INVESTIGATION OF THE EFFECT OF POSITIVE AND NEGATIVE CROSSFALLS ON ROAD SAFETY AT ROUNDABOUTS

A dissertation submitted by

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Abstract

Roundabouts are a common form of road intersection and can be used to allow self-regulating flow of traffic. As part of a roundabout there are generally three critical geometric considerations, namely, approach geometry, the circulating carriageway and the departure geometry. In many instances this geometry is compromised and designed to slow traffic. Horizontal geometry is a significant aspect of the introduced compromise. Road Design Guides rely on the use of horizontal radii and crossfall to develop safe curves in road design. Consequently, the crossfall of a roundabout’s circulating carriageway becomes an important design consideration. The crossfall must be designed to allow a smooth transition and adequate drainage performance of the circular carriageway. There are two common approaches to roundabout crossfall in Australia, positive and negative crossfalls. This dissertation investigates and analyses the road safety performance of existing roundabouts with these different crossfalls to evaluate the safety benefits that each arrangement may offer.

Data was obtained for crashes at roundabouts in Queensland. The data spanned from 2001 to 2012 and was analysed to determine the trends, proportions and common causes of roundabout accidents. The data was limited to Queensland to highlight the differences in performance between conventional, negative crossfall roundabouts and positive crossfall roundabouts, which are sufficiently scattered throughout Queensland.

Corresponding road design information such as horizontal radii, pavement crossfall and speed limits were obtained using aerial imagery, road design plans and crash reporting records. The data was used to contextualise the crashes and ultimately determine the role that the type of crossfall at the roundabout played in the crashes.

Crash data and review of literature indicated five major crash types at roundabouts, with four types linked to the crossfall at the roundabout. Crash
types included approach rear end, entry/circulating, single vehicle and overturned crashes.

Analysis of the data concluded that speed zoning played a significant role in all crash types, with crossfall a secondary affectation of speeds. It was found that positive crossfall sites were overrepresented in approach rear end crashes and overturned crashes. Negative crossfall sites were overrepresented in single vehicle and entry/circulating crashes. The results obtained were unevenly distributed against crossfall and statistically indicate that crossfall is a significant affectation of accidents at roundabouts.

More in-depth research is required into specific case study sites and crashes. Consideration could include traffic volumes and crash severity at the different roundabout crossfall sites. This will aim to validate and extend on the literature and crash data analysis in this dissertation.
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I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

V. Stanton

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• Members of Queensland Department of Main Roads’ Data Analysis Unit
• My Family, friends and colleagues
# Table of Contents

1. **Introduction** ............................................. 12

2. **Literature Review** ..................................... 17
   2.1: Roundabout Design Methods ......................... 17
   2.2: Crashes at Roundabouts .............................. 23
   2.3: Summary of Literature Review & Basis of Research 32

3. **Methodology** ........................................... 35
   3.1: Review of Research Methods ........................ 35
   3.2: Focus of Research .................................... 37
   3.3: Adopted Research Method ............................ 39

4. **Results** ................................................ 45
   4.1: Approach Rear End Crashes ........................ 45
   4.2: Entry/Circulating Crashes ........................... 53
   4.3: Single Vehicle Crashes .............................. 60
   4.4: Overturned Crashes .................................. 68
   4.5: Summary of Results ................................ 77

5. **Discussion** .............................................. 80
   5.1: Approach Rear End Crashes ........................ 80
   5.2: Entry/Circulating Crashes ........................... 88
   5.3: Single Vehicle Crashes .............................. 91
5.4: Overturned Crashes

6. Conclusion

7. Recommendation

8. References

9. Appendix A: Project Specification

10. Appendix B: Approach Rear End Crash Data

11. Appendix C: Entry/Circulating Crash Data

12. Appendix D: Single Vehicle Crash Data

13. Appendix E: Overturned Crash Data

### Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Typical Section of positive crossfall roundabout (Stanton, 2014)</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>Typical Section of negative crossfall roundabout (Stanton, 2014)</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>Austroads suggested roundabout design with reverse curve approach (Austroads, 2009)</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>Arndt's roundabout crash prediction equation for entry/circulating crashes (Arndt, 1998)</td>
<td>21</td>
</tr>
<tr>
<td>5</td>
<td>Approach rear end crashes at roundabouts</td>
<td>46</td>
</tr>
<tr>
<td>6</td>
<td>Comparison of positive and negative crossfall roundabout crashes with the number of crash sites</td>
<td>47</td>
</tr>
<tr>
<td>7</td>
<td>Proportion of approach rear end crashes with wet/dry road surface</td>
<td>49</td>
</tr>
<tr>
<td>8</td>
<td>Proportion of approach rear end crashes by speed zone</td>
<td>50</td>
</tr>
<tr>
<td>9</td>
<td>Vehicle types involved in approach rear end crashes</td>
<td>51</td>
</tr>
<tr>
<td>10</td>
<td>Entry/circulating crashes at roundabouts</td>
<td>54</td>
</tr>
<tr>
<td>11</td>
<td>Entry/circulating crashes by speed zone</td>
<td>55</td>
</tr>
<tr>
<td>12</td>
<td>Vehicle types involved in entry/circulating crashes</td>
<td>56</td>
</tr>
<tr>
<td>13</td>
<td>Proportion of entry/circulating crashes with wet/dry road surface</td>
<td>57</td>
</tr>
<tr>
<td>14</td>
<td>Intended movement of at-fault vehicle in entry/circulating crashes</td>
<td>58</td>
</tr>
<tr>
<td>15</td>
<td>Single vehicle crashes at roundabouts</td>
<td>61</td>
</tr>
<tr>
<td>16</td>
<td>Single vehicle crashes by speed zone</td>
<td>62</td>
</tr>
<tr>
<td>17</td>
<td>Vehicle types involved in single vehicle crashes at roundabouts</td>
<td>63</td>
</tr>
<tr>
<td>18</td>
<td>Proportion of single vehicle crashes with a wet/dry road surface</td>
<td>64</td>
</tr>
<tr>
<td>19</td>
<td>Intended movements of vehicles involved in single vehicle crashes</td>
<td>66</td>
</tr>
<tr>
<td>20</td>
<td>Overturned crashes at roundabouts</td>
<td>69</td>
</tr>
<tr>
<td>21</td>
<td>Number of overturned crashes compared to number of crash sites</td>
<td>70</td>
</tr>
<tr>
<td>22</td>
<td>Overturned crashes in different speed zones</td>
<td>71</td>
</tr>
<tr>
<td>23</td>
<td>Overturned crashes by vehicle type</td>
<td>72</td>
</tr>
<tr>
<td>24</td>
<td>Overturned crashes by wet/dry road surface</td>
<td>73</td>
</tr>
<tr>
<td>25</td>
<td>Intended movements of vehicles involved in overturned crashes</td>
<td>75</td>
</tr>
<tr>
<td>26</td>
<td>A negative crossfall roundabout at Grey Street/Ernest Street, South Brisbane (Google, 2014)</td>
<td>82</td>
</tr>
<tr>
<td>27</td>
<td>A positive crossfall roundabout at Sunshine Motorway ramps/Yandina-Coolum Road, Coolum Beach (Google, 2014)</td>
<td>84</td>
</tr>
<tr>
<td>28</td>
<td>Safe speeds on horizontal curves</td>
<td>85</td>
</tr>
<tr>
<td>29</td>
<td>Aerial view of typical low speed zone roundabout. Roundabout at Robinson Road W/Kirby Road, Aspley. (Google, 2014)</td>
<td>90</td>
</tr>
<tr>
<td>30</td>
<td>Aerial view of roundabout at Aquatic Centre Drive/Burpengary-Caboolture Road intersection, Burpengary (Google, 2014).</td>
<td>93</td>
</tr>
<tr>
<td>31</td>
<td>Aerial view of roundabout at Dawson Highway/Harvey Road intersection, Clinton (Google, 2014)</td>
<td>94</td>
</tr>
</tbody>
</table>
Figure 32 Triangular cross sectional flow at centre island kerbing on positive crossfall roundabouts (Federal Highway Administration, 2011).

Figure 33 Lateral acceleration on curves

Figure 34 Vehicle rollover (LTSA, 2002)

Tables

Table 1 Summary of differences for positive and negative crossfall roundabouts

Table 2 Overview of existing roundabout design methods (Arndt, 2008)

Table 3 Proportion of wet weather, single vehicle crashes by intended movement

Table 4 Summary of Results

Table 5 Summary of crashes at roundabouts greater than 60km/h

Equations

Equation 1 Relationship between rollover and pavement crossfall (Milliken & de Pont, 2004).

Equation 2 Point mass equation for horizontal curves (Austroads, 2009)
**List of Acronyms**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARRB</td>
<td>Australian Road Research Board</td>
</tr>
<tr>
<td>DOT</td>
<td>Department of Transportation</td>
</tr>
<tr>
<td>FHA</td>
<td>Federal Highway Administration</td>
</tr>
<tr>
<td>HeTSAC</td>
<td>Heavy Truck Safety Advisory Council</td>
</tr>
<tr>
<td>ITE</td>
<td>Institute for Transportation Engineers</td>
</tr>
<tr>
<td>km/h</td>
<td>kilometres per hour</td>
</tr>
<tr>
<td>LTSA</td>
<td>Land Transport Safety Authority</td>
</tr>
<tr>
<td>NTC</td>
<td>National Transport Commission</td>
</tr>
<tr>
<td>PBS</td>
<td>Performance Based Standards</td>
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<tr>
<td>TERNZ</td>
<td>Tertiary Education Research New Zealand</td>
</tr>
</tbody>
</table>
1. Introduction

Vehicular traffic has presented various engineering issues for many decades and authorities have introduced engineering solutions to mitigate risk and improve service to road users. A common form of this engineering solution is the use of a circular carriageway artificially designated at the intersection of roads, often two intersecting roads only. This form of intersection is known as a roundabout intersection. (New Hampshire Department of Transportation (DOT), 2009)

A roundabout is required to manage conflicting traffic streams by providing opportunity to slowly and safely traverse a circulating carriageway, and exit in their desired directions. The geometric elements of a roundabout provide guidance to drivers approaching, entering and travelling a roundabout (Federal Highway Administration (FHA), 2000).

This definition highlights the issues facing drivers at roundabouts and the many different opportunities for collision or loss of vehicle control at a roundabout. This dissertation reviews roundabout design guidelines and defines the different opportunities for crashes to occur. These opportunities are then considered with respect to crossfall on the circular carriageway of the roundabout. There are two means of designing roundabout pavement crossfalls in Australia. These are positive (sloping inward) and negative (sloping outward) crossfalls for the circular carriageway of roundabouts. The effects of crossfall towards roundabout performance will be analysed in this dissertation. Roundabouts that are located on longitudinal grades will provide variable crossfall and promote varying degrees of rotation for vehicles. This limits the significance of the data obtained at these sites. This dissertation will aim to only consider sites of similar environment with consistent crossfall.

As defined by the US Department of Transportation, a roundabout is required to guide traffic from approach to departure of the circular carriageway. This dissertation will examine the different elements of the roundabouts from
approach geometry, the circular carriageway and departure geometry with respect to the different types of pavement crossfall.

The approach geometry of a roundabout is required to calm and slow the approaching traffic from all approaches. This calming effect is often achieved with the use of horizontal curvature. The use of this horizontal curvature designed to slow traffic must consider the use of crossfall.

The circular carriageway is the core component of a roundabout design and it is the area of significant vehicle direction changes. The roundabout presents a large amount of opportunity for vehicles to enter and exit at different angles and paths. The use of different forms of crossfall on the circular carriageway simultaneously benefits and disadvantages different vehicle movements.

Departure geometry is designed to allow vehicles to clear the roundabout intersection in an efficient manner. The design of the departure legs of a roundabout must consider the ability of vehicles to transition from the circular carriageway to each respective departure leg of the intersection.

Based on these three elements of a roundabout, this dissertation will examine the impact of positive and negative crossfall. The findings will be supported with crash data from Queensland Transport’s crash recording systems.

The successful selection of crossfall on a roundabout can improve the performance of the intersection. There are many benefits in providing a safer intersection for vehicles. These benefits include:

- Improved road safety
- Improved intersection performance and efficiency
- Reduced intersection delays
- Reduced asset management cost
- Public expenditure savings
The following briefly outlines the different crossfall types that are currently used within Queensland and will be considered further in this dissertation.

**Positive crossfall roundabouts**

Positive crossfall roundabouts are circular carriageways that are constructed with road pavement sloping downwards towards the central island. The central island becomes the lowest element of the roundabout. This form of roundabout is shown in Figure 1.

![Figure 1 Typical Section of positive crossfall roundabout (Stanton, 2014)](image1)

**Negative crossfall roundabouts**

Negative crossfall roundabouts provide identical function to positive crossfall roundabouts albeit with road pavement sloping away from the central island. The central island becomes the highest element of the roundabout. This form of roundabout is shown in Figure 2.

![Figure 2 Typical Section of negative crossfall roundabout (Stanton, 2014)](image2)
Project Aim

Currently Australian road authorities, namely Queensland Department of Transport and New South Wales Roads and Maritime Services promote varying policies and guidelines on the design of roundabouts. A major point of difference is in regards to the use of positive and negative crossfall. New South Wales do not promote the use of positive crossfall roundabouts in their supplementary road design guides. Both road design authorities are members of Austroads, Australia’s national committee for development of road design guidelines and policies and would be expected to offer similar advice in regards to such a common intersection treatment.

This dissertation will aim to deliver findings regarding crossfall selection at roundabouts. As per the project specification, this dissertation will:

• Perform a literature review of published material to identify and analyse roundabout design standards used for positive and negative crossfall roundabouts in Australia.

• Identify the types of crashes and contributing factors to crashes at roundabouts

• Collect and analyse crash data at roundabouts to determine the type of crash. Identify the corresponding roundabouts and collect design information to allow analysis of each crash

• Perform analytical calculations using design standards to determine safe vehicular thresholds at roundabouts

• Analytically compare incidences at roundabouts with positive and negative crossfalls to determine whether crossfall contributes to crashes and if so, how the different crossfalls affect different vehicles and crash types.

• Present findings to identify impacts of crossfall on road safety at roundabouts.
• Identify opportunities for further research into this topic

It is assumed that crash reports obtained from Queensland crash reporting systems (i.e. Web Crash, Road Crash 2, etc) are accurate since local police and investigative authorities have prepared them as primary evidence. For consistency, this dissertation will only examine and use information presented in the crash data.
2. Literature Review

This dissertation will examine the different background and design information available for roundabouts. The discussion of existing material is intended to review and examine the significance of existing knowledge to this dissertation and identify opportunities for research that will be undertaken in subsequent areas of this dissertation.

2.1 Roundabout Design Methods

* Austroads Guide Road Design: Part 4B Roundabouts* provides road design practitioners with guidance on roundabout design. Austroads recognises the need to provide safe and efficient intersections in order to reduce road fatalities, injuries and the associated socio-economic impacts.

According to this Austroads guide, roundabouts are proven to contribute to fewer casualties due to the reduced speed differential between vehicles on different legs of the intersection. This scenario is unique to roundabouts since it allows vehicles to interact and proceed subject to suitable gaps. Other intersection types require vehicles to behave as a result of a fixed trigger such as traffic signals (Austroads, 2009). The speed differential at traffic signals is potentially the posted speed limit. NSW Roads and Maritime Services’ Centre for Road Safety propose that an introduction of a roundabout compared to traffic signals lowers the rate of cross traffic flow crashes by 70%.

Similarly, Austroads promotes the use of roundabouts to address the traffic flow issues of most intersections. It is recognized that larger volumes of traffic at intersections inevitably require traffic signals. This theory is supported by the explanation that two methods, increased roundabout size and/or increased lanes within the roundabout achieve increased capacity. Both of these alternatives diminish the potential safety benefits of roundabouts when compared to traffic signals (Austroads, 2009).
The design principles for roundabout design in Australia as mandated in *Austroads Guide to Road Design Part 4B: Roundabouts* are listed below. The guide refers to these criteria as preliminary considerations when designing a roundabout.

- Roundabout should be clearly visible from approach sight distance.
- Entering drivers must be able to see both circulating traffic and potentially conflicting traffic from other approaches early enough to safely enter the roundabout.
- Approach entry curvature is used to limit speed on all approaches.
- Exits should be designed to enable vehicles to depart efficiently.
- Periphery of roundabout must be large enough to accommodate all intersecting legs without overlap.
- Circulating roadway should be wide enough to accommodate swept paths of design vehicles for all vehicle movement on roundabout.
- Sufficient entry, circulating, and exit lanes should be provided to ensure that the roundabout operates at an appropriate level of service.
- Number of legs should desirably be limited to four.
- Legs should desirably intersect at 90 degrees.

These considerations generally apply to the geometrical design of a roundabout and include driver behaviour issues. These principles do not provide guidance on the use of crossfall on a roundabout. One could ascertain that the horizontal geometry would subsequently control the application of crossfall and the guide consistently provides reference to optimizing the horizontal design, specifically sizing of the central island, horizontal approach geometry and horizontal departure geometry.
This focus on horizontal geometry provides an indirect suggestion of support for negative crossfall roundabouts. Figure 3 shows the use of a reverse curve approach with the recommended 2.5% - 3% super elevation on each horizontal curve. Using the suggested super elevation it would be necessary to provide negative crossfall on the roundabout. The main consideration from Austroads is the ability of the approach geometry to reduce entry speeds and increase the ability of a driver to maintain safe vehicle control.

![Figure 3](image.png)

Figure 3 Austroads suggested roundabout design with reverse curve approach (Austroads, 2009)

In regards to the design of the circulating carriageway Austroads provides guidance on the area and width to ensure the carriageway can accommodate vehicles turning safely and within the road pavement area.

Austroads makes the distinction that road pavement should be limited between 2.5 - 3%. The guide discusses some advantages and disadvantages of positive and negative crossfall. These are listed in Table 1.
Table 1 Summary of differences for positive and negative crossfall roundabouts

<table>
<thead>
<tr>
<th>Positive Crossfall</th>
<th>Negative Crossfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induces poor vehicle dynamics for left turning vehicles</td>
<td>Higher central island allowing improved driver recognition</td>
</tr>
<tr>
<td>Lowers single vehicle crashes for trucks</td>
<td>Drainage not required on central island</td>
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</table>

The guide provides advice on exit geometry. It is suggested that simple and efficient exit paths are used to reduce the potential for crashes at the exit of the circular carriageway.

In essence, Austroads advocates the use of speed reducing horizontal geometry on approach to the roundabout with adequate space provided on the circulating carriageway to allow turning vehicles to manoeuvre followed by simple exit geometry for efficient exit.

Arndt’s research into crash rates at roundabouts similarly uncovered that geometric design of roundabout approaches is critical in reducing crash rates. The approach geometry was found to have the largest contribution to the reduction of crashes. Approach geometry has the most affectation towards crash rates at roundabouts (Arndt, 1998).

Arndt’s research outlines the proportion of crashes that were recorded during a four-year period from 1986 to 1990. The types of crashes show a distinct overrepresentation towards entering roundabout crashes. Of the 492 crashes assessed across 100 roundabout sites, a total of 250 (50.8%) of crashes were attributed to entering collisions. These crashes were characterized as failing to give way and colliding with the circulating vehicle. The report justifies the lack of speed reduction in the approach geometry as the major contributor to these collisions and ultimately the majority of collisions at roundabouts.
Figure 4 Arndt's roundabout crash prediction equation for entry/circulating crashes (Arndt, 1998)

\[ A_e = C_1 \times Q_a^x \times \sum (Q_i^{y} \times S_{z}^{r}) + \zeta \]

where:
- \( A_e \) = number of entering/circulating vehicle accidents per year
- \( C_1, C_2 \) = constants
- \( x, y, z \) = constants
- \( Q_a \) = average annual daily traffic on the approach, i.e., one way traffic only (veh/d)
- \( Q_{ci} \) = the various average annual daily traffic flows on the circulating carriageway adjacent the approach from each direction according to Figure 10 (veh/d)
- \( S_{ni} \) = the various relative 85th percentile speeds between vehicles on the approach curve and vehicles on the circulating carriageway from each direction according to Figure 10 (veh/d)

Arndt's equation, shown in Figure 4, was developed following research into roundabout crash rates. Mathematically, “the crash rate is directly proportional to the traffic flow on the approach”. In order to limit the crash rate for entering vehicles “the relative speed between entering and circulating vehicles must be limited”.

Queensland Transport’s Road Planning and Design Manual lends support for designer consideration of the approach geometry. “Single vehicle crash rates reduce as the decrease in speed between successive horizontal elements reduces”. This statement supports Arndt’s original findings and includes requirement that reduction in approach speed across successive geometric elements should be limited. This prevents large reductions in speed occurring in single geometric elements. Higher speed zone roundabouts would be required to utilize a combination of geometric elements to produce a safe approach path for vehicles. The manual labels this aspect of a design as one
that “significantly affects crash rates at roundabouts” (Queensland Transport, 2006).

The United Kingdom’s *Design Manual for Roads and Bridges* advocates for speed control to be provided on the approach curve of a roundabout, again reaffirming industry belief in controlling entry speeds of vehicles. Arndt followed up his 1998 research with development of new criteria for the control of speed through roundabouts. The research compared current industry practices across the world to assess the merits of each. An overview of each method of speed control and subsequent safety improvements are highlighted in Table 2.

<table>
<thead>
<tr>
<th>Design methods</th>
<th>Australian Method</th>
<th>UK Method</th>
<th>USA Method</th>
<th>Queensland Method</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Deflection</td>
<td>Maximum entry path radius</td>
<td>Maximum decrease in speed between successive elements</td>
<td>Maximum entry speed Maximum decrease in speed between successive elements Maximum relative speeds between entering and exiting vehicle paths Maximum difference in potential side friction</td>
</tr>
</tbody>
</table>

Table 2 highlights the research undertaken by Arndt to produce a model that considered vehicle dynamics across the range of movements at roundabouts.

The remaining methods cater for the entry path and addressing subsequent crashes occurring on such path. From the above approaches to design, the crossfall of the circulating carriageway is not directly considered.
2.2 Crashes at Roundabouts

Arndt, Maycock and Hall and others have carried out extensive empirical research throughout different countries and periods to determine the proportions and types of crashes occurring at roundabouts. Arndt’s research, in similar fashion to Maycock and Hall, categorized roundabout crashes into the following types (Arndt, 1998):

1. Approaching Rear-End – two vehicles collide in a front to rear manner upon entry to the circulating carriageway.

2. Entering/Circulating – an entering vehicle fails to give way and collides with a vehicle on the circulating carriageway.

3. Single Vehicle – a vehicle loses control and becomes errant, colliding with a roadside fixture, or overturns (rollovers).

4. Exiting/Circulating – an exiting vehicle, driving from the inner circulating lane attempts to cross to a departure leg and collides with a vehicle on the outer circulating lane that is continuing to circulate around the roundabout.

5. Sideswipe – a collision between two vehicles travelling on a different path but in the same direction.

Other minor crash types have been researched by the US Department of Transportation. They primarily involve other road users such as cyclists and pedestrians. The level of crashes between vehicles and pedestrians or cyclists is overrepresented due to the lack of measures to control the interaction between the two parties (FHA, 2000).
Approaching rear end crashes

Approaching rear end crashes are categorized as frequently occurring at many intersections forms, including roundabouts. The primary location of rear end collisions is at traffic control sites such as traffic signals, stop lines and give way lines that designate priorities amongst vehicles. This results in collisions if following traffic is not aware of the impending stop (NHTSA, 2014). The NHTSA reports that rear end collisions regardless of their location in a road setting tend to be caused by driver behaviour issues such as following too closely, negligent driving or failure to remain alert to delineation and signposting. These issues lead to approximately 2.5 million collisions per year in the United States. The design, itself, of the road or intersection control is very rarely the cause of increased rear end collisions.

Austroads offers an alternative suggestion that approach rear end collisions, in some instances result from lack of recognition of an approaching roundabout. It is suggested that positive crossfall on a circulating carriageway may reduce driver recognition of the island thereby suggesting approach rear end crashes could increase at these sites.

Entering/circulating crashes

Entering/circulating crashes are the most common type of crash occurrence at roundabouts. Arndt’s research found that approximately 50% of crashes studied were approach crashes. The FHA similarly found that approach crashes were the most frequent type of crash occurring at roundabouts. Despite the frequency of approach crashes, most are not fatal due to the smaller difference in relative speeds (Arndt, 1998). This concept is reaffirmed by Austroads.

To limit the majority of crashes Arndt confirms, “approach geometry design that successively reduces vehicle speeds would significantly reduce crash rates at roundabouts”. A specific value of 35km/h is affirmed as the threshold
for safe entry speed. Beyond this value it is found that speed differential increase and consequently the rate of crashes increases. No correlation between the application of crossfall on the circulating carriageway and approach crash rates is contemplated. From Part 3 of the *Austroads Guide to Road Design*, it is suggested that pavement rotations are to be limited and Part 4 recommends that 2.5 - 3% super elevation be applied to approach geometry. Effectively, both authors support the correct application of crossfall on curves although do not recognise crossfall on the circulating carriageway as a contributor to approach crashes.

More specifically, Arndt provides design recommendation for speed control at roundabouts. The proposed method involves:

1. Absolute and desirable entry path radii for various approach speeds and number of lanes based on vehicle path models

2. Absolute and desirable minimum central island radii for various approach speeds and number of lanes.

The intention of the proposed method is to provide more robust design criteria for roundabouts. Arndt's parameters rely on vehicle entry speed and the use of geometric design principles to ascertain probable maximum speeds and consequently limit entry speed to consequently reduce entry/circulating crashes, among others.

Similarly, Maycock and Hall's research in 1984 proposed specific findings for entry geometry, aimed at reducing the entry speed of vehicles. Findings included control of entry path radii, not just lane radii, to ensure probable maximum speeds could be limited in all instances (Maycock and Hall, 1984). Neither of these methods addresses the design of the circulating carriageway or the interaction between horizontal geometric elements and pavement crossfall.
Single vehicle crashes

Robinson’s 1992 research found that 23% of all crashes at roundabouts in NSW were single vehicle crashes. Arndt found that 18.3% of the crashes studied were single vehicle with a further breakdown that indicated 57% of the single vehicle crashes occurred on the circulating carriageway. The remaining proportion of single vehicle crashes were evenly distributed between approach, entry and departure locations to the roundabout. Based on Arndt’s figures, 10% of crashes at roundabouts are single vehicle occurring on the circulating carriageway.

The loss of control in single vehicle crashes was found to be a result of one or more of the following (NHTSA, 1977):

- Excessive speed
- Driver overreaction
- Driver negligence
- Driver judgment error/fatigue

This dissertation does not focus on the driver psychology and behaviour aspects when assessing single vehicle crashes. In a road setting context, the two significant causes of single vehicle crashes were confirmed to be excess speed (Arndt, 1998) and driver overreaction (NHTSA, 1977).

The issue of excessive entry speed is reaffirmed in the various design criteria developed by various authors including Arndt, Maycock and Hall, the FHA and more recently Austroads (refer to Table 2). Driver overreaction is caused by unexpected or undesirable situations in which the reaction applied is excessive leading to a loss of vehicle control (NHTSA, 1977). This is a broad crash causation factor although when applied to roundabout crashes it
accounts for the majority of single vehicle crashes. The remaining proportion of single vehicle crashes is comprised of overturned crashes (NHTSA, 1977).

The NHTSA presented countermeasures to reduce vehicle speeds including speed limit reductions and other minor traffic measures. Speeding is confirmed as major causation of crashes and validates the need for an approach speed design criteria at roundabouts.

Furthermore, their research indicated that 184 of 1370 studied single vehicle crashes were attributed to driver overreaction. Driver overreaction crashes, from their assessment were preceded by “unexpected situations of hazards” to which “natural reaction was to brake and/or swerve excessively”. The NHTSA’s research was not limited to intersections and therefore the requirement to brake excessively in the roundabout context would be closely linked to excess approach speed. The need to brake excessively is reduced at lower speeds (NHTSA, 1977).

The proportion of crashes caused by vehicle factors was not of significance (NHTSA, 1977). Rollovers were generally caused by a combination of environmental and driver factors. However, the NHTSA proceed to question the validity of design criteria to address different vehicle’s stability and performance. “Design criteria could be related to the ratio of track width to height of the vehicle centre of gravity, roll angle and other suspension system characteristics.” Their findings did not include heavy vehicles although they forecast the rate of single vehicle rollover crashes to increase with heavy vehicles considered.

Their research found that zero of 106 overturned crashes (light vehicles only) occurred on wet pavement with their findings concluding that “there is a strong relationship between pavement friction and capabilities and vehicle configuration”.
Single vehicle crashes (Heavy Vehicles)

Research by Kharazi and Thomson indicated that heavy vehicles are involved in an overrepresented amount of single vehicle crashes. Their research focused on roll and yaw instability. This supplements the 1977 findings of the NHTSA; that vehicles with high centre of gravity are likely to become involved in overturned crashes due to inherent vehicle dynamics. Further research supported this by finding that heavy vehicles, particularly articulated, were more likely to induce rollover or instability when turning at roundabouts, particularly the circulating carriageway which would include the ideal conditions for instability and possibly rollover. (Inderscience, 2008).

The NTC has introduced PBS for heavy vehicles. These are a set of vehicle performance standards to mandate on road performance of heavy vehicles. Greater access to the road network is available for vehicles that perform to or exceed specified standards, regardless of the prescriptive legislation limits (NTC, 2008).

This criteria is currently, the only recognized criteria for holistic heavy vehicle performance within Australia. Although Australian Design Rules indicate maximum and minimum performance values, they are limited to components of vehicles (ARRB, 1999). The PBS system models the actual performance and dynamics of a heavy vehicle as a combination. This provides an actual indication of on road performance and allows the NTC to determine safe levels of access (ARRB, 1999).

Of the twenty assessment criteria used for assessing heavy vehicles, roundabouts and stability are included. The applicable criteria to heavy vehicle performance on the circulating carriageway include:

- Load transfer ratio
- Static roll threshold (SRT)
- Roundabouts
The above factors include two performance and an infrastructure criteria. Of importance is the NTC’s criteria for infrastructure criteria since roundabouts are intersections “that have a direct impact on safety” for negotiating heavy vehicles.

The static rollover threshold measures roll stability. This value indicates the maximum lateral acceleration sustainable by a vehicle without rolling over during a turn (Brusza, 2009). It has “been strongly linked to rollover crashes”. The minimum accepted rollover threshold is 0.35g (NTC, 2008). HeTSAC conducted research in 2006 to determine the proportion of heavy vehicles operating in Tasmania that did not meet this PBS requirement. A sample of 96 heavy vehicles was selected with approximately 13% found to be non-compliant for the static rollover threshold. Their findings supported other research that found “heavy vehicles with poor rollover stability have a higher rollover crash rate than other vehicles”. PBS standards are not mandated for heavy vehicle roadworthiness or Australian compliance (HeTSAC, 2006). As outlined in the NHTSA’s 1977 report, the NTC examined the feasibility of introducing such a standard; it determined that productivity losses, costs and feasibility would not be viable. Recommendations included a targeted approach to improve poorly performing divisions within the transport sector. Importantly, the report identifies the potential risks of ongoing non-compliance and lack of performance regulation.

The Land Transport Safety Authority of New Zealand (LTSA) found that the 15% of vehicles with an SRT of less than 0.35g were involved in 40% of rollover crashes. This supports the 2006 HeTSAC findings. LTSA found that speed and other vehicle criteria such as centre of gravity, suspension stiffness, tyre friction and track width were important factors that influence heavy vehicle rollover. Pavement crossfall was not identified as a factor that contributes to load transfer and reducing vehicle stability.
Milliken and de Pont conducted research in 2004 to assess the link of road geometry to heavy vehicle crashes. Their findings over a five-year period from crash records in New Zealand found that of the crashes where “lost control” was reported, road geometry most likely contributed. 3239 crashes were reported as “lost control” with 53% of these crashes being single vehicle crashes during turning manoeuvres. The report does not distinguish what proportion occurred at roundabouts although highlights the increased risk of rollover and lost control when turning a heavy vehicle (Milliken & de Pont, 2004). The report presents a mathematical expression to quantify the influence of road crossfall on the SRT.

\[ a_r = (SRT_{veh} \pm \theta) \]

where
- \( a_r \) = lateral vehicle acceleration producing rollover
- \( SRT_{veh} \) = Static vehicle rollover threshold(g)
- \( \theta \) = road crossfall(\%)

A favourable crossfall (positive) increases the lateral acceleration threshold required to produce rollover, therefore reducing the probability of crash rates when cornering (Milliken & de Pont, 2004).

The load transfer ratio indicates the amount of load transfer during manoeuvres (Milliken & de Pont, 2004). When negotiating roundabouts, heavy vehicles experience load transfer. A safe maximum threshold of 0.6 is mandated by the NTC. The load transfer ratio was found to vary depending on the type of coupling (A or B), road geometry and other factors. The ability of road design to account for load transfer is difficult since it is a performance
factor that is not “clearly beneficial or clearly detrimental” (Milliken & de Pont, 2004).

Roundabouts were considered with respect to geometric layout and turning envelope to satisfy PBS requirements. The NTC “recognize the importance of road safety” at roundabouts. As part of gaining approval, turning and spatial requirements are checked. No technical calculations are performed, especially with respect to the crossfall of a roundabout.

In summary, a collection of research acknowledges the impact of turning manoeuvres at roundabouts; Equation 1 defines the link between crossfall and lateral acceleration although design standards do not cater for heavy vehicle limitations. As a result, an overrepresentation of overturned heavy vehicles is expected.

**Exiting/Circulating Crashes**

Exiting crashes are not as frequent as entering crashes (Arndt, 1998). Of the 492 crashes assessed by Arndt, only 6.5% were found to occur when vehicles were exiting. The collisions were caused by inner circulating vehicles failing to give way to outer circulating vehicles. This causation does not appear related to road geometry and crossfall. This dissertation will not address exiting/circulating crashes any further.

**Sideswipe Crashes**

Similar to exiting crashes, sideswipe crashes occur on the circulating carriageway although is caused by vehicles taking different paths (Arndt, 1998). This causation does not appear related to road geometry or crossfall. This dissertation will not address sideswipe crashes any further.
2.3 Summary of Literature Review & Basis of Research

Roundabouts are considered the safest form of intersection when considering crash rates. This dissertation will aim to present further evidence for improved understanding of crossfall and the effect it has on crash rates and types at roundabouts.

The *Austroads: Guide to Road Design*, Australia’s adopted road design guide, provides horizontal design criteria and considerations for roundabouts. Design entry speeds are the focus of the guidelines. It supports Arndt’s and Queensland Transport’s findings that indicate reductions in entry speed provide the largest reductions in crash rates at roundabouts.

However, both parties focus on vehicle entry paths as a horizontal alignment consideration, little consideration is explicitly given to the application of crossfall at roundabouts.

When considering crashes, Arndt and others categorise five major types occurring at roundabouts. These include approaching rear end, entering/circulating, single vehicle, exiting/circulating and sideswipe crashes. Of the five types of crashes, approaching rear end, entering/circulating and single vehicle crashes were most likely influenced by the application of crossfall at the roundabout.

*Austroads* suggests that the use of positive crossfall on roundabouts obstructs vision of the roundabout island and may deceive approaching traffic. This could be reflected in a higher rate of approaching rear end crash rates.

Arndt proved that entry/circulating crashes were the most common type at roundabouts and indicated that entry speed was a major causation factor. This led to his proposed design criteria and method of considering probable vehicle entry paths and aiming to limit the maximum vehicle entry speed. This research supported Maycock and Hall’s 1984 research that provided similar
criteria. Both research findings did not refer to the application of crossfall at roundabouts.

Arndt and Robinson proved that single vehicle crashes accounted for approximately one fifth all roundabout crashes. Arndt clarified this by proving that approximately half of the single vehicle crashes occurred on the circulating carriageway.

Similar research into crash causation by the NHTSA found that driver overreaction and vehicle speed were leading causes of single vehicle crashes. The NTHSA proposed speed limit reductions and similarly targeted measures to reduce entry speeds. Their findings provided support to Austroads, Maycock and Hall and Arndt.

Alternatively, the NHTSA outlined shortcomings in design criteria including the lack of consideration for vehicle configurations and their physical performance capabilities on roads. Heavy vehicles were identified as potential vehicle type susceptible to increased single vehicle crashes particularly rollovers, due to their size and mass.

Subsequently, PBS requirements for heavy vehicles are the first accepted criteria to assess heavy vehicles for road access within Australia. Roll stability is a performance target governed by PBS. HeTSAC confirmed that heavy vehicles with lower roll stability thresholds are more susceptible to rollover crashes. Additionally, TERNZ conducted research using crash data and PBS requirements. They found an overrepresentation of single vehicle crashes involving heavy vehicles where the PBS criteria was not met. This confirmed the NHTSA’s commentary that vehicle configuration criteria would be required to address crashes.

A second PBS criteria used for rollover likelihood is the load transfer ratio. The reviewed literature indicated reliance on speeds, driver paths and load restraints among others. It is practical to suggest this vehicle performance
factor is outside the capacity of road design authorities to anticipate and mitigate during design.

Roundabouts are considered during PBS assessments although assessment is limited to horizontal geometry and turning envelopes. No consideration is applied to crossfall by the NTC. Entry speeds, another major causation, are not a focus of the NTC assessment due to notion that heavy vehicle drivers are more professional and higher skilled.

The final crash categories identified include exit/circulating and sideswipe crashes. According to Arndt and Robinson’s separate research, both of these crashes are a minority type at roundabouts and generally attributed to driver error or poor delineation.

Essentially, there is no or minimal consideration of the application of crossfall expect indirect Austroads policy from an alternate section of the Guide to Road Design. Entry speed is identified as a critical contributor to roundabouts crash rates. Heavy vehicles are identified as most susceptible to crossfall changes particularly during turning manoeuvres.

Based on researched literature, investigation is required to determine the effect of crossfall on crash rates and types at roundabouts. This statement will form the basis for the following sections of this dissertation.
3. Methodology

3.1 Review of Research Methods

There have been number of reports prepared on road safety and the relationship of road design, vehicles and crash rates. The research into crossfall at roundabouts effecting crash rates depends on valid and reliable methods to produce accurate results. This section of the report outlines the procedures and justifications for these procedures. The intention of this section is to provide a valid and accurate platform for results to be presented in the subsequent section of this dissertation.

The basis for the majority of literature reviewed in section 2 of this dissertation; including that of Arndt, the NHTSA, HeTSAC and others has been the use of historical crash data, with some integration of mathematical analysis. This is the most preferred method for highlighting correlation between road safety and road features. Statistically, a sample is considered to be sufficient in size to indicate trends once reaching at least 30 samples (Stattrek, 2014). The use of larger sample sizes reinforces findings if appropriate controls are properly applied.

The use of controls is required to ensure variables that contribute towards results are noted or eliminated from analysis if required. In Arndt’s 1998 research, 492 crashes were considered. Little control was placed on these crashes except for the location being roundabouts. The reasoning was the broad nature of the research aim. Arndt endeavoured to prove a correlation between crash rates and the geometry of roundabouts. In order to create a mathematical relationship the sites were examined and headline statistics produced. Subsequently, the sites were assessed further and a mathematical relationship developed once geometric and traffic information from the sites was known.
The use of 492 roundabout crashes proved sufficient to capture and acknowledge the range of different roundabout crashes. The findings presented proved to be valid. Arndt's research provided support to preceding research, particularly Maycock and Hall’s research in 1984. His findings also presented a basis for further research by Queensland Transport and Austroads acknowledgement in their *Guide to Road Design*.

An ITE report prepared in 2008 for roundabout safety principles highlighted different safety principles, many corresponding with Arndt’s and others’ findings. The report addressed and promoted principles of design, supported by crash data and crash rates. In addition, the report provided commentary on key elements of roundabout design, particularly crossfall. The commentary was not supported by crash data or mathematical analysis although provided technical commentary on the issue. Further research to validate the discussion in the ITE report is required.
3.2 Focus of Research

As outlined in the literature review, the effect of crossfall at roundabouts is currently considered minor with little research attributing crossfall to crash rates. This lack of research has formed the basis for this dissertation.

There are three key areas that the analysis of crashes in this dissertation will focus, these include:

1. Effect of crossfall on approaching rear end crashes

Austroads presents information that positive crossfall roundabouts limit vision to the central island, deceiving following traffic. This should be represented in the crash rates at sites with positive crossfall.

2. Effect of crossfall on entering and single vehicle crashes

The majority of research into crashes at roundabouts identified high entry speeds. This is a logical causation factor given a roundabout operating well relies on reduced speed differential of conflicting streams (Austroads, 2009). Research focused on probable maximum vehicle speeds following arbitrary entry paths. In order to comply with recommended design guidelines and provide positive crossfall multiple pavement rotations are required over a short length. As per road design guidelines, the proportion of entering crashes would be increased if rates of pavement rotation at roundabouts were not controlled. If not correctly implemented at sites, an increased entering and single vehicle crash rate could be expected. Lower speed zones present inherent difficulties in rotating pavement suitably for positive crossfall and may be overrepresented in these accident types.

3. Effect of crossfall on heavy vehicles at roundabouts

The NTC with their PBS requirements acknowledge roll stability and roundabouts in their criteria. Research indicates that the crossfall of the roundabout affects the rollover likelihood of heavy vehicles. Negative crossfall
is mathematically proven to increase the likelihood of rollover. This should be represented in heavy vehicle rollover crash rates at negative crossfall roundabouts.
3.3 Adopted Research Method

The basis of this dissertation is to provide technical insight into the areas of need as identified in Section 2 of this dissertation. Historical crash data and roundabout design information will be used at sites with crash history to identify links between crossfall type, crash types and rates.

Crash rates provide historical proof of road safety performance. The use of crash reports and information will be used to develop findings. Crashes are a key indicator of road safety. Crash data provides a portrayal of real world, unsolicited events. The focus of the analysis in subsequent sections of this dissertation is to identify the effect of crossfall on such crashes.

In order to develop a relationship between crashes and crossfall additional information is required to provide relevance to the data. Each crash site would be examined to observe geometric layout and record the type of crossfall. This information is significant in developing valid relationships between crossfall types and crash data.

Both sets of information are required for valid analysis to be conducted and discussed. The use of historical crash data is a valid method of developing road safety findings. Firstly, crash data indicates actual, unsolicited events caused by factors involving a vehicle, road and driver. The use of crash data individually, has limited benefit, except to provide headline statistics. All material reviewed in Section 2 of this dissertation accounts for trends between crash data and other features such as vehicles or road infrastructure. Likewise, this dissertation will present data in conjunction with the road setting and crossfall. This information provides weighting to the role of crossfall in roundabout crashes.

Developing models for simulation would be an ideal method of assessment. However, modelling by simulation would require application of mathematical and theoretical principles. The use of modelling would only provide crash estimates consistent with the input data. This would aim to extend the view of
the model developer. Acceptance of the model requires validation by the way of real world performance (Smith, 2010). Real world testing is not feasible nor an efficient means of producing a wide spread spectrum of results for this dissertation.

This dissertation will rely on historical crash data to develop proven relationships between crossfall and crash data. A potential result of this research could include refinement of roundabout crash models to consider crossfall.

**Crash Data Collection**

Crash data forms the basis for the research and discussion in this dissertation. The data was obtained from Queensland Transport's Department of Main Roads crash reporting systems. The use of crash data relies on accurate data entry and reporting to produce valid results.

Queensland's crash reporting system relies on emergency service personnel reports from crashes. The crash reports are compiled as primary evidence reports with critical information about the crash included. The information provided includes vehicle details, environment, location, weather and driver profiling. This information allows data to be analysed accurately.

There are some assumptions and expectations in adopting the crash reports. Firstly, local authorities familiar with the scene of a crash should complete crash reports unabated otherwise common tendencies of involved drivers to alter facts prevail and potentially distort causation factors of the crashes. A secondary expectation is the requirement for data to be entered accurately, as primary evidence. This is expected of local authorities and improves validity of the database. Analysis of crash reporting errors is beyond the scope of this research. One could be expected to accept the risk associated with data entry error as minor and not significant to the overall research outcomes. This risk is further mitigated with the use of a large and longer-term sample size for
The longer-term risks associated with site information are discussed in the following section.

A limitation to the use of crash databases is the fact that crashes often occur without authorities attending. The amount of unattended crashes has potential to provide a skew of results towards larger, reported crashes. Repeated minor crashes may indicate stronger trends although may not be captured in the crash reporting system. This is however beyond the scope of this dissertation and information not reported in the crash databases would not be considered. Non-captured data would not be available to any research parties and is therefore considered minor and not significant to this research.

Details such as driver speed allegations are not considered in this dissertation. Although local authorities attend and aim to report accurately, reliance on driver and witness testament is required in some instances. Given the liability associated with crashes, falsification of preceding events is highly plausible (Ogden, 1996). This is a limitation in producing speed zone findings since the posted speed limit may not have been adhered to.

The ability to provide reliable and actual speed data is very limited. This limitation is applicable to all research reviewed in Section 2 of this dissertation which acknowledged speed as a causation although all authors did not quantify the level of speeding.

Crash data will be used to capture all reported crashes at roundabouts in Queensland between 2001 and 2012. The records will be used to identify the following:

- Crash type
- Crash vehicle type (for at fault vehicle in multiple vehicle crashes)
- Speed zone of roundabout (relevant approach speed limit where they vary)
- Road surface condition
• Intended movement at the roundabout (for at fault vehicle)

The latter four criteria were commonly alluded to as affecting factors in reviewed literature. They will be used to analyse the type of crashes and influencing factors. Additional information such as the direction, latitude and longitude coordinates; weather conditions and degree of damage/injury from each crash will be observed as means of validating the consistency of each crash report.

Sites or information that is not consistent with the crash recording will be removed from analysis. This process aims to improve the quality and confidence in the results.

**Roundabout Design Data Collection**

Roundabout design data forms an important component of this research. The data is required to provide context and value to the crash data and rates. The data is required to indicate site geometry and crossfall type.

Accuracy of the roundabout design information is critical to facilitating discussion and identifying relationships between crashes and crossfall types. Inaccuracies or inconsistent reporting would limit the validity of the research. It is paramount that design information observed from the sites is clear and accurate.

The design information will be collected using a variety of media. The use of different media presents opportunity to utilise the most appropriate resources to deliver quality observations. The use of a single medium, preferably roundabout design plans, would be difficult to obtain for each site. It would also require extensive time allocation to pursue and assess design plans for each crash site.
Where available, design plans used to construct the roundabout sites remain the most preferred and accurate means of identifying the required design parameters such as crossfall and radii. The design plans would include all of the information necessary to allow mathematical and theoretical analysis to be conducted for vehicle and crash types. Where available, the use of design plans is considered a safe and accurate approach for this research task.

The limitations involved with the use of the design plans are minor, that is, the design plans may be slightly inaccurate due to variations adopted during the construction or maintenance works. Without major reconstruction it is not feasible to significantly alter the crossfall of the roundabout. The risks associated with changes to the crossfall are minor, given the scope and likelihood of occurrence is minor.

Road browsing software will be used where design plans are unavailable. It will enable efficient and accurate observations of crossfall types for all sites. Google’s Street Viewer mapping is freely available and provides coordinated aerial and on road imagery. It also allows efficient observation of a roundabout from different approaches. This can be cross-referenced against the crash data records to identify the most applicable area of the roundabout to the crash therefore improving the level of reporting.

Similarly, coordinated aerial imagery will be utilised to determine additional geometrical information such as horizontal radii on approach to roundabouts. The use of coordinated aerial imagery will be considered sufficiently accurate to survey and measure radii and horizontal elements. This approach is considered accurate for the purposes of determining horizontal geometry information.

The use of a long-term period of crash data presents opportunities for information accuracy issues to arise, particular with road construction works. Records of crashes have been obtained from 2001, totalling a period of 11 years. The extended time period poses a risk to the validity of research outcomes given the likelihood of on road changes.
The use of larger sample sizes (over 10,000 reported crashes) assists in offsetting the identified risks and limitations. Secondly, a considered approach has been adopted to remove any potential inconsistent data, including sites of road construction works. For transparency purposes, the amount of data removed from analysis for these reasons has been outlined in Section 4 of this dissertation. Date stamped aerial imagery from Google also provides assurances for the validity of data.

On this basis, the proposed methods are deemed consistent with adopted practices and therefore sufficient to facilitate research into the effects of crossfall on road safety at roundabouts.
4. Results

4.1 Approach Rear End Crashes

Approach rear end crashes are the most frequently occurring crash type at intersections (Yan, 2005). The requirement for drivers to respond to the evolving conditions coupled with distraction or inattention can lead to rear end crashes. In the context of this research an analysis of roundabout crashes in Queensland from January 2001 to December 2012 was undertaken to determine the correlation between approach rear end crash rates at roundabouts and the contribution of the crossfall of the circulating carriageway.

As discussed in Section 2 of this dissertation, Austroads indicated that positive crossfall could lead to higher approach crash rates. It was suggested the central island would be obstructed from the view of approaching traffic, resulting in reduced awareness of the intersection and subsequent rear end collisions. It is an extension of this commentary that an increased approach rear end crash rate for positive crossfall sites is expected.

Of the 10,458 reported crashes in this period, a total of 1162 were classified as rear end crashes. This corresponds to a proportion of about 11% of roundabout crashes. In comparison to Arndt’s research, which assessed 492 crashes from 1986 to 1990, there is a 7.2% reduction in the proportion of rear end crashes at roundabouts. This could be explained by two factors:

- Arndt’s database of crashes was significantly smaller (less then 5%) than the number of crash records collated for this research

- Vehicle safety standards have improved markedly since the period of Arndt’s research. Specific features such as anti-lock braking systems, improved tyre technology and stability control systems have contributed to overall reductions in rear crash rates. (Allianz, 2014).
Figure 5 shows the proportion of crashes between the roundabouts of different crossfall. Positive crossfall sites accounted for the largest number of crashes, with 633, supporting Austroads commentary. Negative crossfall roundabouts accounted for 301 whilst 228 of the crashes were unable to be verified due to other factors. The unverified sites and/or crashes have been removed from any subsequent statistical analysis in this section.

**Number of Approach Rear End Crashes at Roundabouts**

![Pie chart showing the proportion of crashes between positive and negative crossfall roundabouts. Positive Crossfall: 633, Negative Crossfall: 301.]

Based on Figure 5, it is evident that positive crossfall roundabouts account for a higher volume of approach rear end crashes. Further analysis was undertaken to consider the effects of competing factors to the causation of approach rear end crashes at roundabouts.

**Rate of crashes per roundabout**

Repeated crashes at each site indicate design or environment deficiencies. An uneven weighting of results in this analysis would indicate that crossfall...
and approach rear end crashes, being the only common elements, have a high positive correlation.

As confirmed in Figure 6, the number of crash sites during the 12-year period was very similar (refer to red columns) between the two crossfall types. 633 positive crossfall crashes occurred across 214 unique sites whilst 301 negative crossfall crashes occurred across 211 unique sites. This is an even distribution of crash sites yet heavily skewed distribution of the crash count per unique site.
This discrepancy highlights the recurring crashes at the same positive crossfall roundabout sites. A recurring pattern of crashes at each site could be attributed to positive crossfall sites experiencing higher traffic volumes. Without specific long-term investigations, there is little evidence to verify the number of movements per crash at such sites. This is a limitation of this investigation.

Otherwise, a significantly higher recurrence of crashes at the same sites indicates a design or site deficiency. Based on the 2:1 overrepresentation of approach rear end crashes at positive crossfall roundabouts a strong correlation exists between positive roundabout crossfall and approach rear end crashes, supporting Austroads commentary.

**Proportion of approach rear end crashes on wet roads**

Wet road surfaces are proven to result in increased approach rear end crashes (Yan, 2005). A high proportion of wet surface crashes diminish the significance of the findings since wet road pavement results in reduced grip and therefore reduced stopping capacity of vehicles.
Number of Approach Rear End Crashes with Wet/Dry Pavement

From the crash records, the number of approach rear end crashes at roundabouts is significantly lower during wet weather periods. However, the data collated has not considered the number of wet weather days compared to dry weather days to determine a weighted occurrence rate. This is beyond the scope of this investigation.

The minor proportion of approach rear end crashes in wet weather adds value to the significance of other elements such as the type of crossfall. The impact of wet weather and potential reductions in grip leading to inflated approach rear crash rates are limited since wet weather crashes account for less than 15% of the total recorded.

In both weather conditions approximately two thirds of the crashes occurred on approach to positive crossfall roundabout proving the diminished travel conditions associated with wet weather have not affected the crash distribution between positive and negative crossfall. This is most likely
attributed to the common design guidelines applied to the approaches of positive and negative crossfall sites. The variation in crossfall occurs only on the circulating carriageway.

It can be concluded wet pavement does not affect the proportion of approach rear end crashes, regardless of the crossfall of the circulating carriageway.

The proportion of approach rear end crashes has a positive correlation to the operating speed zone. Contrary to the overall rate of crashes, negative crossfall sites are overrepresented in speed zones of 50km/h and less. At 60km/h, the proportion of crashes at each type of roundabout reverts to the statistical normal with positive crossfall sites accounting for 2/3 of the reported crashes. Beyond 60km/h, the trend increases in magnitude with positive

![Proportion of approach rear end crashes by speed zone](image)
crossfall sites accounting for a larger amount of approach rear end crashes. Increases to the posted speed limit correlate strongly to increased proportions of approach rear end crashes at positive crossfall roundabouts.

**Approach rear end crashes by vehicle type**

Figure 9 highlights the distribution of vehicle types involved in approach rear end crashes. The results are reflective of the overall results skew towards positive crossfall sites. Neither vehicle type is overrepresented given the statistical information on registered road fleets.

There is a strong indication that vehicle type does not affect approach rear end crash proportions at roundabouts. This places added significance on site factors including crossfall.

![Figure 9 Vehicle types involved in approach rear end crashes](image-url)
Key findings - approach rear end crashes

- Positive crossfall sites account for approximately 2/3 of approach rear end crashes

- Neither crossfall type exhibited varied proportions of crashes during wet conditions

- At low speeds (0-50km/h), negative crossfall roundabouts account for an overrepresented proportion of approach rear end crashes

- The majority of the approach rear end crashes occur in 60km/h speed zones with positive crossfall sites accounting for 2/3 of these crashes.

- Above 60km/h, negative crossfall sites account for an underrepresented proportion of approach rear end crashes.

- Neither type of crossfall exhibited varied proportions of crashes for different vehicle types
4.2 Entry/Circulating Crashes

An Entry/circulating crash is the most common form of crash at roundabouts. The data collected identified 3,848 of the 10,458 crashes as entry/circulating crashes. This equates to approximately 40% of the total roundabout crashes.

Extensive investigation has been undertaken by academics to explain this type of crash since it accounts for the largest proportion of roundabout crashes. The general consensus of findings indicates approach speed is a major causation factor and reductions in the approach speed translated successfully to a reduction of entry/circulating crashes at roundabouts.

The majority of roundabout design principles and reference material supports the practice of reducing speed limits of approach geometry towards a roundabout. Arndt’s crash research, including his crash prediction modelling indicates the major proportion of crashes is the entry/circulating type at roundabouts. No investigation has been undertaken to determine the potential causation effects of these proportions and trends based on the crossfall of the circulating carriageway.

Multiple criteria are examined in this analysis to attempt to identify a correlation between the crash proportions and rates, and the type of crossfall at roundabouts.

For this investigation, roundabout crashes in 2010 were used to deliver trends and findings. A single year was chosen due to the relatively large number of crashes per individual year. A total of 466 crashes were recorded in 2010. This is sufficient sample to analyse and extract trends. 17 crashes occurred at roundabouts that have since been upgraded or unable to accurately sighted. These have been removed from subsequent analysis in this dissertation. The use of 2010 resolves limitations and risks of superseded data and changes to the road environment since the time of crash.
A majority of entry/circulating crashes occurred at negative crossfall roundabouts. This trend is inversely proportional to the approach rear end crash results. There is an overrepresentation of almost 2:1 for entry/circulating crashes at negative crossfall roundabouts. Further statistical analysis was undertaken to determine co contributing impacts.

**Proportion of entry/circulating crashes by speed zones**

The approach speed zones were collated and assessed to determine the weighting of speed towards these crashes. Arndt, Maycock and Hall and others identified speed as a leading contributor to entry/circulating crashes. As shown in Figure 11, lower speed zones, in this instance, speed zones at 60km/h or lower are extremely overrepresented. They account for more than 95% of all entry/circulating crashes. Given the majority of results occur in two speed zones, they are both consistent with the overall proportion of positive
and negative crossfall crashes shown in Figure 10. The effect of crossfall is diminished by the stronger correlation with lower speed zone roundabouts.

As speed zones increase the rate of entry/circulating crashes diminishes proving that high-speed zones do not significantly affect the rate of entry/circulating crashes. Furthermore, the split between the types of crossfall approaches parity at these speed zones. It is noted that the number of results in these speed zones is relatively small. Regardless, a relatively even distribution of the high-speed speed zone crashes indicates a random nature of events, less dependent on recurring circumstances.

A limited correlation between crossfall and entry/circulating crashes is available. Speed zones appear to be the primary affectation factor, especially at low speed negative crossfall roundabouts.

### Entry/Circulating Crashes in different Speed Zones

![Chart showing number of crashes in different speed zones](chart.png)

**Figure 11** Entry/circulating crashes by speed zone
Vehicle types involved in entry/circulating crashes

Light vehicles account for the large majority of vehicles at fault, which is consistent with the road registered fleet being 94% light vehicles (e.g. cars) (Queensland Transport, 2013).

The mixture of vehicle types involved in entry/circulating crashes at roundabouts closely represents the registered road fleet in Queensland and is adherent to the 2:1 overall ratio between positive and negative crossfall. It is conclusive that vehicle type does not affect the rate and proportion of entry/circulating crashes.

The information in Figure 12 is consistent with the data in about speed zones in Figure 11 since those roundabouts are generally smaller and trafficked by light vehicles, accounting for the large proportion of light vehicle involvement.
Proportion of entry/circulating crashes on wet roads

As per the vehicle type comparison, the overall 2:1 ratio of crashes between crossfall types is closely maintained in Figure 13. This indicates wet road surface conditions impact both types of sites equally.

Approximately 17% of crashes occurred on a wet road surface, which is similar to the 15% of approach rear end crashes that occurred on wet road surfaces.

Entry/Circulating Crashes under different road surface conditions

Figure 13 Proportion of entry/circulating crashes with wet/dry road surface

Intended movements for at-fault vehicles in entry/circulating crashes

Straight through movements are an overriding majority in entry/circulating crashes, as shown in Figure 14, accounting for 72% of entry/circulating crashes. Although in relatively minor amounts, right turning vehicles are in nearly twice as many entry/circulating vehicles as left turning vehicles, 18% and 10% of the total crash count respectively.

The straight through movement proportion mirrors the overall ratio of crashes between positive and negative crossfall sites. However in instances where the
at-fault vehicle intended to turn (left or right) at roundabouts the proportion of crashes between positive and negative crossfall approaches parity.

Effectively, the rate of involvement in entry/circulating crashes increases for vehicles turning left or right at positive crossfall sites. Straight through movements follow the aforementioned trends for entry/circulating crash rates and do not vary in proportion.

**Figure 14 Intended movement of at-fault vehicle in entry/circulating crashes**

**Key findings - entry/circulating crashes**

- Negative crossfall sites account for approximately 2/3 of entry/circulating crashes
- Low speed zones (0-60km/h) account for approximately 96% of the entry/circulating crashes
- Higher speed zones are underrepresented entry/circulating crashes
- Neither crossfall type exhibited varied proportions of crashes during wet conditions
• 72% of entry/circulating crashes occurred with the vehicle intending to travel straight through.

• The proportion of entry/circulating crashes at positive crossfall sites approached parity for turning movements
4.3 Single Vehicle Crashes

Single Vehicle crashes are defined in Section 2 of this dissertation and comprise crashes which the vehicle on the roundabout has lost control. Results of these accidents include:

- Existing the road area in an uncontrolled manner
- Colliding with roadside objects
- Colliding with other stationary vehicles

Single vehicle crash statistics do not include overturning accidents. These will be discussed independently in the following section.

Single vehicle crashes accounted for 2,865 crashes of the 10,458 crashes, equating to 27% of all roundabout crashes in Queensland between 2001 and 2012. The following investigation of single vehicle crashes focuses on such crashes occurring in Queensland during 2010. 269 accidents were identified, which includes 17 crashes at roundabouts that have since been upgraded or unable to accurately sighted. These have been removed from subsequent analysis in this dissertation. The effective total of 252 has been analysed.

The single vehicle crashes occur with a higher rate on negative crossfall roundabouts. The breakdown of single vehicle accidents is similar to the breakdown of entry/circulating crashes between crossfall types.

A similar assessment of causation factors was undertaken to determine the weighting of crossfall on circulating carriageway, contributing to these crashes.

As shown in Figure 15, negative crossfall sites accounted for 62% of the single vehicle crashes in 2010.
Proportion of single vehicle crashes by speed zone

Similar to entry/circulating crashes, there is a large overrepresentation in speed zones up to 60km/h with 94% of crashes occurring in these speed zones.

At 60km/h, the proportion of crashes between the different sites approaches parity. This parity between crossfalls is not reflected at speeds other than 60km/h. At speed zones other than 60km/h, the proportion of single vehicle crashes at positive crossfall crash sites reduces to approximately 25%.

At speed zones above 60km/h there are further reductions in the participation of positive crossfall crash sites, accounting for 3 of 15 (20%) of the total.
The profile of vehicles involved in single vehicle crashes does not accurately reflect vehicle traffic and the registered road fleet. Traffic volumes are not available to determine the volumes of traffic and vehicle types using each roundabout however based on the results shown in Figure 17, particular vehicle types are overrepresented.

Motorcycles and bicycles are heavily overrepresented in single vehicle crashes. They account for approximately 18% of the total. This is a significant proportion given that motorcycles represent a minority of the road-registered fleet of vehicles in Queensland. According to the Australian Bureau of Statistics, they accounted for less than 5% of total registrations in Queensland in 2010. Consistent with the overall proportion of single vehicle crashes in Figure 15, negative crossfall roundabouts result in a higher rate of motorcyclists losing control.
Figure 17 Vehicle types involved in single vehicle crashes at roundabouts

Proportion of single vehicle crashes on wet roads

Figure 18 illustrates the impact of a wet road surface in a single vehicle crash at roundabouts. In this assessment, wet surfaces are present in almost 40% of all single vehicle crashes. This is significantly larger than the mean value of 16% for wet surface involvement in approach rear end and entry/circulating accidents.
The rate of accidents under dry conditions is consistent with overall findings. In relative terms, negative crossfall is represented in approximately twice as many single vehicle crashes as positive crossfall sites. There are a significantly higher proportion of crashes on positive crossfall sites with a wet road surface. The proportion approaches parity.

Further consideration of motorcycles crashes reveals that six crashes occurred in wet conditions and on negative crossfall roundabouts. This equates to 6 of the 34 (18%) identified in the previous section. 1 of 12 (8%) crashes was recorded on a wet positive crossfall site. There is sufficient evidence to suggest a correlation between motorcycles, wet surface conditions and the crossfall of a roundabout with positive crossfall performing better in wet conditions.

Light vehicles comprised the majority of wet surface accidents, accounting for 42 of the 46 at negative crossfall sites and 44 of the 49 at positive crossfall
sites. These proportions are consistent with the overall representation of light vehicle involvement in single vehicle crashes at roundabouts.

Apart from motorcycles, the rate of single vehicle crashes at positive crossfall sites increases on a wet road surface with 47% of single vehicle crashes at involving a wet road surface. At negative crossfall sites, 32% involved wet surfaces. Both proportions are relatively high when compared to other crash types. The near 50% involvement in single vehicle crashes at positive crossfall roundabouts indicates a strong correlation between wet road surfaces and positive crossfall roundabouts.

**Intended movements in single vehicle crashes**

As with entry/circulating accidents, the intended movement of the crashing vehicle is often a straight through movement. In single vehicle crashes, the vehicle is performing a straight through movement in over 75% of crashes. Neither crossfall is overrepresented in any of the movements. Right turn crashes result in a slightly higher proportion of positive crossfall crashes. The increase is not significant given the relatively small proportion of accidents observed compared to the large amount of movements performed.
Figure 19 highlights the correlation between straight through movements and single vehicle crashes. The effect of crossfall is less prominent.

However, Table 3 outlines the proportions of crashes for each intended movement with a wet road surface. The results are consistent with the proportions described in the previous section with positive crossfall forming a consistent majority of crashes in wet conditions.

<table>
<thead>
<tr>
<th>Intended Movement</th>
<th>Positive Crossfall</th>
<th>Negative Crossfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Turn</td>
<td>37%</td>
<td>33%</td>
</tr>
<tr>
<td>Straight Through</td>
<td>50%</td>
<td>30%</td>
</tr>
<tr>
<td>Right Turn</td>
<td>42%</td>
<td>27%</td>
</tr>
</tbody>
</table>
The consistency between Table 3 and Figure 18 highlights the overriding contributor to single vehicle crashes is the wet road surface, particularly at positive crossfall sites. Under wet conditions, the intended movement of the vehicle is a minor factor with each movement similarly impacted.

**Key findings - single vehicle crashes**

- Negative crossfall sites account for approximately 2/3 of single vehicle crashes at roundabouts
- 94% of crashes occurred in speed zones of 0-60km/h speed zones
- Higher speed zone crashes underrepresented on positive crossfall roundabouts. Accounted for 20% of these crashes (3 of 15)
- Motorcycles are overrepresented in single vehicle crashes, accounting for 18% of all crashes with a higher representation of motorcycle crashes at negative crossfall sites.
- Positive crossfall roundabouts reduced rate of motorcycle crashes in wet weather.
- 47% of positive crossfall and 32% of negative crossfall crashes occurred on a wet road surface.
- Approximately 77% of crashes occurred with the vehicle intending to perform a straight through movement.
4.4 Overturned Crashes

Overturned Crashes are preceded by large lateral forces on vehicles. As outlined in literature reviewed in Section 2, roundabouts provide an ideal environment to promote rollover of vehicles. Overturned crashes are a specific form of single vehicle crash that will be considered separately in this section.

For the assessment of overturned crashes, data was collated for all roundabouts in Queensland between 2001 and 2012. A total of 159 overturned crashes occurred during this period. 12 occurred on roundabouts that have since been upgraded or were unable to be accurately sighted. These have been removed from subsequent analysis in this dissertation. An effective total of 147 has been analysed in this section. This equates to an overturning proportion of approximately 1.5% of crashes, which is consistent with the statistical research by Arndt in 1998.

Figure 20 outlines the overrepresentation of positive crossfall overturned crashes. Positive crossfall sites account for 70% of the total overturned crossfall crashes recorded.
Figure 20 Overturned crashes at roundabouts

Rate of crashes per roundabout

A repeated crash type at roundabouts indicates a design deficiency or external factor that creates a hazard to traffic. As shown in Figure 21, the difference between the numbers of sites for positive and negative crossfall crashes compared to the number of crashes recorded at positive crossfall sites is larger.
68 unique positive crossfall sites provided 102 overturned crashes, whilst 42 negative crossfall sites provided 45 overturned crashes. The discrepancy is significant with the identified positive crossfall sites accounting for an average of 1.5 overturned crashes whilst negative crossfall sites appeared to produce the single crash.

This high recurrence across multiple positive crossfall roundabouts highlights the strong correlation between the design of positive crossfall roundabouts and overturned crashes.

**Proportion of overturned crashes by speed zone**

Over 75% of overturned crashes at roundabouts occurred in speed zones of 0-60km/h. Two distinct trends are shown in these low speed zones. Overturned crashes on negative crossfall sites at or below 50km/h are...
overrepresented. They account for approximately 63% of the accidents in this speed zone range.

At 60km/h, the trend reverses with the proportion of overturned crashes at negative crossfall sites reducing to 36%. Two thirds of all overturned crashes occurred at 60km/h.

Beyond 60km/h, positive crossfall roundabouts are infinitely overrepresented with 35 accidents compared to none recorded at negative crossfall roundabouts. This is a large overrepresentation and a strong indication of the link between high-speed roundabouts, positive crossfall and overturned crashes.

![Overturned Crashes in different speed zones](image)

Figure 22 Overturned crashes in different speed zones

**Overturned crashes by vehicle type**

Figure 23 highlights the proportion of vehicle types involved in overturned crashes. As suggested in section 2, there are a substantial proportion of
heavy vehicles represented in vehicle rollovers. Including, other vehicles which are special purpose vehicles and heavy in nature, they account for over 40% of the overturned crash statistics. This finding is consistent with the Milliken and de Pont research that found that heavy vehicles were involved in 40% of rollovers at horizontal curves. Considering the heavy vehicle fleet comprises less than 15% the registered vehicle fleet in Queensland (Australian Bureau of Statistics, 2014) this is a significant overrepresentation.

In relative terms, 70% of heavy vehicle rollovers occurred at positive crossfall sites, which is identical to the proportion of light vehicles involved in positive crossfall rollovers. This diminishes the relationship between positive crossfall and heavy vehicles and broadens it to all vehicle types.

![Number of Overturned Crashes by Vehicle Type](image)

**Figure 23 Overturned crashes by vehicle type**
Proportion of overturned crashes on wet roads

Figure 24 highlights the ratio of overturned crashes on wet and dry road surfaces. The proportion of dry weather crashes is consistent with overall findings.

Number of Overturned Crashes under different road surface conditions

The proportion of wet surface crashes to dry surfaces is relatively high, although consistent with the single vehicle crash proportions. Approach rear end and entry/circulating crashes are multi vehicle crash types and had wet weather involvement of approximately 15%.

Single vehicle crashes including overturned, have dramatically higher involvement with approximately 40% on wet surfaces. Contrary to this overrepresentation of wet surface crashes; negative crossfall roundabouts are underrepresented, accounting for less than 7% of the total crashes, compared to 33% for positive crossfall sites.
63% of the accidents that occurred in speed zones of 70km/h and greater occurred on wet road surfaces. This confirms a strong propensity for overturned crashes between high-speed zones, a wet road surface and positive crossfall roundabouts. Under the same conditions, no accidents were reported at negative crossfall sites, confirming the contribution of positive crossfall in these crashes.

**Intended movements of vehicles in overturned crashes**

Figure 25 highlights the different intended movements of the overturned vehicles. During all movements, excluding the straight though movement, the amount of accidents approaches parity, indicating an underperformance of negative crossfall sites or improved performance of positive crossfall sites. The overall findings indicated two-thirds of crashes were on positive crossfall sites however when considering movements alone, the proportion reduces to an almost even distribution for turning movements.

The results for overturned crashes by vehicles intending to travel straight at roundabouts is significantly in favour of negative crossfall sites and completely offsets any benefits positive crossfall may offer turning vehicles. Almost half of all overturned crashes occurred with vehicles travelling straight at positive crossfall sites.
Additionally, 49% of the straight through crashes at positive crossfall sites included wet road surfaces. This is significantly higher proportion than negative crossfall crashes of the same type. This indicates a strong correlation between positive crossfall sites, straight through movements and particularly with a wet road surface.

**Key findings - overturned crashes**

- Positive crossfall sites account for approximately 70% of overturned crashes
- Higher rate of crashes at each positive crossfall roundabout assessed
- 63% of overturned crashes in 0-50km/h speed zones occurred with negative crossfall roundabouts
• Above 60km/h, positive crossfall sites accounted for all overturned crashes.

• Heavy vehicles accounted for 40% of all crashes with 75% of these occurring at positive crossfall sites.

• 40% of crashes occurred on a wet road with 83% of these at positive crossfall sites.

• 63% of crashes in speed zones above 60km/h occurred on a wet road with all of these at positive crossfall sites.

• 46% of all crashes occurred at positive crossfall sites with the overturned vehicle performing a straight through movement at the roundabout. 49% of these crashes included wet roads.

• The proportion of overturned crashes at both crossfall types approached parity for turning movements
### 4.5 Summary of Results

Table 4 Summary of Results

<table>
<thead>
<tr>
<th></th>
<th>Overall Proportion</th>
<th>Impact of Speed Zone</th>
<th>Impact of Wet Weather</th>
<th>Impact of Vehicle Type</th>
<th>Impact of Intended Movement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Approach Rear End</strong></td>
<td>Positive crossfall accounts for 2/3 majority</td>
<td>Negative crossfall overrepresented in 0-50km/h speed zones. Majority of crashes occur at 60km/h with positive crossfall accounting for two-thirds. Above 60km/h, positive crossfall overrepresented</td>
<td>None</td>
<td>None</td>
<td>Not Applicable</td>
</tr>
<tr>
<td><strong>Entry/ Circulating</strong></td>
<td>Negative crossfall accounts for 2/3 majority</td>
<td>96% of entry/circulating crashes occurred in 0-60km/h speed zones Higher speed zones significantly underrepresented</td>
<td>None</td>
<td>None</td>
<td>72% of crashes intended straight through movements with 2/3 of these crashes on negative crossfall sites Crossfall had negligible impact on turning movements with almost even distribution</td>
</tr>
<tr>
<td></td>
<td>Overall Proportion</td>
<td>Impact of Speed Zone</td>
<td>Impact of wet weather</td>
<td>Impact of Vehicle Type</td>
<td>Impact of intended Movement</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Single Vehicle</strong></td>
<td>Negative crossfall accounts for 2/3 majority</td>
<td>94% of crashes occurred in 0-60km/h speed zones  Positive crossfall underrepresented in higher speed zone crashes</td>
<td>47% of positive crossfall crashes and 32% of negative crossfall crashes occurred on a wet road surface</td>
<td>Motorcycles overrepresented, accounting for 18% of crashes with a higher representation at negative crossfall sites.</td>
<td>77% of crashes intended straight through movement with neither crossfall overrepresented.</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Significant reduced rate of motorcycle accidents in wet weather on positive crossfall roundabouts</td>
<td></td>
</tr>
<tr>
<td><strong>Overturned</strong></td>
<td>Positive Crossfall account for 70% majority  Higher rate of crashes at each positive crossfall roundabout assessed</td>
<td>Negative crossfall overrepresented in low speed zones.  Positive crossfall infinitely overrepresented in higher speed zones</td>
<td>Wet road surfaces accounted for 40% of overturned crashes. 83% of these crashes were at positive crossfall sites.</td>
<td>Heavy vehicles are involved in 40% of crashes. 75% of these crashes were at positive crossfall sites.</td>
<td>Straight through movements at positive crossfall sites were significantly overrepresented accounting for almost half of the overturned crash total. 49% of these crashes occurred with a wet road surface. Negative crossfall sites overrepresented in turning movement rollovers</td>
</tr>
</tbody>
</table>

At speed zones above 60km/h, wet road surfaces were significantly overrepresented, contributing to 63% of all crashes.
Higher Speed Zones (above 60km/h)

An underlying theme in the results presented throughout Section 4 is the significantly higher number of crashes that occurred at higher speed zone, positive crossfall roundabouts. Table 5 highlights the discrepancy between the positive and negative crossfall roundabouts, when higher speed zone crashes are isolated. The strong correlation is a testament to the potential unsuitability of positive crossfall roundabouts in higher speed zones. Factors affecting the various crash types will be discussed further in Section 5.

Table 5 Summary of crashes at roundabouts greater than 60km/h

<table>
<thead>
<tr>
<th></th>
<th>Positive Crossfall Crashes</th>
<th>Negative Crossfall Crashes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach Rear End</td>
<td>124</td>
<td>14</td>
</tr>
<tr>
<td>Entry/Circulating</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>Single Vehicle</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Overturned</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>169</td>
<td>36</td>
</tr>
</tbody>
</table>
5. Discussion

5.1 Approach Read End Crashes

Positive crossfall roundabouts resulted in a two-thirds majority involvement in approach rear end crashes. The result supports the commentary in *Austroads: Guide to Road Design* that suggests the sunken island, a unique part of positive crossfall roundabouts would limit approach sight and contribute to a higher rate of approach rear end crashes.

A significantly higher amount of crashes were recorded at positive crossfall roundabouts despite a similar number of positive and negative crossfall roundabout sites. This discrepancy highlights the nature of approach rear end crashes at positive crossfall roundabouts and supports the basis of this research.

Approach rear end crashes rely on approaching drivers sighting roundabout traffic and making a decision to enter the roundabout or give way. Following traffic must make a consistent decision otherwise there is potential for an approach rear end crash or at least heavy braking (Ogden & Newstead, 1994).

When considering positive and negative crossfall sites, a number of approaches and roundabout island views were observed as part of this research. Negative crossfall roundabouts were overrepresented in low speed zones. As shown in Figure 26, the availability of approach sight to adjacent legs of the roundabouts can be limited because of surrounding land use. This scenario is especially common in low speed zones.

These roundabouts are generally designed with less deflection and little consideration of vehicle performance. In many instances of the data collection process, it was observed that they were a retrospective intersection treatment for local roads. Another low speed roundabout is shown in aerial view in
Figure 29. The similarities in layout are representative of the majority of low speed zone roundabouts.

Negative crossfall roundabouts also formed the majority of low speed zone roundabouts due to the inherent difficulties in constructing a positive crossfall roundabout at a local road intersection. Constructing a positive crossfall roundabout requires additional drainage works to the central island and reconstruction of pavement to invert the crossfall and remove the crown of the road. There is also the requirement to extend the area of works to develop smooth crossfall transitions from edge draining approaches (negative) to centre draining (positive) pavement.

In the context of local roads works, these are major civil construction tasks. It is much more cost efficient for local road authorities to construct negative crossfall roundabouts. Local road authorities are most hindered by financial constraints and scope of work limitations. As a result, negative crossfall roundabouts comprised a significant portion of low speed zones.

For these reasons, it is not possible to develop a rigorous link between negative crossfall at roundabouts and the overrepresentation of approach rear end crashes since the trend is confined to low speed, smaller roundabouts which do not allow one to isolate crossfall as a significant cause.
Roundabouts in speed zones of 60km/h and above were generally much larger in size and often contained multiple lane approaches. It is in this context that approach rear end crashes increased significantly and the trend is reversed from low speed findings to show an increase proportion of approach rear end crashes at positive crossfall roundabouts.
As outlined, the nature of roundabout design and location is significantly varied for different speed zones. There are two main differences in roundabouts that are located in higher speed areas.

- Larger radii islands
- Increased number of lanes and delineation

These elements combine to create a road environment that is inherently more difficult to comprehend and process for approaching drivers. As proposed by Ogden and Newstead, the increased information that a driver is forced to contend with, the increased likelihood that incorrect judgements are made.

In the specific context of this research, the number of lanes and delineation are not specific to positive crossfall roundabouts. However, the complementary crossfall on the central island increases the probable travel speeds for roundabout vehicles increases.

As outlined in Section 1 of this dissertation, the intention of the roundabout is to minimise speed differential at conflict points. The two factors listed above contribute to increased vehicles speeds on the circulating carriageway. Conversely, approaching traffic is faced with reductions in decision-making time, increased difficulty of judging the rate of approach of circulating vehicles. This is compounded for following vehicles.
Figure 27 A positive crossfall roundabout at Sunshine Motorway ramps/Yandina-Coolum Road, Coolum Beach (Google, 2014)

Figure 27 depicts a positive crossfall roundabout with a view of the circulating carriageway. The critical difference is that the crossfall is complementary to vehicles on the circulating carriageway. The speeds attainable on this carriageway are significantly larger than negative crossfall equivalents.

A simple assessment of the point mass equation (refer to equation 2), as extracted from Austroads: Guide to Road Design allows the production of the graph in Figure 28.
Equation 2 Point mass equation for horizontal curves (Austroads, 2009)

\[ e + f = \frac{V^2}{127R} \]

where:
- \( e \) = crossfall (m/m)
- \( f \) = side friction factor
- \( V \) = speed (km/h)
- \( R \) = curve radius (m)

**Figure 28 Safe speeds on horizontal curves**

Figure 28 shows the discrepancy between safe speeds attainable on the circular carriageway when the crossfall varies between positive and negative. For the purpose of this assessment a side friction factor of 0.5 has been used. This is irrelevant as it is constant for both crossfall types.
The intention of Figure 28 is to highlight the positive correlation between safe speeds and the central island radius. This corresponds with the data discussed in Section 4. Higher speeds zones are overrepresented in approach rear end crashes.

There is a definite link between high-speed zones and positive crossfall roundabouts. Naturally, high-speed zones require increased deceleration and speed changes to avoid collision (Yan, 2005) however positive crossfall roundabouts in these zones are characterized by larger central island radii. Larger radii coupled with positive crossfall greatly increase the speed attainable on the circulating roundabout. Cars are most capable of exploiting the higher speeds and as shown in Figure 9, account for an extremely large proportion of the approach rear crashes. One could conclude the increased speed of circulating roundabout traffic results in reduced decision-making time for approach traffic and therefore presents increased hazard as vehicles brake at an increased or unpredictable rate to avoid collision.

The Austroads commentary that indicates that a sunken island is not as visible to following traffic is difficult to prove as a cause of approach rear end crashes. However, based on Figure 26 and Figure 27, the respective islands are always accompanied by a combination of signposting, road furniture, vegetation and approach islands. These elements are conspicuous in a road environment and would negate the potential lack of sight to the central island, in a similar fashion that traffic signals negate the lack of sight to stop lines at signalised intersections.

In summary, the speed zone and context of the roundabout plays a significant role in approach rear end crashes. The increased amount of approach rear end crashes observed in higher speed zones corresponded with positive crossfall roundabouts facilitating higher travel speeds reducing the capacity of approaching drivers to make timely, suitable decisions. Negative crossfall roundabouts do not afford circulating vehicles the ability to maintain higher
speeds and therefore do not shorten approach times between conflict points. The overrepresentation of approach rear end crashes at low speed, negative crossfall roundabouts is attributed to the greater number of these sites and their commonality.
### 5.2 Entry/Circulating Crashes

Entry/circulating crashes are the most common accident type at roundabout intersections, accounting for almost 40% of the recorded crashes. As outlined in Section 2, the entry speed of vehicles is considered the largest cause. Analysis of the 449 crashes that occurred at Queensland roundabouts in 2010 produced a two-thirds majority of crashes at negative crossfall sites.

Besides the majority occurring at negative crossfall roundabouts there are two significant factors that exhibit a larger role than a site’s crossfall. The following overrepresentations confirm speeding and lack of approach sight distance as significant factors in entry/circulating rashes:

- Straight through movements were intended in 72% of the crashes
- Most crashes occurred at generally smaller sized roundabouts, as supported by the high contingency of low speed zone roundabouts.
- 96% of crashes occurred at roundabouts in 0-60km/h speed zones

These factors are consistent with creating a propensity to maintain speed through the roundabout. There are several justifications that support these findings:

- There is less deflection at smaller and lower speed zone roundabouts allowing drivers to maintain relatively straight alignments and therefore higher approach and departure speeds. The ability to maintain momentum of the vehicle is increased as deflection and changes in direction are minimised. Close reference to Figure 29 highlights the trafficked areas on the road pavement. The trafficked areas resemble ‘racing lines’ coinciding with apex of the straight through movements.
- There is significantly less approach sight distance at smaller and lower speed zone roundabouts reducing the imminence of other traffic. As
shown in Figure 26, the typical urbanised roundabout setting includes property development boundaries that are within a few metres of the roadway. This reduces the sight to oncoming traffic and increases the likelihood of crashes for risk taking driver behaviour.

• Straight through movements allow drivers to maintain momentum on approach since the lateral forces on the vehicle do not near those induced when turning. As a point of reference, vehicles performing turning movements and becoming involved in entry/circulating crashes were relatively underrepresented and evenly distributed across all speed zones and both crossfall types.

• There are significantly wider sight envelopes between approaching and circulating vehicles at higher speed roundabouts. The sight envelope allows additional time to avoid a collision by giving way. The higher speed zone roundabouts also include multiple, wider lanes. This additional area improves the chances of crash avoidance since drivers on the circulating carriageway are afforded the option of taking defensive or evasive manoeuvres in advance to avoid fast approaching vehicles or those which do not give way. The same benefits are not available in low speed, local road settings.
There is an overrepresentation of roundabouts promoting faster, direct approaches coupled with the scarcity of positive crossfall equivalents in the same settings. This results in a numerical bias towards negative crossfall roundabouts and subsequent overrepresentation in entry/circulating crashes. Approach geometry design standards and requirements do not differ between the crossfall types. The pattern of results lends itself to speeding and roundabout approach design as the most significant causes. These findings coincide with the Arndt, Maycock and Hall and Austroads research examined in Section 2 of this dissertation. The effect of crossfall in entry/circulating crashes is not apparent in this study.
5.3 Single Vehicle Crashes

Single vehicle crashes are a broad category of crash however they result in a common outcome with the crashing vehicle leaving the road or colliding with an object. A single vehicle crash is usually preceded by a loss of control. The four primary causes are outlined in Section 2 of this dissertation.

The results collated for single vehicle crashes in Queensland, 2010 produced a two-thirds majority occurring at negative crossfall roundabouts. This result under represents the significance of positive crossfall in single vehicle crashes. The results indicated, similar to entry/circulating crashes, that the majority (96%) occurred in 0-60km/h speed zones. As discussed in Section 5.2, the nature of these roundabouts is significantly different to higher speed roundabouts.

The proportion of crashes at 60km/h zones was approximately equal between the crossfall types. However, 85% of the positive crossfall crashes occurred in this speed zone. Another 14% occurred in 0-50km/h range. The significant weighting of positive crossfall, single vehicle crashes at lower speed roundabouts proves its lack of suitability to these speed zones.

The similarity in crash totals is reflected by the similar nature of the roundabouts at lower speeds. There is little difference in the performance of the positive and negative crossfall at low speed roundabouts. Referring to Figure 28, positive crossfall roundabouts provide minimal speed advantage compared to an equivalent negative crossfall roundabout at low speeds. The difference in safe speeds lessens as the size of the roundabout is reduced. This proves at smaller sized roundabouts (coinciding with lower speed zones) there is little difference between the crossfall types.

Beyond 60km/h, there is a sudden reduction in single vehicle crashes on positive crossfall sites. This can be attributed to the higher safe speed thresholds when compared to negative crossfall sites. Negative crossfall sites accounted for 80% of all single vehicle crashes in speed zones above
60km/h. As shown in Figure 28, the difference in safe speed thresholds widens considerably as the size of the roundabout increases.

Two examples of roundabouts are shown below. Figure 30 depicts a negative crossfall roundabout at the Aquatic Centre Drive/Burpengary-Caboolture Road intersection, Burpengary. Figure 31 shows a positive crossfall roundabout at the intersection of Dawson Highway and Harvey Road, Clinton. Both roundabouts are located in 60km/h speed zones and contain a central island radius of 20 metres. The significant difference in the context of single vehicle crashes is the different travel speeds that traffic can safely sustain on the circulating carriageway. The roundabout at Burpengary provides a safe travel speed of approximately 27km/h whilst the roundabout at Clinton would allow speeds of approximately 37km/h on the circulating carriageway. This increased threshold is reflected in the reduction in single vehicle, higher speed zone crashes at positive crossfall roundabouts.
Near even distribution of crashes between crossfall types at lower speeds indicates that the primary cause of single vehicle crashes is not the crossfall on the circulating carriageway. Elements of these roundabouts are discussed in previous sections and demonstrate the confined nature and limitations with such roundabouts. Specifically, the lack of deflection, driver propensity to maintain speed and predominance of straight through movement involvement again leads one to conclude that speed is the overriding factor in single vehicle roundabout crashes at smaller roundabouts.

The smaller roundabouts, such as Figure 29, highlight the ease with which drivers can perform relatively minor, sudden direction changes to circumvent the island and continue through the roundabout. These movements are erratic, create sudden forces on the tyres and are proven by the ‘racing lines’ on the road pavement.
Wet road surfaces featured extensively in single vehicle crashes. At positive crossfall sites, 47% of crashes were affected by road surfaces and 32% for negative crossfall sites. The increased amount of crashes with wet road surface conditions indicates the sensitivity of the relationship with single vehicle crashes. The nature of the low speed zone roundabouts allow drivers to perform short, sudden turning movements to deflect pass the small central islands. This leads to friction capabilities being tested. With wet roads, this friction is reduced and results in losses of control. The presence of moisture accounted for a significant portion of single vehicle crashes.

More significant, was the proportion of involvement in positive crossfall crashes. Analytically, the reduction in friction affects the safe speeds in similar proportions and would not bias a particular crossfall. However, the results indicated the proportion of involvement in positive crossfall crashes was 47%, compared to 32% for negative crossfall. The major point of difference is the
need for positive crossfall roundabouts to channel water towards the central island. As shown in Figure 27, the central island includes kerbs and other drainage inlet points to allow the water to enter the central island drainage system.

The analysis of hydraulics is beyond the scope of this investigation although remains pertinent to these crash findings. In summary (Ghandour et al, 2010):

- The depth of flow is a significant factor in the available friction between tyres and a wet road
- Depth of flow increases as drainage flow path lengths increase.

Drivers tend to follow delineation provided and edge features (Austroads, 2009). In the instance of positive crossfall sites during wet weather, the guidance is along the centre island and littered with relatively deep water flows, pollutants from vehicles, litter and sediments that reduce friction at the tyre road interface (Ghandour et al, 2010).

Furthermore, Austroads recommends a one-metre width of flow guidance on road drainage in usually 10-year ARI storm events. The majority of roundabouts observed for analysis did not include island side shoulders, indicating that the width of flow requirements, even if satisfied would be up to one metre inside the travel lane. It is acknowledged that roundabout lane widths are wider than conventional traffic lanes due to turning requirements however, incremental increases in flow depth at the island result in proportionally larger increases in flow width due to the triangular channel flow cross section. This results in a maximised intrusion of water into trafficked areas of the circulating carriageway.
Asset management practices and design guidelines would need to more sensitive to these operational issues.

With positive crossfall promoting these hydraulic issues, there is a strong justification for the larger proportion of single vehicle crashes at positive crossfall sites with wet road surfaces.

Assessment of crashes by vehicle type and intended movements indicated motorcycles and straight through movements were overrepresented. The involvement of motorcycles, mostly in dry road surface conditions indicates driver behaviour and tendency to utilise higher speed thresholds offered by a motorcycle. The Motorcycle Council of NSW acknowledges large overrepresentation of motorcycles in single vehicle crashes as most often a driver behaviour issue. Ghandour also found that the weight force on the tyre significantly affected the friction available at the tyre road interface. Negative crossfall roundabouts accounted for a larger amount of motorcycle crashes. This could be attributed to the increased relative lean angle on adverse crossfalls such as at negative crossfall roundabouts. This is reaffirmed by the significantly reduced amount of wet weather, motorcycle accidents on positive crossfall roundabouts.

The straight through movement is the fastest potential movement at a roundabout. This tendency to maintain momentum and speed overrides the crossfall used on circulating carriageways. However, turning movements
require drivers to slow, especially on smaller roundabouts. This is reflected by the relatively even distribution of single vehicle crashes for turning movements on both crossfall types.

In summary, there is a large proportion of single vehicle crashes in low speed zones and at smaller roundabouts. This result suggests that type of crossfall has a minor influence at low speed roundabouts with driver behaviour, speed and the design of the roundabout posing more significant road safety issues. With increased speed and roundabout sizing the application of positive crossfall complements the roundabout and forces generated by vehicles on the circulating carriageway. In the majority of higher speed zone applications positive crossfall roundabouts reduced single vehicle crashes, particularly for motorcycles. Positive crossfall fared worse in wet weather, with the design substantiating hydraulic issues at the central island.
5.4 Overturned Crashes

Overturned crashes were a minority occurrence at roundabouts. 1.5% of all roundabout crashes involved rollovers. The severity of rollover crashes is higher given the nature of the crash, potential for injury and recovery effort required. The results indicate negative crossfall roundabouts are more suitable at resisting overturned crashes since they accounted for 30% of all overturned crashes. This contradicts the theoretical benefits of positive crossfall on the circulating carriageway, particularly for resisting lateral forces on a vehicle since negative crossfall is adverse to the vehicle’s turning movement on the circulating carriageway. 70% of overturned crashes occurred on positive crossfall roundabouts.

The turning movement of vehicles on a circulating carriageway is distinguished into three areas as outlined Section 1. They include the entry, circulating carriageway and exit of the roundabout. The transition between edge draining crossfall (found on all approaches) to positive crossfall on the circulating carriageway and subsequently reverting to edge draining crossfall for the exit generates multiple vehicle rotations and dynamic changes that do not occur on negative crossfall roundabouts. These rotations and changes in lateral slope of the road generate momentum and roll instability, which increases the likelihood of rollovers (ARRB, 1999).

The limitations in providing positive crossfall roundabouts at low speed zones were primarily outlined in Section 5.1. Negative crossfall roundabouts featured in the majority of overturned crashes at low speed (0-50km/h) roundabouts.

Rollover thresholds for light vehicles are relatively high, approximately 1.0g (UMTRI, 2000). The overrepresentation of light vehicles in this category of roundabouts is consistent with the composition of traffic. Low speed zone roundabouts are generally smaller and therefore trafficked by smaller vehicles. A smaller roundabout promotes higher lateral acceleration rates if taken at increased speeds.
Figure 33 highlights the different lateral accelerations achieved when performing turning movements at different speeds. The graph highlights the rapid increase in lateral acceleration achievable on smaller radii curves, such as low speed zone roundabouts.

On smaller roundabouts the lateral acceleration of a vehicle can increase markedly with speed changes of less than 10km/h. There is a sensitive relationship between speed and lateral acceleration at smaller roundabouts. As identified with single vehicle crash results, speeding driver behaviour at these smaller roundabouts accounts for the rollovers. The type of crossfall is inconsequential to such overriding factors.

As with the approach rear end crashes, a large amount of crashes were found to repeat at the same positive crossfall roundabouts. This result indicates sites issues associated with positive crossfall. The positive crossfall roundabouts identified accounted for 50% more crashes than number of sites whilst negative crossfall sites accounted for less than 8% more crashes than number of sites. One could suggest the results at negative crossfall sites, are more random and not linked to site issues. This would support the discussion above suggesting driver behaviour and speeds are the main cause, rather than a crossfall.
Positive crossfall roundabouts accounted for a large proportion of overturned crashes as the speed zone of the roundabout increased. Figure 33 highlights the proportional relationship between speed, lateral acceleration and radii. Increasing of the radii, as found on higher speed zone sites allows increased vehicle speeds. Additionally, Equation 1 highlighted the benefits of positive crossfall towards resisting rollover forces. Based on these two principles, rollover at larger, higher speed roundabouts with positive crossfall would require relatively higher speeds to overcome the compounding countermeasures of positive crossfall and a larger circulating carriageway.

This contradicts the findings, however, the effect of pavement rotation, necessitated by positive crossfall roundabouts, greatly varies the dynamic state of the vehicle. Sudden rotations result in increased tendencies for overturned crashes for vehicles travelling at higher speeds on larger radii,
positive crossfall roundabouts. The rotation of pavement is required to vary between positive and negative for the approach to circulating carriageway to exit sequence of travel. The movement of the vehicle along this path results in rotations that are not found on negative crossfall roundabouts. The rotations create roll instability as the lateral momentum of the vehicle shifts between opposing sides of the vehicle. In-depth mechanical analysis of this process is beyond the scope of this dissertation however; rollover is initiated when the vertical force on one side of the vehicle is zero. This is caused by the lateral force generating a moment that exceeds the weight force on one side of the vehicle; refer to Figure 34 for a diagram of these forces.

![Figure 34 Vehicle rollover (LTSA, 2002)](image)

Negative crossfall roundabouts present increased theoretical basis for promoting rollover however the pavement crossfall is self-explanatory and
consistent throughout the roundabout movement. This predictability allows a driver to ‘feel’ the lateral acceleration and make corrections. In the instance of positive crossfall, the pavement rotations are sudden and would initiate rollover prior to the driver being able to reduce their speed. Self-explaining road environments are key to many of the proposals in Austroads: Guide to Road Design.

The effect of positive crossfall at roundabouts is highlighted by the performance of heavy vehicles. In the analysis of the data, heavy vehicles accounted for 40% of overturned crashes. This is a significant proportion for a minority vehicle type. 75% of the heavy vehicle rollovers occurred on positive crossfall roundabouts, another significant overrepresentation and strong indication of the correlation between positive crossfall roundabouts, heavy vehicles and overturned crashes.

Another finding included the strong correlation between overturned crashes and wet roads. 33% of all rollovers occurred under these circumstances whilst 7% occurred on wet, negative crossfall roundabouts. On wet roads, this is almost a 5:1 overrepresentation of rollovers on positive crossfall roundabouts. The presence of wet roads reduces the available friction between a vehicle’s tyres and the road pavement, using Equation 2, it is evident that safe speed threshold reduces with a reduction in friction. This would indicate that there is an increased likelihood of skidding or loss of control preceding rollover since vehicles would exceed the friction threshold prior to exceeding the lateral acceleration threshold.

The rotation of pavement, presence of traffic islands and varying pavement skid resistances would all positively contribute to maintaining a loss of control and ‘tripping’ the vehicle. The likelihood of rollover increases dramatically once the vehicle rotates perpendicular to the direction of travel (NHTSA, 1977). This is a common method of vehicle rollover and would account for the large proportion of overturned crashes, particularly at positive crossfall
roundabouts. The crash data obtained does not include extensive reporting of incident details to determine preceding events to the rollover of the vehicle.

In summary, rollovers at negative crossfall roundabouts were concentrated in the 0-50km/h speed zone. This is explained by the preference for local roads to adopt negative crossfall roundabouts in most instances. At speed zones of 60km/h and beyond, overturned crashes at positive crossfall roundabouts increased dramatically, despite increased island sizes and supportive crossfall. This contradiction of theory draws attention to the sequence of crossfall rotations through the roundabout movement sequence. Positive crossfall roundabouts have excessive pavement rotations that promote destabilizing forces. Consequently, heavy vehicles were overrepresented. Wet roads were also significantly represented at positive crossfall sites indicating that losses of friction precede rollover crashes.
6. Conclusion

The intention of this dissertation was to investigate the road safety effect of different crossfall at roundabouts.

The review of literature undertaken in Section 2 outlined the existing design guidelines for roundabouts in Australia. A difference in approaches was identified, as in positive and negative crossfall sites. These approaches provided different methods for the design of pavement crossfall at roundabouts, with both aiming to achieve similar objectives. This formed the basis for this dissertation.

A review of literature was extended to examine the benefits and expectations of the respective crossfalls. Little evidence on positive crossfall roundabouts was uncovered although a large amount of information was found regarding crossfall in general, its wider effect on the road and traffic. Literature was also examined on crash rates, proportions and the types of crashes at roundabouts.

Five major crashes types were identified and their relationship to crossfall presented. The evaluation of the road safety aspect of this dissertation stemmed from analysis of these crash types with respect to roundabouts and the type of crossfall.

The methodology employed in this process has been efficient and allowed a large range of data collection and processing to be completed. The results presented address the shortcomings that were identified in the review of existing literature in Section 2 of this dissertation.

Pertinent to the original aim of the dissertation, the following are valuable findings identified in this research.

• The type of crossfall at a roundabout is a significant factor for single vehicle crashes at roundabouts.
• Significant overrepresentation of overturned and approach rear end crashes at positive crossfall roundabouts in higher speed zones
• The use of positive crossfall was found to generally reduce the proportion of single vehicle crashes (excluding overturned crashes) occurring at positive crossfall roundabouts.
• Overturned crashes exhibited a strong correlation with positive crossfall roundabouts. The rotation of pavement required for travel through positive crossfall roundabouts may account for the higher proportion of overturned crashes.
• A wet road lead to a relatively large increase in single vehicle crashes at positive crossfall roundabouts.
• Heavy vehicles were distinctly overrepresented in overturned crashes at positive crossfall roundabouts.
• Motorcycles were distinctly overrepresented in single vehicle crashes at negative crossfall roundabouts.

Many secondary findings, which are not explicitly relevant to the aim of the dissertation, were realised:

• Lower speed roundabouts are ineffective in achieving common roundabout design and safety objectives.
• Multiple vehicle crashes are more prevalent at lower speed, smaller roundabouts.
• Local road authorities have not implemented many small, positive crossfall roundabouts due to the inherent difficulties and costs when compared to negative crossfall roundabouts.
• Wet weather had a low involvement rate in multiple vehicle crashes compared to single vehicle crashes.
This research has resulted in the realisation of valuable outcomes. The results remain broad due to the scope and methodology limitations of this research. The following highlights limitations relevant to the research findings presented:

- The accuracy of accident information is unverifiable
- Crash reports with statements and written descriptions were not utilized in this analysis. They would have improved the value of the information and allowed more accurate categorization of data.
- Traffic volumes at the roundabouts have not been considered. The ability to compare traffic volumes would have allowed analysis and comparison of the relative rates of different crashes and occurrences between the different crossfall types.
- Economic cost of the crashes has not been considered to determine the implications of selecting a particular crossfall type.
- Crash severity was not considered in analysis of the road safety impacts.
- The marginal effects of variations in crossfall were not considered since each site was categorised by positive or negative crossfall only. Further distinction between numerical values of crossfall would improve justification of some findings, particular for overturned crashes.

These limitations illustrate the context with which this research has been conducted, the context with which it should be regarded and importantly, highlights opportunities for further improvement in future research undertakings in this area.
7. Recommendation

There is significant scope to develop the research presented in this dissertation into a series of future works. The original intention of evaluating the effects of crossfall at roundabouts should be maintained although refined and evaluated to greater depths. Many of these recommendations for future work stem from the aforementioned limitations attached to this dissertation.

Future works could include:

- Specific case studies to focus on higher speed zone, positive crossfall roundabouts and their crash performance. Extensive research could be undertaken on this, given the number of sites available in Queensland. Findings could be used to better inform designers’ understanding on the situation to best apply or avoid positive crossfall roundabouts.

- Specific case studies, using detailed crash reports from Queensland Transport’s Road Crash 2 system, which provides descriptions and written statements. Specific sites could also be surveyed to determine numerical values of crossfall relevant to crashes and crash types. This would allow analysis to consider the amount of crossfall present at crashes and potentially refine findings presented in this dissertation.

- Commissioning of specific traffic studies to examine the volume of roundabout traffic over a corresponding period of crash recording. This would allow costs, relative rates and proportions of crash types to be directly compared between positive and negative roundabouts.

- Consideration of road safety could be extended to include crash severity and associated economic costs. A comparison of positive and negative crossfall would outline the overall economic difference in road safety as a result of positive and negative crossfall.
The ultimate aim of this dissertation is ongoing and was undertaken to improve the knowledge regarding the application of crossfall at roundabouts, particularly positive crossfall. The lack of current knowledge regarding positive crossfall at roundabouts is apparent and the roundabout design guidelines and knowledge in Australia do not adequately make this lack of knowledge apparent. Further examination of the consequential effects of the application of crossfall is required to improve awareness of the implications of positive and negative crossfall at roundabouts.
8. References


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9. Appendix A: Project Specification
FOR: Vernon STANTON

TOPIC: INVESTIGATION OF THE EFFECT OF POSITIVE AND NEGATIVE CROSSFALLS ON ROAD SAFETY AT ROUNDABOUTS

SUPERVISOR: Dr Soma Somasundaraswaran

ENROLMENT: Semester One, 2014 – ENG4111
Semester Two, 2014 – ENG4112

PROJECT AIM: Roundabouts are a common form of road intersection and are used to allow self-regulating flows of traffic. As part of a roundabout there are generally three critical geometric considerations, namely, approach geometry, the circular carriageway and the departure geometry. In many instances this geometry is compromised and designed to slow traffic. Consequently, the crossfall of a roundabout becomes an important design consideration. The crossfall must be designed to allow a smooth transition and adequate drainage performance of the circular carriageway. There are two common approaches to roundabout crossfall in Australia, positive and negative crossfalls. This report will aim to investigate and analyse the road safety performance of existing roundabouts with these different crossfalls to evaluate the safety benefits each arrangement may offer.

PROGRAMME: Issue B, 6th January 2014

1. Perform a literature review of published material to identify and analyse roundabout design standards used for positive and negative crossfall roundabouts in Australia.

2. Identify the types of crashes and contributing factors to crashes at roundabouts

3. Collect and analyse crash data at roundabouts to determine the type of crash. Identify the corresponding roundabouts and collect design information to allow analysis of each crash

4. Perform analytical calculations using design standards to determine safe vehicular thresholds at roundabouts

5. Analytically compare incidences at roundabouts with positive and negative crossfalls to determine whether crossfall contributes to crashes and if so, how the different crossfalls affect different vehicles and crash types.
6. Present findings to identify impacts of crossfall on road safety at roundabouts

7. Identify opportunities for further research into topic

AGREED _______________ (Vernon Stanton)

_______________ (Dr Soma Somasundaraswaran)

DATE: ___/___/2014             ___/___/2014

EXAMINER/CO-EXAMINER: ________________________________
10. Appendix B: Approach Rear End Crash Data
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<th>Speed Limit</th>
<th>Road Conditions</th>
<th>Other Conditions</th>
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<td>2</td>
<td>1</td>
<td>14 Sin</td>
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<td>60 km/h</td>
<td>Green</td>
<td>1 Car/Station</td>
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*Note: The table lists various accidents that occurred at different roundabouts around the Mount Peter area. Each entry includes the date, time, location, description of the event, number of vehicles involved, number of casualties, type of event, contributing factors, speed limit, road conditions, and other events or conditions.*
<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Speed Limits</th>
<th>Traffic Control</th>
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<td>Maroochydore Rd State controlled Intersection - Roundabout</td>
<td>Darkness - Limited Visibility</td>
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<tr>
<td>2010 Apr</td>
<td>15:00</td>
<td>Caloundra - Mooloolaba Rd State controlled Intersection - Roundabout</td>
<td>Darkness - Limited Visibility</td>
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<tr>
<td>2010 Jan</td>
<td>10:00</td>
<td>Eumundi - Noosa Rd State controlled Intersection - Roundabout</td>
<td>Darkness - Limited Visibility</td>
<td>60</td>
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<tr>
<td>2010 Feb</td>
<td>09:00</td>
<td>Old Gympie Rd State controlled Intersection - Roundabout</td>
<td>Darkness - Limited Visibility</td>
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<td>2010 Dec</td>
<td>14:00</td>
<td>Poolwood Rd State controlled Intersection - Roundabout</td>
<td>Darkness - Limited Visibility</td>
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<tr>
<td>2010 Nov</td>
<td>08:00</td>
<td>Caloundra - Mooloolaba Rd State controlled Intersection - Roundabout</td>
<td>Darkness - Limited Visibility</td>
<td>60</td>
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</tbody>
</table>

**Location Details:**
- Maroochydore Rd
- Caloundra - Mooloolaba Rd
- Eumundi - Noosa Rd
- Old Gympie Rd
- Poolwood Rd
- Caloundra - Mooloolaba Rd
- Eumundi - Noosa Rd
- Old Gympie Rd
- Poolwood Rd

**Timing:**
- 2010 May 12:00
- 2010 Apr 15:00
- 2010 Jan 10:00
- 2010 Feb 09:00
- 2010 Dec 14:00
- 2010 Nov 08:00

**Crashes:**
- Darkness - Limited Visibility
- Darkness - Limited Visibility
- Darkness - Limited Visibility
- Darkness - Limited Visibility
- Darkness - Limited Visibility
- Darkness - Limited Visibility
- Darkness - Limited Visibility
- Darkness - Limited Visibility

**Situations:**
- Open
- Open
- Open
- Open
- Open
- Open
- Open
- Open

**Driver Actions:**
- Give Way
- Give Way
- Give Way
- Give Way
- Give Way
- Give Way
- Give Way
- Give Way

**Police Actions:**
- Report
- Report
- Report
- Report
- Report
- Report
- Report
- Report

**Conditions:**
- Rain
- Rain
- Rain
- Rain
- Rain
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- Rain
13. Appendix E: Overturned Crash Data
| ST | Object Type | Incident | Date/Time | Event Type | Reason | Speed Zone | Control of Path | Road Surface | Road Condition | Traffic | Light | Road Markings | Police Attendance | Cause of Crash | Report | Event Type | Road Surface | Road Condition | Traffic Light | Police Attendance | Cause of Crash | Report |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Overturned Single | Vehicle | November 2010 | Tuesday | 9 | Overturned Single | 60 | Dry Clear | Darkness | Straight:Out | 201079 | Hospitalisation | 2009 | September | Sunday | 0 | Overturned Single |
| 2 | Overturned Single | Vehicle | September 2007 | Tuesday | 10 | Overturned Single | 60 | Dry Clear | Daylight | Straight:Out | 200710 | Hospitalisation | 2007 | August | Tuesday | 10 | Overturned Single |
| 3 | Overturned Single | Vehicle | August 2007 | Tuesday | 10 | Overturned Single | 60 | Dry Clear | Daylight | Straight:Out | 200708 | Hospitalisation | 2007 | July | Saturday | 21 | Overturned Single |
| 5 | Overturned Single | Vehicle | June 2007 | Saturday | 21 | Overturned Single | 60 | Dry Clear | Daylight | Straight:Out | 200706 | Hospitalisation | 2007 | May | Saturday | 23 | Overturned Single |
| 6 | Overturned Single | Vehicle | May 2007 | Saturday | 22 | Overturned Single | 60 | Dry Clear | Daylight | Straight:Out | 200705 | Hospitalisation | 2007 | April | Saturday | 24 | Overturned Single |
| 7 | Overturned Single | Vehicle | April 2007 | Saturday | 23 | Overturned Single | 60 | Dry Clear | Daylight | Straight:Out | 200704 | Hospitalisation | 2007 | March | Saturday | 25 | Overturned Single |
| 8 | Overturned Single | Vehicle | March 2007 | Saturday | 26 | Overturned Single | 60 | Dry Clear | Daylight | Straight:Out | 200703 | Hospitalisation | 2007 | February | Saturday | 27 | Overturned Single |

**Note:** The table continues with similar entries.
Appendix F: Assorted Roundabout Design Plans
Parish of Smithfield

Legend:
- Area restricted by visibility requirements:
  - Width in meters from top of existing kerb as shown.
  - Includes growth no higher than 0.5m above top of existing kerb.
- Area of restricted landscaping:
  - Minimum height of growth for landscaping approach.
  - Minimum height of growth for landscaping kerb.
  - Minimum height of growth for side of zone restricted by visibility requirements.

Design Criteria:
- Reaction time 4 seconds
- Approach design speed from Cairns 64km/h
- Approach design speed from Mossman 62km/h
- Approach design speed from Holloways Beach 59km/h
- Roundabout design speed 45km/h

Survey Books:
- CANBERRA HIGHWAY (CAIRNS - MOSSMAN)
- CAPTAIN COOK HIGHWAY (CAIRNS - MOSSMAN)
- MAXIMUM PLANTING HEIGHTS FOR LANDSCAPING

Queensland Government
Department of Main Roads

Job No: 158/201/225
Drawing No: 356455

Approved: 07.11.2015
Sheet 1 of 2