table 6.1: Suggested amendments to *Guide to Road Design Part 3: Geometric Design*

Section	Existing guide text	Suggested amendments
6.2	Intersections should not be hidden behind crest curves as shown on Figure 6.4. Intersections should be located with care to ensure that adequate sight distance is available on each approach. Intersections located in long sag vertical curves generally provide good sight distance to the intersection area.	Consider adding wording about removing or combining existing intersections where possible.
Table E 1	Requirements and restrictions for narrow median with wire rope safety barrier: Profiled (audio-tactile) edge line on both sides of median required when median width 2.2–6.2 m.	Reword to highlight the use of audio-tactile linemarking (ATLM). General finding was that lack of a ATLM increased the crash estimate by a factor of 1.23. This was not specific to the narrow medians; however, the benefit of providing ATLMs can be extended to narrow medians. Suggest inclusion of ATLMs is considered for all narrow medians.
F.2	A wide centreline treatment (WCLT) is a dividing line, including audio-tactile linemarking (ATLM), that is 1 m wide (centre of full line to centre of full line) for application mainly in higher speed environments (posted speed limits of 80 km/h or greater). This treatment provides additional separation between vehicles travelling in opposite directions to improve safety, in particular to reduce the potential for head-on crashes. The use of WCLT together with ATLM, as shown in Figure F 1, has demonstrated a substantial reduction in the number of crashes on higher volume two-lane rural roads.	Reword to highlight the use of ATLM. This general approach is supported by the findings to reduce risk of run-off-road casualty crashes.
F.6.1	The presence of culvert headwalls or narrow structures (bridges, culverts or floodways) are to be considered when installing WCLT because roadside hazards close to the road can increase the severity of crashes...Where the resultant length of narrow WCLT would be more than 100 m, excluding tapers, then the linemarking over the structure should be installed as standard centre-linemarking with adoption of ATLM.	Reword to highlight the use of ATLM. This general approach is supported by the findings to reduce risk of run-off-road casualty crashes.
F.6.1	The presence of culvert headwalls or narrow structures (bridges, culverts or floodways) are to be considered when installing WCLT because roadside hazards close to the road can increase the severity of crashes.	Consider removing or changing to 'increase the likelihood of casualty crashes.' Severity modelling showed that hazard offset did not have a measurable effect on increasing casualty crash severity. Austroads (2014a) showed a minor effect in relation to barriers which was largely not significant either.
J.1	For most curves, the average car driver can achieve a suitable transition path within the limits of normal lane width. However, with particular combinations of high speed, heavy vehicles and a large difference in curvature between successive geometric elements, the resultant vehicle transition path can result in encroachment into adjoining lanes.	Consider adding text about considering rural arterial speed management solutions (e.g. warning or perceptual) in order to reduce rollover risk on curves for HVs.

Table 6.2: Suggested amendments to *Guide to Road Design Part 6: Roadside Design, Safety and Barriers*

Section	Existing guide text	Suggested amendments
4.2.1	Draft text: Austroads (2011) reported that about 40% of run-off-road casualty crashes occurred on roads where the clear zone exceeded 8 m. It is therefore essential that with this knowledge in mind, designers are aware of potential hazards that may exist beyond the clear zone and further assessment of the risks and treatments is deemed appropriate.	Change to 'Austroads (2014)', i.e. Austroads (2014a) in this study. Consider updating the reference to Austroads (2014a), the final report from that study. The statement is true; however, the Guide should also recognise that a roadside free of objects is also hazardous to errant vehicles.
4.3.1	A roadside hazard is an object or feature located between the edge of a traffic lane and road reserve boundary, or within a median, that could cause significant personal injury (including fatal injury) to vehicle occupants when impacted by an errant vehicle. The road designer should identify and list all roadside hazards within the area of interest (based on clear zone widths). It should be noted that road safety barriers are classified as hazards despite the fact that their sole purpose is to prevent a vehicle from encountering a more severe hazard.	The research findings in this project show that an object-free roadside is a hazard to errant drivers. This was also shown in Austroads (2014a). The wording and philosophy should be reconsidered to suggest that 'roadsides are hazardous to errant vehicles, and the object of design is to minimise fatalities and serious injuries for all road users.
4.3.3	Batters may be hazardous due to the combination of height, slope and surface condition, as well as what may be on the slope or at the base of the embankment. The batter slope has been found to become critical when the slope exceeds 3:1 as vehicles are likely to overturn. It is preferable to prevent errant vehicles travelling onto a steep fill slope, however where this cannot be achieved, a warrant for treatment of fill batters on high-speed roads is shown in Figure 4.5 and an embankment assessment process is described in Section 4.3.5.	The literature review found that the relative risk of a rollover crash increases significantly as batter slopes steepen, e.g. the relative risk of a rollover doubled where a slope increased from 10:1 to 6:1 and compared to a 3:1 slope the relative risk was almost 6 times. The reference to the warrant for treatment of batters, Figure 4.5, should also be reviewed. However, further research is required to develop guidance information. Any change would need to be reflected in other Austroads guides. As an interim the following is suggested: Fill batters may be hazardous due to the combination of height, slope and surface condition, as well as what may be on the slope or at the base of the embankment. ***The relative risk of rollover crashes increases as batter slopes steepen, and batter slopes should be provided as flat as possible***. ~~has been found to become critical when the slope exceeds 3:1 as vehicles are likely to overturn~~.
5.2	A clear, unimpeded roadside gives drivers of errant vehicles an opportunity to reduce speed, recover control of the vehicle, and thereby lessen the severity of the consequences of encroachment into the roadside. Therefore, in these cases, the creation of a safer roadside may involve measures such as: ...provision of shoulders, verges and medians.	Change to 'A clear, unimpeded roadside ***may*** lessen the severity…' Austroads (2014a) demonstrated via referenced US NCHRP research that regaining control and stopping safely was largely a myth when applied to run-off-road events on high-speed roads (although applicable to minor shoulder incursions). It would be therefore more appropriate to modify this statement accordingly.

Section	Existing guide text	Suggested amendments
5.2	A site-specific assessment should be made considering the operating speeds, roadside environment, road users (e.g. motorcyclists and pedestrians), and the benefits and costs of the installation of any safety barrier. A clear, unimpeded roadside gives drivers of errant vehicles an opportunity to reduce speed, recover control of the vehicle, and thereby lessen the severity of the consequences of encroachment into the roadside. Therefore, in these cases, the creation of a safer roadside may involve measures such as: ...Where these or other measures cannot be applied or are considered insufficient and/or impracticable, it may be necessary to consider the provision of road safety barriers or crash attenuators.	Combining the findings of this project with Austroads (2014a) findings suggests that forgiving barriers would be preferable to open roadsides and less-forgiving barriers. Consider rewording the treatment priorities accordingly.
5.4.1	There are two possible treatments for dealing with trees: • Installation of road safety barriers. Provision of barriers will depend on a number of factors relating to site conditions, **crash history**, economics and the environment. However, such action should only be taken where it is determined that collision with the barrier is less severe than collision with the existing hazard (i.e. trees).	Change to 'crash risk'. It is proposed to use objective crash risk of the site rather than crash history, which may be subject to significant statistical variation. Otherwise supported by the findings. Suggest replacing 'crash history' with 'severe injury risk assessment'.
5.4.8	As for other roadside furniture, traffic signal poles **can** pose a hazard for any errant vehicles. They are often necessarily located close to the travelled path at intersections, which could lead to a higher risk of impact, although some measures can be taken to minimise this risk. Such measures include not locating a traffic signal pole on the outside of a curve, setting poles as far back from the travelled path edge as practicable, minimising the number of poles and installing joint-use poles wherever practicable. Provision of high skid resistance at intersections can also reduce the risk of a vehicle losing control at an intersection and skidding into traffic signal poles or other roadside hazards.	Remove 'can' to highlight that they do pose a hazard.
6.3.11	The location of the barrier should be 4 to 5 m from the traffic lane as this offset provides the greater safety benefits compared with other offsets (Austroads 2014).	Not what the Austroads (2014a) report recommended. The recommendation based on research findings was 1.5 m to 5 m. Worth noting this inconsistency for future revisions.
C3.1	Kloeden and McLean (1999) conducted a study of roadside hazard involvement in fatal and severe injury crashes in South Australia. Analysis of fatal crash records for the 12-year period from 1985 to 1996 revealed that 95% of fatal crashes involving a collision with a roadside object occurred between 0 and 10 m adjacent to the road (Figure C3 1). However, the impact of the speed zone and traffic volume as factors influencing crash frequency was not considered.	Old research, out of date. Consider replacing content with newer Austroads research referenced in Austroads (2014a).

Section	Existing guide text	Suggested amendments
Commentary 1	Key factors that may contribute to run-off-road crashes are: *see list in indicated section*	Consider revision using the inputs from this project, the run-off-road casualty crash frequency model. Add the following: • tight curvature • narrow roadside object offsets • presence of an intersection • higher traffic volumes • lack of ATLMs • lack of sealed shoulders.

Table 6.3: Suggested amendments to *Guide to Road Safety Part 9: Roadside Hazard Management*

Section	Existing guide text	Suggested amendments
Summary	Irrespective of the reasons behind a vehicle leaving the roadway, the provision of a forgiving roadside that is free of rigid objects, has flattened, smooth-sloped embankments and no other hazards, will reduce the potential for injury or death.	See the proposed insertion 'potential for ***serious*** injury or death' Also, consider additional wording: 'Such roadside cannot be considered a safe solution, as a proportion of casualty crashes will still result in fatal and serious injuries.'
3	Ideally a roadside environment should be free of any hazards that may increase the severity of a crash, should it occur. Such a roadside would prevent injuries in run-off-road crashes by providing drivers with enough space to regain control of their vehicles and stop safely without colliding with any objects or the vehicle rolling over.	The project findings suggest the second sentence is inaccurate. The word 'prevent' is too definite. The findings show that there is always a residual risk of run-off-road casualty regardless of the roadside design. Roadsides and errant vehicles are not compatible. It is suggested to reword the sentence to something like 'Such a roadside would reduce chances of an injury to vehicle occupants.'
3	Ideally a roadside environment should be free of any hazards that may increase the severity of a crash, should it occur. Such a roadside would prevent injuries in run-off-road crashes by providing drivers with enough space to regain control of their vehicles and stop safely without colliding with any objects or the vehicle rolling over. However, it is usually not possible to construct a road environment completely free of hazards.	This is an idealised scenario. Austroads (2014a) demonstrated via referenced NCHRP research that regaining control and stopping safely was largely a myth when applied to run-off-road events on high-speed roads (although applicable to minor shoulder incursions). This study supports a conclusion that a high-speed roadside environment that is free of hazards is still hazardous to drivers and leads to significant probability of severe injury outcomes. Consider replacing the wording accordingly.

Section	Existing guide text	Suggested amendments
3.2	The types of hazards that may be encountered on roadsides can be divided into six broad categories: rigid objects (trees, utility poles, culvert end-walls, etc.), medians (cross median crashes), embankments and cuttings, open drains, bodies of water, kerbs. In priority order, the following approaches should be taken with these hazards: • removal of the roadside hazard • redesign of the hazard so as to make it traversable • relocate hazard to a location where it is less likely to be struck • replacement of the hazard so that it breaks away or is impact absorbing • shield the obstacle with an appropriate barrier and/or a crash cushion • if none of the above is attainable, delineate the obstacle.	Note in Austroads (2014a) challenged this approach with a caveat that a forgiving barrier would be less severe than an open roadside. See the previous comment.
3.2.1	Where existing trees are within a clear zone, and are deemed to pose a risk, the first option is to remove the tree. Where this is not feasible it may be appropriate to install a safety barrier. The piers of bridges over roads (at overpasses) should desirably be protected by a crash cushion or safety barrier.	Austroads (2014a) challenged this approach with a caveat that a forgiving barrier would be less severe than an open roadside.
3.2.2	Batter slopes (5th paragraph) The preferred treatment option for non-recoverable/traversable slopes and critical slopes is to flatten the slope to 1:4 (V:H) or flatter. Where this cannot be achieved safety barriers will need to be considered for all slopes steeper than 1:3.	Replace with same text as suggested for GRD Part 6, Section 4.3.3: Fill batters may be hazardous due to the combination of height, slope and surface condition, as well as what may be on the slope or at the base of the embankment. The ***relative risk of rollover crashes increases as batter slopes steepen and batter slopes should be provided as flat as possible***. ~~has been found to become critical when the slope exceeds 3:1 as vehicles are likely to overturn~~.

Table 6.4: Suggested amendments to *Guide to Traffic Management Part 13: Road Environment Safety*

Section	Existing guide text	Suggested amendments
5.2.2	As part of the cross-section design, traversable batter slopes and clear zones free of non-frangible objects allow for road users who run off the road to regain control or stop without colliding with hazardous roadside objects.	Austroads (2014a) demonstrated via referenced NCHRP research that regaining control and stopping safely was largely a myth when applied to run-off-road events on high-speed roads (although applicable to minor shoulder incursions). Should consider removing/modifying this statement.

Section	Existing guide text	Suggested amendments
5.2.2	As part of the cross-section design, traversable batter slopes and clear zones free of non-frangible objects allow for road users who run off the road to regain control or stop without colliding with hazardous roadside objects. Austroads (2014b) notes that for clear zones the proportion of the casualty run-off-road crashes in which hazards were struck decreased as the clear zone width increased.	Risk of rollover increases with increasing offset to hazards as shown in this project. Consider removing the red text and replacing it with more appropriate text on reduced severity outcomes in absence of roadside hazards. Austroads (2014a) demonstrated via referenced US NCHRP research that regaining control and stopping safely was largely a myth when applied to run-off-road events on high-speed roads (although applicable to minor shoulder incursions). Presence of a sealed shoulder appears to play some role in regaining control as we see consistently fewer crashes after installation of shoulders. All other loss of control scenarios were shown to result in rapid loss of control and no ability to regain it.
5.2.9	Vehicle run-off-road crashes on rural roads at night might not necessarily involve a failure to detect single objects with which a collision must be avoided, but rather a failure to detect, recognise, and correctly interpret patterns of information from which the position of the vehicle on the roadway and the direction of immediate and subsequent travel can be ascertained.	This sentence is difficult to follow. Consider reviewing it. What evidence is it based on? It would be logical that road alignment is more difficult to follow in darkness.
5.2.2	The cross-section width enables the provision of a forgiving road environment. Sealed shoulders and wide lanes (on two-lane, two-way roads) provide more space for avoiding minor tracking errors which can lead to crossing the centreline or running off the road. A simultaneous increase of lane and shoulder width in curves has been found to increase crash rates (Hanley, Gibby & Ferrara 2000 cited in Elvik et al. 2009). Wider sealed shoulders provide more space for emergency manoeuvres without the road user experiencing a lower friction supply, and provide space for vehicles to stop well clear of the traffic lanes. Narrow shoulders with emergency lay-bys at regular intervals are less likely to provide the same opportunities. Wider sealed shoulders also provide more durable pavement and minimise moisture ingress into the pavement edge near the outer wheel path. Austroads (2015c) highlighted the safety reasons for sealing shoulders and reported that provision of wider sealed shoulders reduces the risk of casualty crashes along rural roads. (Note: Austroads (2015c) quoted in the text is *Road Geometry Study for Improved Rural Safety*, AP-T295-15 (Austroads 2015) in the reference list)	How robust is this secondary reference? Worth revisiting in the future. Generally, wider rural cross-section on curves has been systematically linked to improved safety. See Austroads (2017b) report, Section 3.4.

Section	Existing guide text	Suggested amendments
5.2.2	***Austroads (2014)*** notes that for clear zones the proportion of the casualty run-off-road crashes in which hazards were struck decreased as the clear zone width increased. However, it was also shown that as the clear zones increased the proportion of casualty rollover crashes also increased.	Change the reference. The project findings partially support these earlier findings. Update the reference to Austroads (2014a).
5.2.4	As outlined in Section 5.2.2, Austroads (2014) noted that for clear zones, the proportion of casualty run-off-road crashes in which hazards were struck decreased with **decreased** clear zone width, however the proportion of rollover crashes increased.	Change to 'decreased with ***increasing*** clear zone width'. The project findings partially support these earlier findings. Update the reference to Austroads (2014a).

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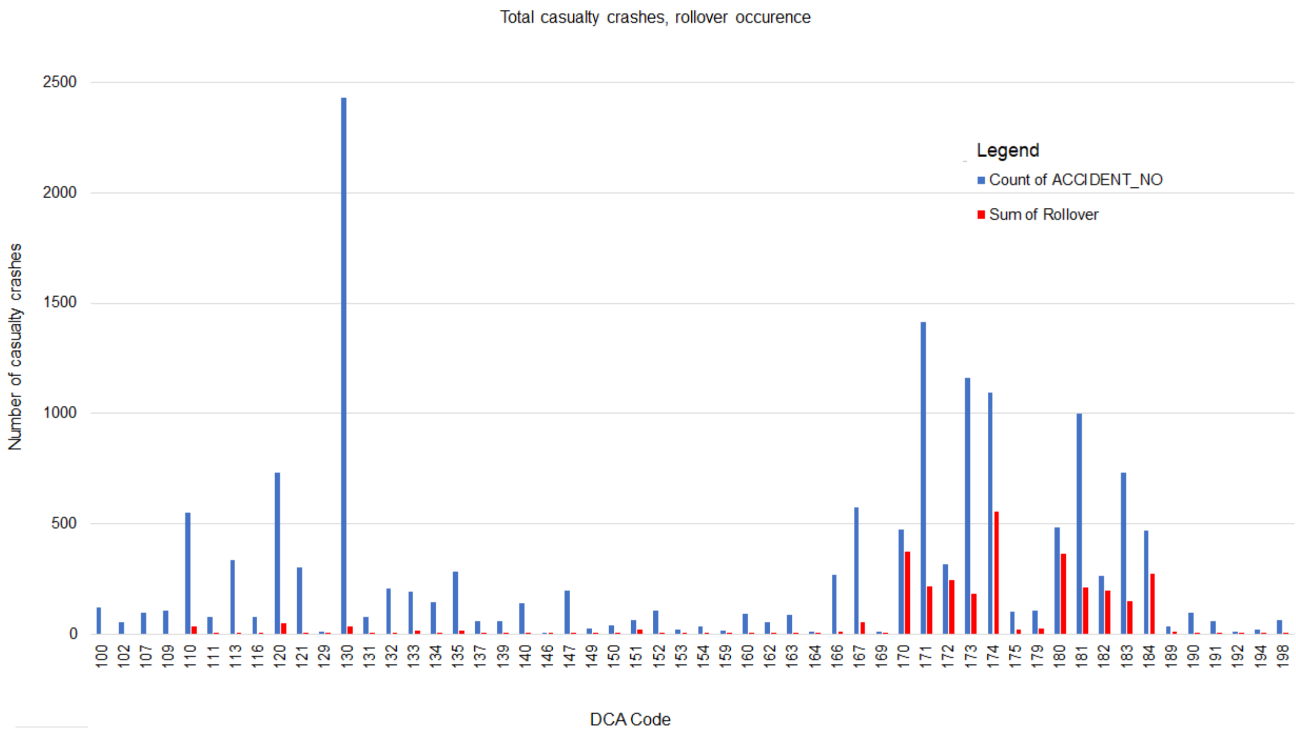
Appendix A Crash Data Analysis

The crash data analysis is presented below.

A.1 Preliminary Analysis

Figure A 1: Total casualty crashes by DCA



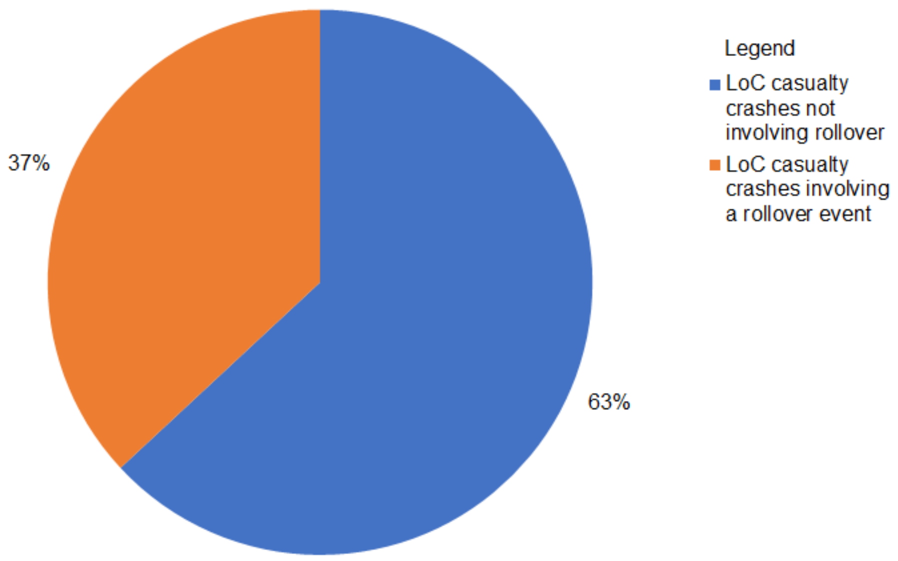
Notes:

Where the number of crash numbers is < 20 and there are no rollovers, the crash detail has not been shown.

DCA Codes 170–179 are loss-of-control casualty crashes on straights.

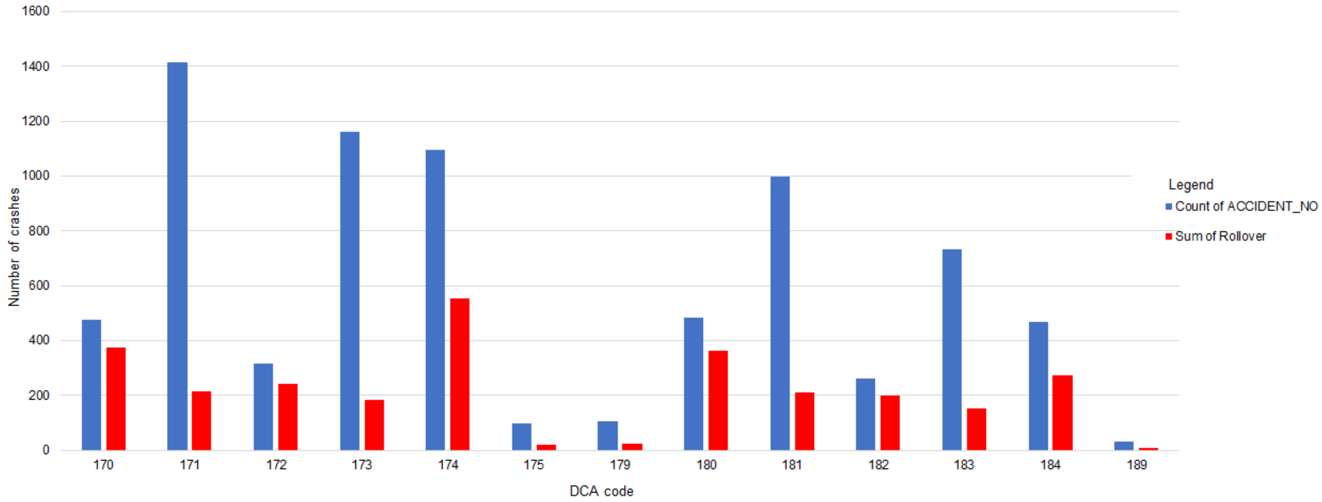
DCA Codes 180-189 are loss-of-control casualty crashes on curves.

Figure A 2: Proportion of loss-of-control (LoC) casualty crashes with rollover



Note: LoC means loss-of-control.

Figure A 3: Loss-of-control casualty crashes and rollover occurrence, by DCA



Notes:

DCA codes 170–179 are casualty crashes on straights.

DCA codes 180–189 are casualty crashes on curves.

DCA codes 170–173 are ROR to the left/right casualty crashes.

DCA codes 171, 173, 181 and 183 are LoC casualty crashes where an object was hit.

Figure A 4: Loss-of-control casualty crashes vs number of vehicles

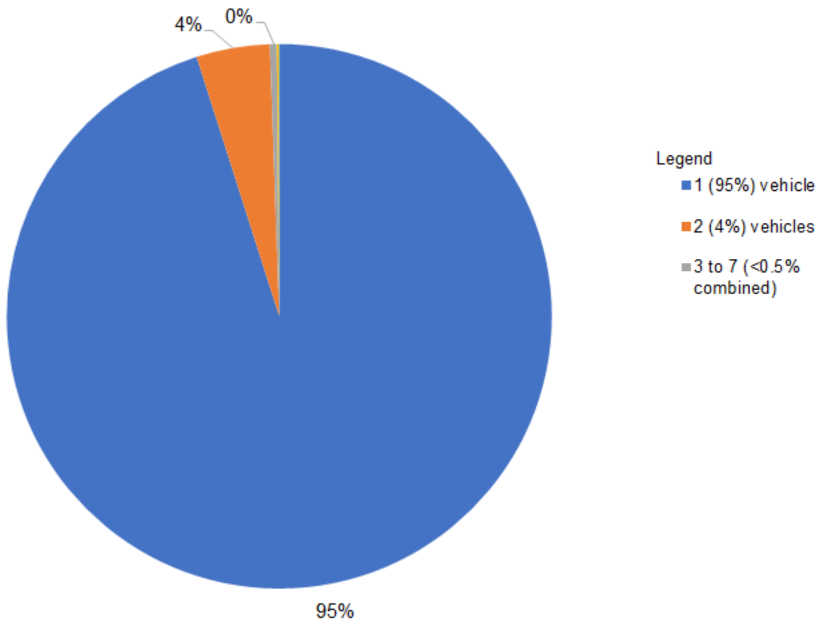
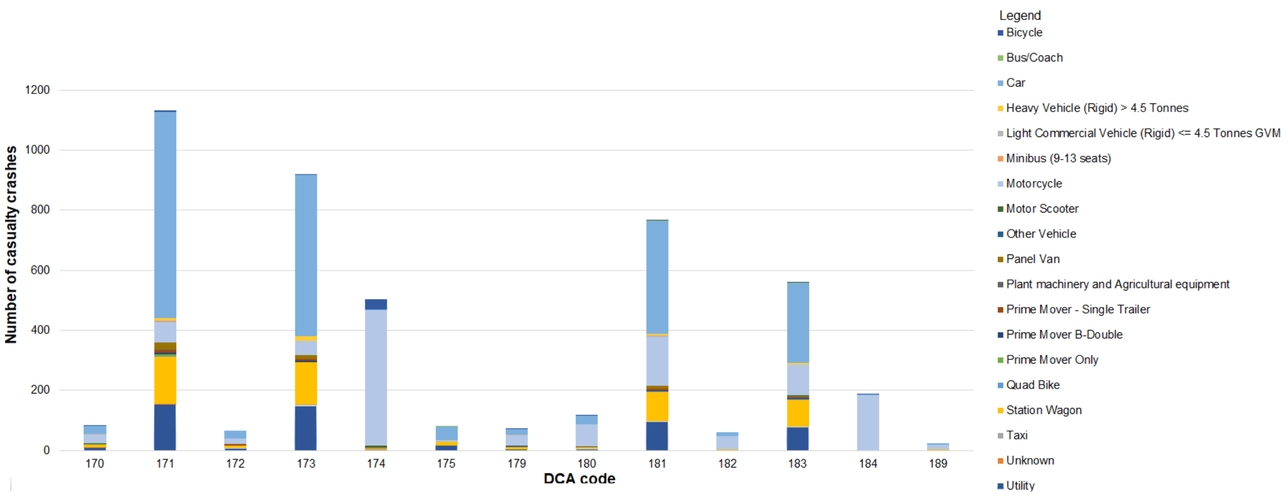


Figure A 5: Loss-of-control single casualty crashes by DCA with no rollover event vs vehicle type



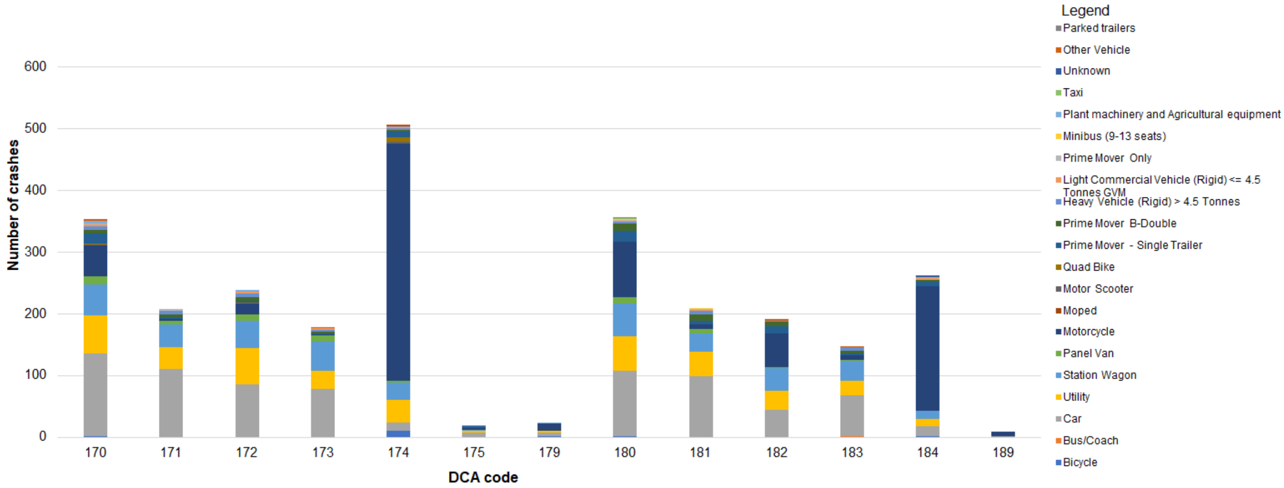
Notes:

DCA codes 170-179 are LoC casualty crashes on straights.

DCA code 174 is a LoC 'on-carriageway' on a straight section of road casualty crash.

DCA codes 180–189 is LoC casualty crash on curves.

Figure A 6: Loss-of-control single casualty crashes by DCA with rollover event vs vehicle type



Notes:

DCA codes 170-179 are LoC casualty crashes on straights.

DCA code 174 is a LoC 'on-carriageway' on a straight section of road casualty crash.

DCA codes 180–189 is LoC casualty crash on curves.

Figure A 7: Single run-off-road casualty crashes by year and rollover event

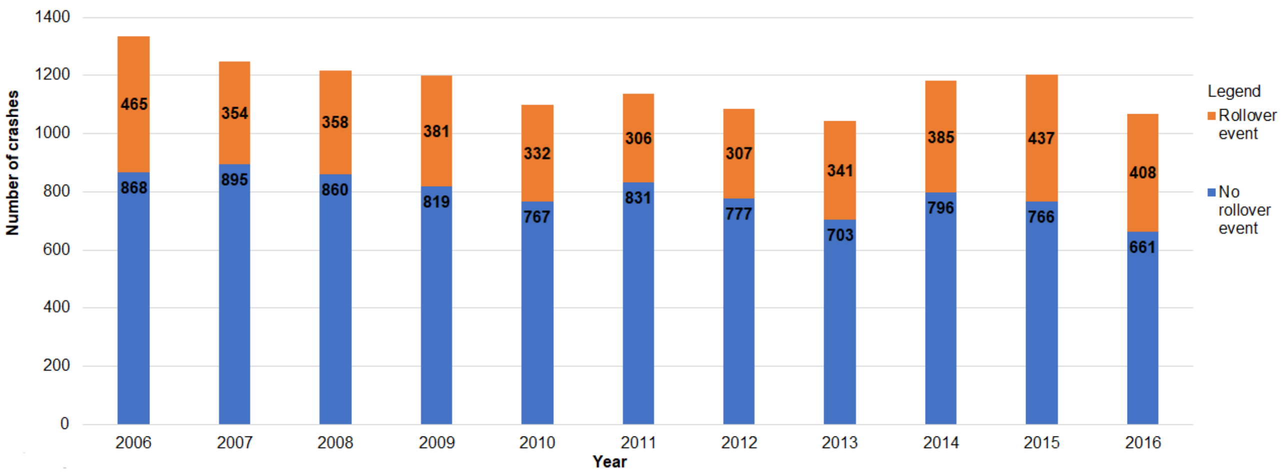


Figure A 8: Single run-off-road casualty crashes with rollover event, by year and vehicle type

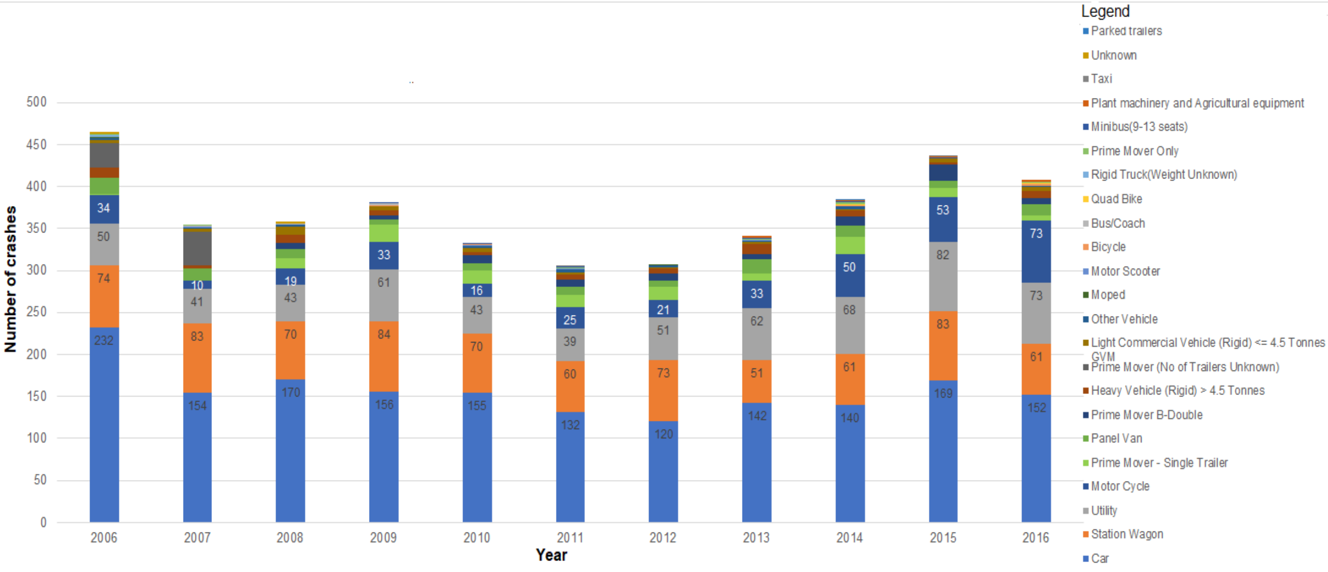


Figure A 9: Single run-off-road casualty crashes with no rollover event, by year and vehicle type

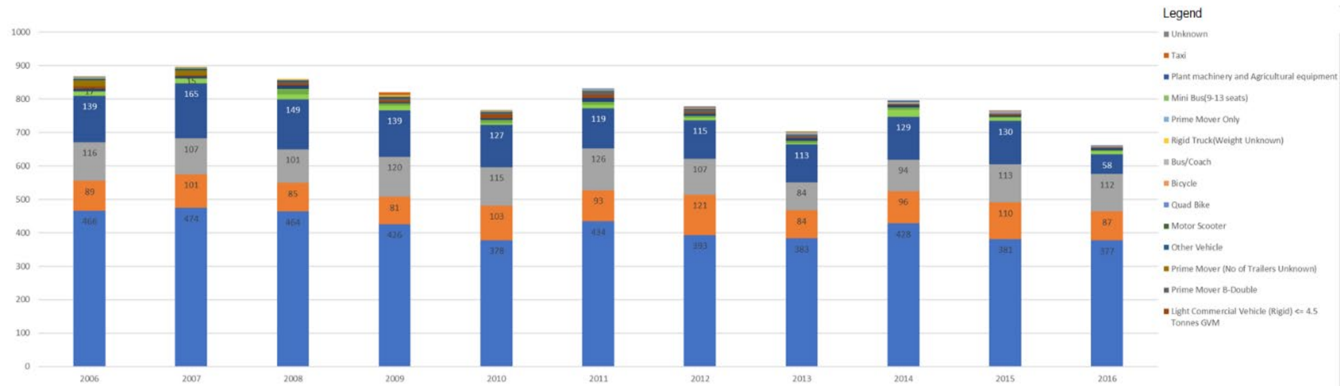
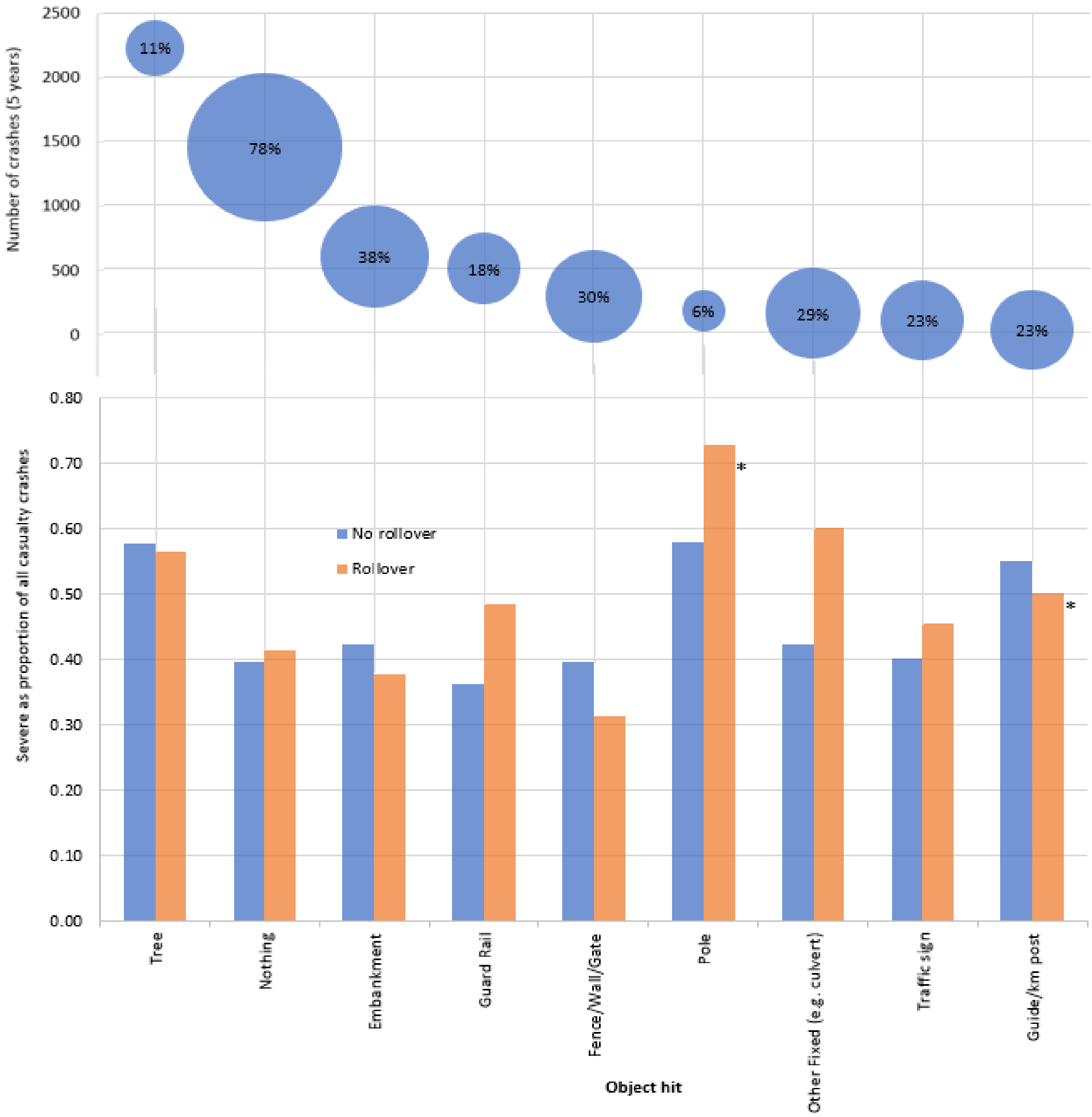


Figure A 10: Single vehicle run-off-road casualty crash frequency and comparative severity



Notes:

1. Severity as a proportion of all casualty crashes is the ratio of FSI to all casualty crashes.

2. The risk of a casualty rollover crash occurring as a result of striking different roadside hazards is indicated as a percentage for each object.

3. Result based on low number of crashes, not robust.

A.2 Model Results Crash Modification Factors (CMFs)

Table A 1: Run-off-road casualty frequency CMFs

Predictors		CMFs
Shoulder rumble strips (ATLMs)	Present	1.00
	Not present	1.23***
Curvature	Straight or gently curving (R >900 m)	1.00
	Moderate (R 500–900 m)	2.60***
	Sharp (R 200–500 m)	6.19***
	Very sharp (R < 200 m)	9.42***
Road surface condition	Good	1.00
	Medium	1.10*
	Poor	0.93(1)
AADT (double the volume)		1.42***
Roadside hazard distance	(>= 10 m)	1.00
	(5 to < 10 m)	1.14**
	(1 to < 5 m)	1.68***
	(0 to < 1 m)	1.22(1)
Paved shoulder	Present	1.00
	Not present	1.09*
Intersection type	Not present	1.00
	Other	1.66***
	Roundabout	1.24(1)

1 *These results represent non-statistically significant findings ($p > 0.1$). These should not be treated as findings on their own, as they are not significantly different from 1.00, but may be interpreted in broader context of the analysis and other research.*

Note:

*Measure of statistical significance: *** means p-value was < 0.01, ** means 0.01 < p < 0.05, and * means 0.05 < p < 0.1 i.e. should be treated with a degree of caution.*

Table A 2: Rollover and FSI probability CMFs

Predictors		Predicting a rollover event	FSI CMFs	
			Rollover	No rollover
Curvature	Curve	1.56***	–	–
	Straight	1.00		
Roadside hazard distance	(0 to < 1 m)	0.58(1)		
	(1 to < 5 m)	0.76*		
	(5 to < 10 m)	0.80(1)		
	(>= 10 m)	1.00		
Object hit	Embankment	0.08***	0.95(1)	0.89(1)
	Fence	0.04***	0.89(1)	1.00(1)
	Barrier	0.04***	1.27(1)	1.07(1)
	Guide-post	0.04***	0.00(1)	1.48(1)
	Other fixed	0.08***	2.22**	1.48(1)
	Pole	0.01***	2.51(1)	1.87**
	Tree	0.03***	2.13***	2.42***
	Traffic sign	0.06***	1.68(1)	1.16(1)
	Other	0.03***	0.00(1)	1.30(1)
	Nothing	1.00	1.00	1.00(2)
Vehicle manufacturing year	Before 2012	–	1.51*	–
	2012 or after		1.00	
Vehicle type	Station wagon & utility	1.42***	1.12(1)	
	Heavy vehicle (rigid); Prime mover, Prime mover - B double & Prime mover only	2.79***	1.35(1)	
	Motorcycle, moped & motor scooter	0.26***	1.54**	
	Light commercial vehicle (rigid), Minibus & Panel van	3.35***	1.51(1)	
	Passenger car	1.00	1.00	
	–	1.12**		
Number of persons		–	–	0.89***
AADT (double the volume from 2000 to 4000 vpd)		–	–	0.89***

1 *These fields represent non-statistically significant findings (p > 0.1). These should not be treated as findings on their own, as they are not significantly different from 1.00, but may be interpreted in broader context of the analysis and other research.*

2 *It is reasonable to set both values at 1.00 as a separate binary logistic model showed that rollover event makes no difference to severity outcomes.*

Note:

*Measure of statistical significance: *** mean p-value was < 0.01, ** mean 0.01 < p < 0.05, and * means 0.05 < p < 0.1 i.e. should be treated with a degree of caution.*

Austroads

Level 9, 287 Elizabeth Street
Sydney NSW 2000 Australia

Phone: +61 2 8265 3300

austroads@austroads.com.au
www.austroads.com.au