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Examination of the geometric design parameters contributing to heavy vehicle stability and rollover effects at roundabouts in high-speed areas

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Summary

Roundabouts in rural locations typically have high approach speeds and are often criticised for catastrophic incidents. This report reviews the literature on heavy vehicle rollovers at roundabouts, covering the most frequently cited papers. The study emphasised a comprehensive review of geometric features that contribute to the rollover of heavy vehicles in high-speed roundabouts, with a broad focus on studies from overseas.

A global comparison of roundabout design guidelines found that design standards in Australia, the UK, and the USA are more similar, while continental European countries favour smaller roundabout designs. The report described the fundamentals of roll stability, considering the rollover process's static and dynamic aspects. Techniques such as simulations, safety audits, data analysis, and direct observations were good for understanding the causes of truck rollovers; thus, many reviewed articles used one or more of these techniques.

Reviewed studies indicate that the speed of a truck has a substantial impact on the likelihood of a rollover accident occurring. Other factors contributing to rollover occurrence include smaller entry deflection, high visibility, no speed-reducing treatments, a considerable drop in circulating radius within the roundabout, sudden superelevation shifts, and higher kerbs or truck aprons. Application of globally accepted measures highlights that some of the geometric elements that can effectively be designed to slow down the speed, including advanced traffic control devices (such as signs, yield signs, pavement markings, and rumble strips), an extended splitter island, strategies to limit visibility to a safe stopping distance, and specific elements such as the deflection angle and circular island. Additionally, roundabouts sometimes equip their exit and approach curves with truck aprons to facilitate truck movement. The study further investigated recommendations for roundabout design in each state and territory. Thus, this study concludes that a supplementary roundabout design guideline should be developed for designing roundabouts in rural and high-speed areas to reduce unexpected truck crashes, including rollovers. In addition, this study recommended employing simulation modelling in future studies because it benefits redesigning existing roundabout alignments and developing new ones.

1 Introduction

A well-designed roundabout in an appropriate location increases safety, reduces delay and provides economic and environmental benefits (Ritchie & Lenters 2005). Several studies discussed the effectiveness of roundabouts as a safe and efficient form of intersection control, giving about 40% reduction in all types of crashes with a significant injury reduction (Chevuri 2018; Gbologah, Guin & Rodgers 2019).

Rollover crashes involving commercial vehicles on curves and roundabouts contribute substantially to injuries and property damage, and the occurrence is linked to several factors connecting interactions between driver, vehicle, and environment. According to Dahlbeg (2021), the factors contributing to rollover outcomes include the driver falling asleep, a simple steering correction at the high speed of a vehicle with low stability, and the roadway collapsing during cornering. Tomarchio (2019) reported that cars can tolerate a much higher value of side friction at roundabouts than trucks. In addition, if side friction exceeds its tolerance, a vehicle slides, whereas a truck rolls. Kennedy, House & Ride (2008) highlighted that the possible vehicular-related causes for individual truck rollovers depend on their type, speed, and load type. For instance, resonance may arise due to hanging meat carcasses, a partially filled tanker, or issues with the suspension system.

Rural roundabouts are those in high-speed areas. Further, the operational attitudes of the truck drivers at rural roundabouts are not the same as those at urban roundabouts. Overall, truck drivers' attitudes at rural roundabouts may be influenced by factors such as familiarity with surroundings, traffic conditions, time pressure, risk perception, road infrastructure, regulatory enforcement, and interaction with other vehicles.

Chevuri (2018) emphasised the urgent need for informative guidance in the form of a synthesis report or guideline for roundabout designs targeting specially heavy vehicle usage. Tomarchio (2019) carried out a review of the current roundabout standards, Australian and international, and examined them against known heavy-vehicle-specific requirements, and reported that the trucks need to negotiate roundabouts at significantly lower speeds than cars, and unique geometric considerations need to be made to facilitate this. Therefore, there is a need for a supplementary set of standards to accommodate combinations of geometry, signage, and line marking to safely cater for heavy vehicles at rural roundabouts (Tomarchio 2019).

According to Young (2021), the recommendations issued by Austroads and the Department of Transport and Main Roads (TMR) currently propose geometric parameter design values for heavy vehicles on rural roundabouts without being backed by sufficient data to support them. Although studies have made progress in establishing acceptable values, further research is required to investigate the interaction between heavy trucks and high-speed roundabouts in Queensland (Young 2021). Gaffney (2023) highlighted that despite the number of rollover crashes involving heavy trucks, there are no mandated design criteria with the aim of avoiding truck rollovers (Gaffney 2023).

Therefore, the purpose of this study was to conduct a review with the following objectives:

a) Research and understand the unique geometric design requirements necessary for the safe operation of rural roundabouts by heavy vehicles,

b) Determine the level of quantitative research linking geometric parameters to truck rollover crash rates,

c) Determine the level of computer modelling of truck stability as related to individual geometric elements,

d) Collate examples of best-practice geometric combinations to suit rural roundabouts, and

e) Identify recommendations on the safe geometric design for rural roundabouts,

2 Literature review

2.1 International comparison

Kennedy (2007) summarises key points for designing roundabouts in high-speed environments. It also highlights differences between the guidelines across countries, with more detailed information from Germany, France, Netherlands, Australia, Sweden, the UK, and the USA. More importantly, this review study considered the need for different geometric design standards for roundabout design in rural and urban areas and examined the concerns relating to the current UK standard (Kennedy 2007). This study also provides key considerations for designing roundabouts, including recommendations for inscribed circle diameter, truck apron, lane widths, entry and exit radii, entry angle, flaring, provision of cycle lanes and pedestrian crossings, visibility requirements, and landscaping. For example, the UK, Norway, and Australian guidelines suggest that entries may be staggered to increase the deflection angle. It was also noted that extensive entry deflection may lead to larger vehicles hitting the central island or braking sharply, possibly causing shunt crashes in rural areas. The findings highlight the need to consider factors such as geometric design standards, driver's visibility arrangements, and design guidelines for designing spaces allocated for vehicle interactions with vulnerable road users. The study concluded that the roundabout design standards in Australia, the UK, and the USA are more comparable to each other. At the same time, continental European countries prioritise smaller roundabout designs.

Ahac, Džambas & Dragčević (2016) researched roundabout sight distance requirements described in Croatian guidelines and those applied in Austria, France, the USA, Serbia, and Switzerland. They found that unlike American guidelines and Serbian regulations, Croatian guidelines do not use this fastest path vehicle speed in their sight distance analysis. In accordance with Croatian guidelines issued in 2014, visibility through the roundabout is controlled by designing a dome-like elevation at the centre of the circular island. Controversially, experts suggested that the absence of a visibility obstacle might cause some vehicles to drive into the centre island or disregard the right-of-way in the roundabout.

2.2 Truck rollover fundamentals

The Static Rollover Threshold (SRT) is the minimum value of the centrifugal acceleration that causes a heavy vehicle to tip over when travelling along a curved road alignment with a constant speed. Thus, SRT is a simple index of rollover risk. It's generally calculated as the ratio of track width to double the height of the centre of mass as given in Equation 1. The primary measure of roll stability is the SRT, expressed as lateral acceleration in gravitational units (Winkler & Ervin 1999; Hart 2012). A good SRT value for loaded trucks is 0.35g or above. Higher SRT means more stability. Low SRT vehicles are more susceptible to rollover, particularly in tight curves or while turning suddenly (e.g., steering correction).

$$\text{SRT} = \frac{\text{L}}{2\text{H}} - \emptyset = \frac{a}{\text{g}} = \frac{V^2}{\text{Rg}} \qquad (1)$$

Where:

L – truck width in m (distance between rear wheels), H – centre of gravity height (m), ∅ - roll angle, due to the compliances in tyres, suspensions and other parts of the vehicles after considering the effect due to crossfall/superelevation (m/m), and a – lateral acceleration in a gravitational unit, g – gravity (m/s2), V is the speed (m/s), and R is the radius (m) of the curve.

Equation 1 could be modified to estimate safe speeds considering the effect of adverse cross-slope, superelevation, or combination of both when moving through S-bends, which is expected at roundabouts.

Hart (2020) used this theory to examine the height of the apron and found that the heavy truck's right-side wheels may be 120mm higher than the left-side wheels when the vehicle turns right in Australia. This is equivalent to a 6% cross slope and raises the chance of a rollover (Hart 2020). This analysis shows the added effects of an adverse cross-slope (-negative crossfall) and leaning angle due to the apron, which is often the case at a roundabout.

Hart (2012) explained rollover by saying that friction between the tyres and the road pulls the truck and trailer around a corner. Insufficient tyre grip causes the truck to move sideways (sliding). If the tyres grip, the truck may pivot over the outer tyres. Tyre tread arrangement, depth, and pressure influence road grip, where poorly maintained or underinflated tyres slide more (Hart 2012).

In addition, Hart (2012) stated that generally, a semi-trailer will roll over from its rear end. According to Hart, the trailer part tends to rise first, followed by the drive-axle group and the steer axle. The rigidity of the connection between different vehicle portions should also be considered when assessing the risk of rollovers in combination heavy vehicles. The mechanical coupling parameters determine the manner in which vehicle components interact and will differ between the double-axis ballrace turntable and the fixed fifth wheel (Hart 2012).

Rodegerdts et al. (2015) discovered that semi-truck drivers often felt uncomfortable when subjected to more than 0.2g lateral acceleration. As a result, this number functioned as the threshold for determining an appropriate circulation speed. When curvature is constant, lateral acceleration is mostly affected by travel speed. Hence, the suitable truck speed for this investigation was estimated based on the roundabout diameters (Rodegerdts et al. 2015).

A few studies used Dynamic Rollover Threshold (DRT) given in Equation 2 to indicate the likelihood of rollovers (Rodegerdts et al. 2015; Chen et al. 2019), which is derived from side-to-side tyre normal forces.

$$\mathrm{DRT} = \frac{|F_{ZR} - F_{ZL}|}{F_{ZR} + F_{ZL}} \qquad (2)$$

Where: F_{ZR}- Right wheel load (rear axles), and F_{ZL}- Left wheel load (rear axles)

Determining Dynamic Rollover Threshold (DRT) involves a vehicle travelling around a corner with a known radius at a steady speed and observing the speed at which the inner wheels first leave the ground. The dynamic rollover threshold is essential for designing safe trucks and implementing effective safety measures to prevent crashes related to rollovers. This threshold value could be computed using simulation software, but it is a much more complicated calculation than the computing SRT (Gertsch & Eichelhard 2003; Hart 2012; Phanomchoeng & Rajamani 2012; Chen et al. 2020). Gertsh and Eichlhard (2003) reported that the rollover threshold for heavy trucks is about 25% lower than the static stability factor, with a critical speed of approximately 11km/h across a range of loading conditions (Gertsh & Eichlhard 2003). Therefore, trucks may topple on bends at low speeds in specific conditions. Hart (2020) highlighted that safe speeds for semi-trailers can be surprisingly low, sometimes below 30 km/h.

In addition, the estimators assume that the load is firmly secured to the vehicle and does not move relative to its body. This assumption is commonly used in simulation studies and computer-based methods and is valid for most load types. However, the assumption is strictly not correct for most common examples of specific load types, including liquid in tankers with partially filled compartments, refrigerated cubicles hauling hanging meat, and livestock (Winkler & Ervin 1999; Pont 2004).

Due to the varied shapes and sizes of roundabouts, particularly in how vehicles approach and navigate them, accurately forecasting the movements of trucks is challenging without using simulation models.

2.3 Understanding the causes of truck rollovers

The truck rollover outcomes in high-speed rural settings are influenced by various factors such as roundabout geometry, vehicle specifications, driver behaviour, and environmental conditions. VicRoads (2010) highlighted that understanding the causes and implementing remedial measures is crucial for reducing heavy vehicle rollovers (VicRoads 2010). VicRoads (2010) included the following contributing factors leading to rollover crashes: excessive speed, load type being carried, condition of the brakes, and driver distractions, including inattention, dozing or falling asleep.

Kennedy (2007) summarised many possible causes of truck rollover at roundabouts and concluded that it would be a combination rather than a single cause. The top five causes of rollovers at high-speed roundabouts include the following:

- a truck entering the roundabout too quickly (which might be due to excessive visibility and little circulating flow or inadequate entry deflection)
- a tight turn on the circulatory carriageway (which is likely to be due to poor design or a historical layout and is expensive to rectify)
- reverse curves on the approach, often with changes in crossfall direction (which may be improved by introducing a straight between the two curves)
- abrupt changes in crossfall on the circulatory carriageway or exit (if crown lines are used, they should be smoothed), and
- excessive entry deflection.

Further, it can be concluded that these causes remain hypothetical until the research verifies their contributions. They can be confirmed by systematically applying a few assessment methods, such as traffic simulation and modelling, field studies and data collection, pilot studies, long-team monitoring and evaluation using before-and-after studies or cross-sectional studies, and analysis to ensure compliance.

Whether the truck rollover contributing factors are related to the driver or other parameters, the driver, being the person directly involved, is the one who truly understands what happened concerning the crashes. Park and Pierce (2013) surveyed drivers of 60 carriers to gain insight into the challenges commercial truck drivers face at roundabouts, particularly those with five-axle tractor and semi-trailer combinations. This online survey, consisting of 47 questions, focused on demographics, observations from anecdotal roundabout use, and possible solutions to design issues. The analysed survey data identifies the following unique and typical difficulties highlighted by truck drivers as the top-most problems around roundabouts: (1) Roundabouts being too small for larger trucks to accommodation, (2) Instances of truck trailers encroaching into the centre island, (3) kerbs being a hindrance for large trucks while making turns, (4) Truck trailers drifting and using the second lane which causes potential crashes and safety concerns, (5) Difficulty accelerating quickly to merge into traffic, (6) Passenger vehicle drivers not educated enough to give needed room for truck's tractor-trailer, (7) Elevated and sloping kerbs causing truck hang-up problem, and (8) Blind spot being created on the right (left in Australia) side of the truck (Park & Pierce 2013).

2.4 Safety audits and investigation tools

The safety audits are useful for assessing the safety performance of roundabouts based on geometric design and constructed features. However, there are limited study reports available on safety audit studies carried out to investigate the rollover of large trucks at the existing roundabouts.

Lenters (2005) highlighted that although roundabout designs incorporate established guidelines, design checks are required to achieve predicted safety performance and enhancements. The report provided examples of design pitfalls and outlined a list of necessary checks. This report provides safety assessment guidelines for all sizes of roundabouts, except mini-roundabouts with fully traversable central islands (Lenters 2005).

Transfund New Zealand hired the Traffic Design Group in Lower Hutt to conduct audits aimed at raising awareness of safety design practices. The report highlights the aspects of roundabout design and construction that safety auditors have often identified as lacking (Traffic Design

Group 2000). After analysing fifty-roundabout safety audit reports, it was found that insufficient signage (in terms of location, appropriateness, size, and quantity) is a significant factor contributing to high approaching speeds and driver confusion at roundabouts in rural areas of New Zealand. It indicates that guidelines, standards, and research data from sources like Austoroads, Transport Research Limited (TRL), and other publications are valuable resources for practitioners but are often referred to only after things go wrong.

Using simulation models is a compelling investigation technique for improving the safety and efficiency of roundabout designs, reducing truck rollover crash rates, and improving the overall quality of truck movements at rural roundabouts. Computer simulation software, such as TruckSim, AMEsim, MATLAB/Simulink, and DYNA4, are capable of examining the dynamics of truck stability, while some of them are famous for their ability to analyse vehicle tracking, including Civil 3D, AutoTURN, and TORUS.

For example, Chen et al. (2020) used TruckSim software to predict rollover dynamics of tractor-multi-trailer vehicles in roundabouts. The rollover index (RI) as a tool for evaluating rollover likelihood is explained, with emphasis on the rear trailer's lower roll stability. The time trace of the rollover index during left-turn (right turn in Australia) manoeuvres is presented, including RI values when travelling over the apron. The study insights provide valuable information for understanding truck manoeuvrability and rollover risks in roundabout scenarios (Chen et al., 2020). The findings revealed that vehicle size and route choice have a considerable influence on rollover risk in double-lane roundabouts.

A study by Alrejjai and Kasaibati (2023) proposed the use of dynamics simulation modelling software, such as TruckSim, to capture the interactions of truck weight, road profile, and crosswinds. In addition, (Bao & Hu 2015; Ahac et al. 2022; Alrejjal & Ksaibati 2023) discussed the development of simulation and multiple linear regression models to quantify the impact of various factors related to truck rollover risks at roundabouts.

2.5 Study on geometric elements contributing HV rollovers

Dahlberg (2001) indicated that the simulations of dynamic manoeuvring resulting in truck rollover can also explain the relevance of the Dynamic Rollover Threshold (DRT). However, since the analysis today is suited for rigid body analysis, the adaptation to flexible body description is a possible future work. In addition, swept-path simulation can be conducted by considering a range of geometric factors to allow the manoeuvres of design vehicles. Main Roads Western Australia requires high-speed roundabout designs to use simulation to check the acceptance of travel paths.

Ritchie and Lenters (2005) conducted a comprehensive study to identify potential challenges associated with installing roundabouts on roads with 72 kmph (45 mph) or higher speed limits. Although this study was intended as a project in the United States, due to the lack of studies on roundabouts, it sought worldwide resources from Canada, the United Kingdom, France, Germany, the Netherlands, and Australia to obtain reports containing operational safety information at roundabouts located along high-speed corridors or roadways. Thus, this study methodology includes five case studies and statistics from recognised experts, for highlighting the safety benefits and the importance of proper design practices, including geometric and non-geometric measures such as lighting and landscaping. The results documented various design strategies tailored for roundabouts with high-speed approaches and found a lack of evidence linking geometric design to safety performance. This study reviewed the design treatments used around the world, and a modified form of their recommendations is summarised below:

- Provide a minimal stopping sight distance at entrance points depending on the approach operating speed since excessive sight distance may encourage vehicles to continue at high speeds.
- Align approach roadways and see vertical profiles to make the central island visible with landscaping and sight-blocking features; drivers unfamiliar with the roundabout need sufficient visual information to encourage a change in speed and path.
- Extending the splitter island upstream to the yield line to match the proper deceleration length from approach to entry speed.
- Advance signage in combination with appropriate landscape and a well-illuminated transition to the roundabout. Use landscaping on extended splitter islands and the roadside to create a tunnel impression for approaching vehicles.
- Use signs and markings effectively to advise drivers of the appropriate speed and travel path.

Richie and Lenters (2005) reported that even minor adjustments to the design of a roundabout have been shown to have a major impact on the type and frequency of crashes. It was also reported that the crash prediction models established in the UK are likely to be reliable predictors of the effects of design changes in North America. The study results urged designers to provide sufficient deflection in the design of the approaches to induce speed reduction before vehicles reach the yield line. The authors concluded that entry path radii should be less than 230 feet (70 m) for the best results in single-lane roundabouts and less than 330 feet (100 m) for multilane roundabout designs. They concluded that flaring roundabout entries can mitigate the safety impacts of wider entries by reducing entry path curve values to 100 feet (30 m).

A study in the United Kingdom, Kennedy, House & Ride (2008) proposed the following four characteristics make it easy for drivers to approach faster than is advisable: long straight, high-speed approach, little deflection before the giveway line, low circulating flow past entry, and good visibility to the right (left in USA) (Kennedy, House & Ride 2008). Kennedy (2007) suggests that providing excessive visibility to the right (left in the USA) can sometimes result in high entry speeds, potentially impacting decision-making at the roundabout and leading to sudden steering input, contributing to rollovers.

Germanchev, Eady and McKelvie (2011) used simulation models and compared the performance of the concrete agitator truck with a rotating barrel and that of a moving vehicle with the same vehicle with a stationary barrel and load. The models determine the vehicle's Static Rollover Threshold (SRT) and Load Transfer Ratio (LTR). Load Transfer Ratio (LTR) is defined as a measure of load transfer from one side of a vehicle to the other during dynamic maneuvers. An LTR of 0.0 indicates straight-line travel with no load transfer, while an LTR of 1.0 indicates potential rollover. The SRT analysis concluded that the vehicle met stability requirements, but the LTR analysis revealed that a rotating barrel and moving load reduced stability, increasing the risk of rollover. The finding is suitable for concrete agitator vehicles with moving loads. However, the results are also relevant for understanding and reducing the risk of other truck rollovers (Germanchev, Eady & McKelvie 2011).

Park and Pierce (2013) conducted a web-based survey on the difficulties commercial truck drivers encounter when negotiating roundabouts to investigate the elements that may hinder roundabout utilisation by heavy vehicles. This study was carried out in collaboration with researchers at Kansas State University and the American Transportation Research Institute, USA. This survey included an open-ended question in which respondents were asked to identify potential solutions to the problem they encountered. According to most (73%) participants, roundabouts are more of a problem than other intersections. The proposed treatments include better geometric design, enhanced signage, education and outreach, and advanced planning. They highlighted design issues related to approach, circular roadway, and departure manoeuvres (Park & Pierce 2013).

Hou and Ahmadian (2015) simulated the effect of trucks' configuration on roundabout roll stability. Their findings show that the 53-foot (16.2 m) single-trailer and 40-foot (12.2m) double-trailer trucks have weaker roll stability than the single-unit truck (Hou & Ahmadian 2015). It was also found that roundabout geometric layout significantly increases the rollover effect of high-centre of gravity vehicles even at low speed.

Hou et al. (2016) conducted a simulation-based study to improve roundabout truck roll stability. TruckSim is used to create numerous roundabout model configurations and a comprehensive model of the semi-trailer's dynamics. The pneumatic dynamics of the suspensions are modelled in AMESim, a commercial product, and then combined with the TruckSim model of the vehicle using Simulink. The results show that the roundabout cross-sectional arrangements and truck pneumatic suspension systems significantly affect truck roll dynamics at roundabouts, whereas load circumstances have a modest impact (Hou, Chen & Ahmadian 2016).

Ahac, Dzambas & Drahcevic (2016) analysed mainly the visibility towards vehicles with the right of way through roundabouts. Results show that neglecting the fastest path vehicle speed in sight distance analysis results in over-dimensioned sight distances and clear vision areas, especially on circulatory roadways, and non-compliance with obstruction requirements (Ahac, Džambas & Dragčević 2016).

Hall (2014) suggested that Variable Message Signs (VMS) be used to alert truck drivers going too fast to slow down. Exceeding the critical high speed by a truck driver approaching the roundabout triggers the warning message intended to slow down the driver. The distance where the speeds are measured should be as close as possible to the spot with the lowest speed difference but sufficiently far to allow drivers to correct their speeds. This study's results may help determine the best location of the VMS sign. These signs are activated when a vehicle's approaching speed exceeds the threshold speed limit to display the hazard to drivers (Hall 2014).

Another possible measure is better training of truck drivers to improve their traversing ability through roundabouts (Hall 2014). A study reported that rollover crashes in large trucks are primarily caused by driver errors, such as inattention, lack of attention, and control errors, and can be improved through video exposure and simulation training (McKnight & Bahouth 2009).

Tarko et al (2016) investigated the rollover propensity of trucks on high-speed horizontal curves, particularly on highway ramps, intersections, and roundabouts. The methodology involves nonintrusive observation of truck drivers' behaviour and the use of video recording to measure the speeds and paths of trucks, with a focus on analysing the risk of rollover. The study used Vehicle Tracking Systems (VTS) to collect speed and path data from 105 semi-trailers during the day and night. It also reported the potential usefulness of quasi-static models to analyse rollovers, particularly focusing on the static stability factor and its connection to rollover frequency. The study reported that truck drivers tend to be more cautious when approaching the roundabout at night, possibly due to the added difficulty of reading the roundabout geometry from a distance. The study also highlighted the importance of accounting for complex paths and tilt experienced by trucks in roundabouts and emphasised the need for accurate vehicle weight measurements and trajectory estimation methods. They also found that drivers tend to drive more cautiously at night, leading to a decreased tendency for rollovers (Tarko et al. 2016). Arndt (1994) established the relationship between roundabout geometry and accident rates and found that the single-vehicle crash rate at night was three (3) times higher than during the day for all vehicle categories, not just heavy vehicles. Another study by Arndt (2004), 'Relationship Between Unsignalized Intersection Geometry and Accident Rates,' found that the value was 3.5 for the 200-meter road on either side of the intersection. Again, this was for all vehicles.

Another possible concern regarding rollover outcome is using outward sloping crossfall, which is not recommended at large or rural roundabouts in the UK (Kennedy 2007). Chen et al. (2019) elaborated that the circulatory roadway in a roundabout typically has an outward cross-slope for drainage that could result in more lateral load transfer in large trucks, further worsening the rollover risk (Chen et al. 2019).

Truck aprons are intended to be unattractive to cars, for example, by being made of textured material. In the UK, aprons are only recommended at smaller roundabouts and are not considered necessary at larger ones; the kerb should be rounded, and the slope should not be too steep. British drivers accept that trucks will not necessarily be able to keep within their lane whilst entering and negotiating a roundabout and that they should, therefore, be given a wide path.

Surface polishing of the bitumen increases the risk of sideways sliding. Additionally, braking in a roundabout increases the risk of jack-knifing, especially if the road surface is polished (Hall 2014). However, Boodlal et al. (2015) investigated the efficacy of high-friction surface treatments at four treatment locations and three control sites in West Virginia, concluding that there were no consistent changes in operational and driving behaviour after applying the treatments (Boodlal et al. 2015).

Brewer, Lindheimer, and Chrysler (2017) recommend strategies to reduce speed at high-speed approaches to roundabouts. They suggested treatments such as traditional signage, pavement markings, lights, speed-activated signs, and transition zones. The report provides information on effectiveness, installation and maintenance costs, and research needs for specific treatments and countermeasures, particularly for high-speed rural roundabouts (Brewer, Lindheimer & Chrysler 2017). This study highlights several research requirements specific to certain treatments and the necessity for conducting field research on the suggested countermeasures, mainly focusing on approaches to high-speed rural roundabouts.

Mndotresearch (2017) proposed that specially designed signs, pavement markings, illumination, and advanced devices like speed-activated LED warning signs are used ahead of high-speed roundabouts as effective treatments for high-speed approaches. However, each roundabout presents unique challenges because minor differences in the design, so each roundabout presents specific challenges, and local engineers must evaluate the roundabout's characteristics, installation, and maintenance issues before recommending a particular treatment. The study suggests that speed reduction techniques that were effective for horizontal curves, urban-rural transition zones, and isolated rural intersections could also be applied to rural roundabouts with high-speed approaches (Mndotresearch 2017). This study also proposed the following three critical research areas for future studies: Analysing the effectiveness of speed reduction treatments at different locations, Determining the impact of different combinations of treatments, and Analysing the impact of roundabout infrastructure (such as gateway treatments and illumination), various pavement markings and the long-term effects of specific signing treatments. These similar studies are also required to determine Crash Modification Factors (CMFs) for individual treatments.

Tomarchio (2019) Outlines the general intention of reverse curve geometry, provides brief guidance on when to use them, and cautions designers of some of the negative elements. This study also highlighted the issues within the current standard, outlined the general intention of reverse curve geometry, gave brief guidance on when to use them, and vaguely warned designers of some of the pitfalls; however, it stops short of providing recommended combinations of radii, superelevation, and separating tangent lengths. In addition, it added that a roundabout might feature adverse crossfall in the opposite direction to the turning vehicle. In this instance, the crossfall does not contribute to the vehicle's stability when it negotiates the curve with the recommended operating speed (Tomarchio 2019).

Xin et al. (2021) highlighted weaknesses within current safe speed calculations and developed a more accurate calculation method. The study uses a theoretical model and simulation tests on a 30-tonne 4-axle truck to evaluate the dynamic rollover risk levels and verify the results. The results show that a rollover margin of 0.15g reduces the truck's risk level of a critical rollover, providing an accurate algorithm for speed thresholds when the turning radius is less than 250m. This research can be applied to design truck speed warning systems to enhance safe driving (Xin et al. 2021).

Ahac et al. (2022) compared two approaches for designing vehicle steering paths through roundabouts. The first approach (Figure 1) uses short, straight lines between adjacent arcs, while the second approach (Figure 2) uses consecutive circular arcs. In both cases, the roundabout approach leg axes intersect at the centre of the roundabout's outer radius, and a triangular splitter island was selected for investigation. Based on German guidelines, the custom design vehicle was chosen due to its wide swept path when negotiating a roundabout with a tractor and semi-trailer. The vehicle's width was customised to 2.55 m for the investigation. This study conducted computer simulations using Autodesk Vehicle Tracking 2020 software and found that the second approach, while faster and simpler, resulted in turning envelopes that were more offset from the roundabout centres compared to the first approach. Specifically, 72% of right-hand-side (left in Australia) path deviations were between 0.00 and 0.15 m, which has implications for roundabout entry and exit widths and lateral clearances, particularly in areas with heavy pedestrian traffic. The offset of left-hand-side design vehicle trajectories on the circulatory roadway could positively impact deflection around the central island (Ahac et al. 2022). Overall, this study provides insights into the implications of different path construction approaches for designing vehicles at roundabouts, aiding in identifying suitable geometric elements for simulations.

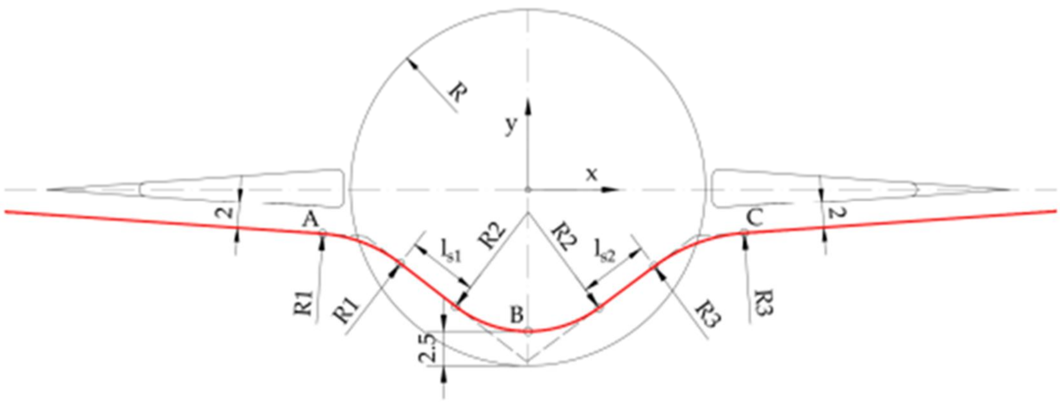

Figure 1 Striagh lines between adjacent arcs (l_{s1} and l_{s2})

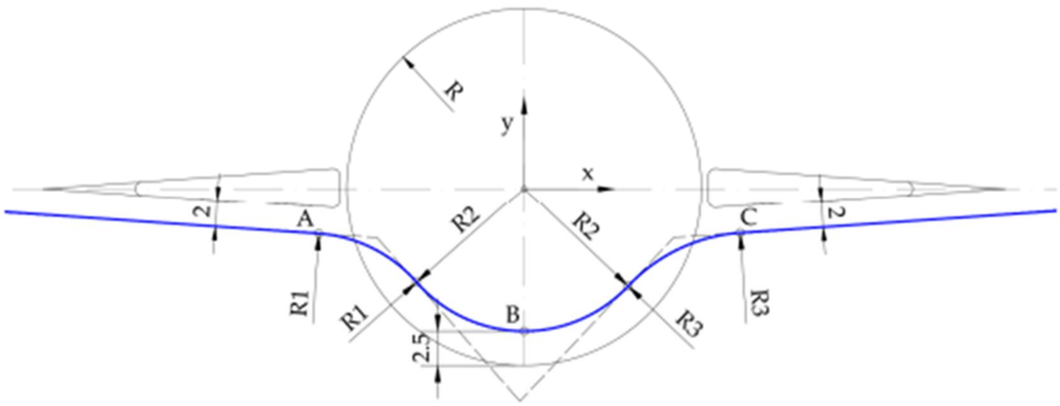

Figure 2 Consecutive circular arcs

Brewer et al. (2023b) investigated the resilience of roundabouts under different traffic scenarios, including the presence of higher percentages of trucks and oversize/overweight (OSOW) than typically observed traffic composition (Brewer et al. 2023b). This study reported the link between operating speed and different geometric components at high-speed, single-lane rural roundabouts, citing NCHRP Project 3-65 by Johnson and Flannery. This NCHRP developed the four types of speed models and identified the most effective geometric parameters as follows: approach speed vs approach width and posted speed limit; entry speeds vs entry (inscribed) curve diameter and effective flare length; circulating speed vs width of truck apron, and exiting speeds vs circulating lane width, and exiting lane width. The study proposed that the results from the similar field data analysis, combined with best practices adopted elsewhere, can be used to develop design guidelines for roundabouts in rural and high-speed locations (Brewer et al. 2023b).

Brewer et al. (2023b) also found that roundabouts can accommodate large daily volumes, heavy vehicles, and OSOW vehicles at a level of service (LOS) that exceeds traditional two-way stop control. Roundabouts with a wider diameter of 180 ft (55 m) exhibited superior performance, while the smallest roundabouts (36 m) were capable of accommodating bigger vehicles at lower traffic volumes. According to Brewer et al. (2023b), roundabouts in rural areas with high-speed approaches may be designed to handle both OSOW and heavy vehicle traffic. The results suggest that roundabouts, especially larger ones, are effective in accommodating high traffic volumes, heavy vehicles, and OSOW vehicles, and the findings can help develop supplementary design guidelines for roundabout design in rural and high-speed locations.

Limited studies (Vinayaraj & Perumal 2023; Carrigan 2016;) developed CMFs for selected geometric elements. The studies also examined the relationship between roundabout geometric parameters and traffic flow performance (Čudina Ivančev et al. 2023). Surdonja et al. (2013) found that the roundabout's entrance and exit parameters and the distance between the conflict points affect its capacity. Figuring out how to make the roundabout as big as it needs to be based on its capacity can help make sense of the space needed (Šurdonja, Aleksandra, & Babić 2013). However, until now, no studies have estimated the CMFs for the geometric elements at high-speed roundabouts.

Gkyrtis and Kokkalis (2024) emphasise the evolving role of roundabouts in the context of new vehicle technologies and the need for continuous research to optimise their geometric design for efficient traffic flow and maximised safety and capacity potentials (Gkyrtis & Kokkalis 2024). Thus, adapting roundabout design elements to accommodate autonomous vehicles is essential for realising the full potential of this technology and creating safer, more efficient, and more accessible transportation systems for everyone.

3 Selected practices to reduce speeds

Most strategies to reduce rollovers at high-speed roundabouts were aimed at reducing speed. Some treatments to reduce speed include effectively using traffic control devices, changing roundabout geometry, and providing entry, exit and apron treatments. Ritch et al. (2005) proposed that any effective treatments must eliminate sudden steering input, limit the surface rotation rate, and increase curve radii to lower the required side friction.

3.1 Roundabout signs

Weber and Ritchie (2005) documented internationally recognised roundabout signs to supplement high-speed approach treatments at roundabouts (Weber & Ritchie 2005). Advanced warning signs (used in advance of roundabouts to raise attention level and slow the vehicle) are recommended to be provided prior to the circulating carriageway, with the advisory speed set to the safe circulating speed for heavy vehicles.

3.2 Limiting visibility to roundabout entry

Raising the central island with suitable landscaping is the most effective method to improve central island visibility for improving the substandard approach to stopping sight distance (GDOT 2023). Another method to control the sight distance is tipping the central island.

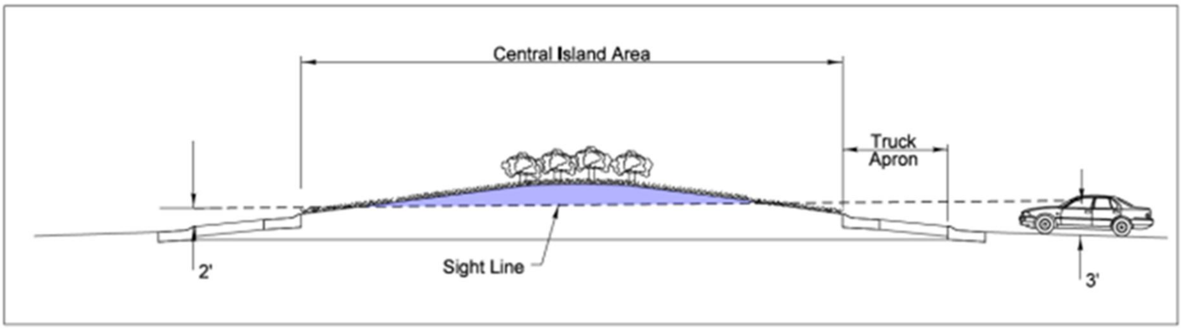

Figure 3: Blocked through sight

(Source: GDOT 2023)

3.3 Auditory and vibratory strips

According to TRL (2019), research conducted worldwide confirms the beneficial effect of auditory and vibratory strips (audio-tactile treatments installed across lanes to warn drivers of approaching roundabouts), describing them as 'one of the highest benefit-to-cost roadside safety treatments. These are often in the shape of a series of slightly elevated strips of varied coloured surface laid over the width of the road. These strips' look and feel are designed to encourage vehicles to slow down.

As shown in Figure 4, transverse yellow bar markings are used under specific situations on high-speed approaches to roundabouts in the UK, either on the main carriageway or on an exit slip lane (Department for Transport, 2018). The marker consists of 90 yellow transverse bars on the principal carriageways. The first bar is installed 50 metres forward of the Give Way line along the carriageway's central line. However, it is important to maintain the appropriate skid resistance and sufficient drainage. In addition, this strip raised some concerns, including the noise introduced into the road environment and the effect on other road users such as cyclists and motorcyclists (TRL 2019). In the UK, rumble strips are often not installed within a closer distance of 275 m from residential properties, and a few safety checks have been proposed to accommodate other users. These markings are unlikely to be approved in such cases unless the accident justification is strong.

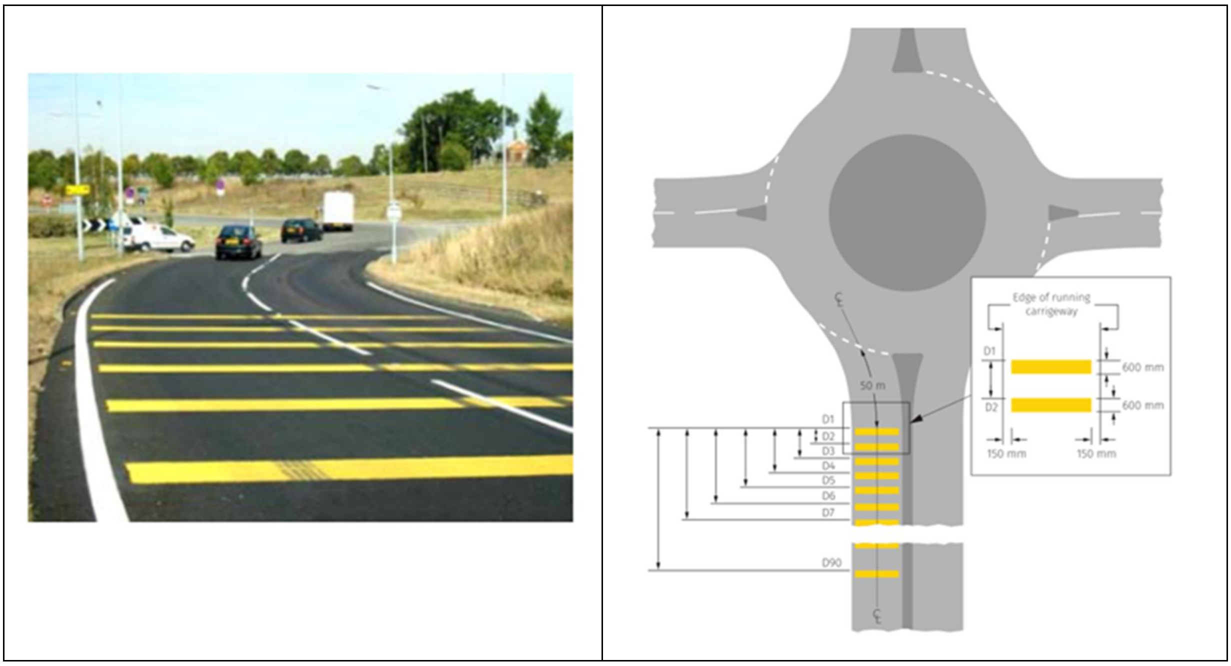

Figure 4. Transverse yellow bar markings, United Kingdom

(Source: Ritchie and Lenters 2005; Department for Transport 2018)

3.4 Reverse curve with extended splitter island

Richie and Lenters (2005) identified a few key design principles, including providing stopping sight distance at the entry point, aligning approach roadways to make the central island visible, extending splitter islands upstream of the yield line, using landscaping to create a tunnel effect, providing roadway illumination, and using signs and markings effectively. This study discussed the impact of entry path curvature on single-vehicle crashes and the importance of avoiding overly tangential or sharply curved entries.

Figure 5 A typical example of extending the length of the splitter island

[Source: Mndotresearch 2017]

In particular, it is essential to extend the length of the splitter island to the necessary deceleration length from the approach to regulate entry speed at a safe speed to reduce the rollover consequences.

3.5 Inner and Outer Apron

Roundabouts allowing large trucks must be designed to accommodate them without causing trailer tyres to ride over the kerb or apron. However, truck aprons are intended as extra space for tailers. Design features used to make roundabouts traversable for large vehicles include mountable aprons around the center island, fully traversable center islands, and gated pass-throughs (Park & Pierce 2013).

Central Island truck aprons are designed for big trucks in that they are accommodated with their larger size and off-tracking trailers. The purpose of these slightly elevated aprons is to prevent cars and light trucks from straying onto the truck apron. Only the drivers of large commercial vehicles can compensate for the off-tracking caused by these designed features. Additionally, as shown in Figure 6, roundabouts sometimes equip their exit and approach curves with truck aprons to facilitate semi-truck movement through the roundabout.

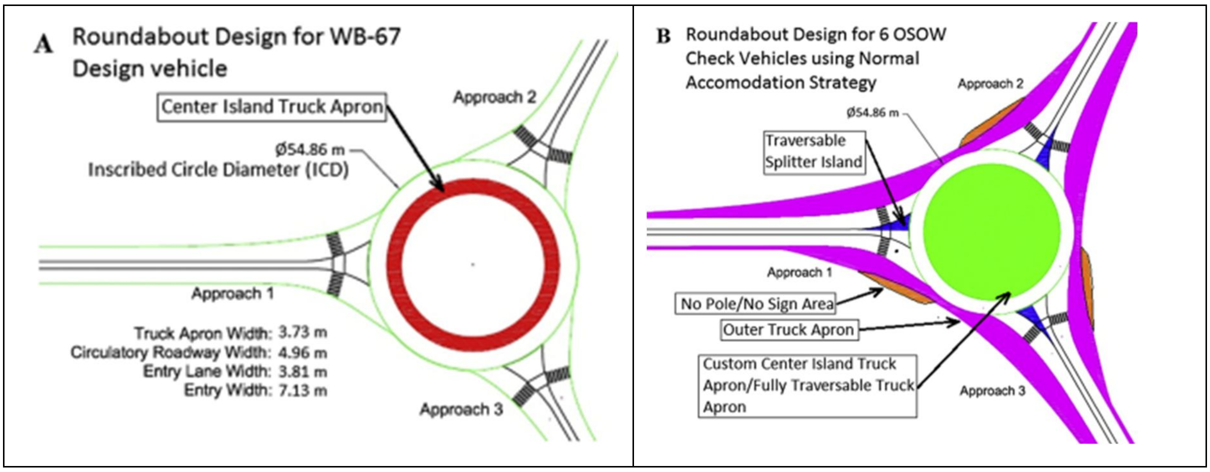

Figure 6: Single lane typical symmetric 3-leg roundabout design with aprons

(Source: Godavarthy et al 2016)

Increasing design vehicle size will have negative consequences. For example, passenger car drivers will take the shortest path while maintaining a higher operating speed.

3.6 Straight passage through the centre island

Accommodating oversized/overweight (OSOW) vehicles at roundabouts is sometimes crucial. Therefore, Godavarthy et al (2016) assessed the effectiveness of the following three alternative roundabout design strategies on accommodating oversized overweighted commercial vehicles: straight passage through the centre island, fully traversable centre island (FTCI), and opposite direction travel (ODT). This study concluded that all three strategies would work but recommended that the designer conduct a swept path analysis to check space constraints when accommodating expected vehicle movements.

Building a direct path through the centre island will allow big truck traffic that is expected to pass on a regular basis. This straight-through lane, however, must have gates so that normal cars do not use it, and this method is being adopted in Germany (Brewer et al. 2023a).

3.7 Application of in-vehicle devices

Han (2023) reported that in recent years, Advanced Driver Assistance Systems (ADAS) and autonomous driving have attracted a lot of attention (Han 2023). A study by Sullivan et al (2004) presents that inbuild Roll Advisory and Control (RA&C) systems such as Roll Stability Advisor (RSA), Roll Stability Control (RSC), and Hard Braking Event Detection (HBED) are becoming effective in reducing vehicular rollovers (Sullivan et al. 2004). For example, the RSA estimates the quasi-static rollover threshold of the vehicle while it is in normal service. However, RSA messages were not delivered immediately upon detecting a risk of rollover but were delivered a short time after the risk had subsided. RSC is an active control system intended to prevent rollover. HBED, like RSA, was a training aid that advised the driver when an unusual braking event had been detected.

Advanced forms of these techniques will have an inventive display unit. The rollover threshold and the current operating level of lateral acceleration are displayed to the driver while travelling and are also recorded to provide fleet managers with a resource for accessing and improving the overall rollover risk of their fleet. In addition, equipping trucks with advanced stability control systems, such as Electronic stability control (ESC), Intelligent speed adaption (ISA), Fatigue monitoring systems, and Rollover stability control, can significantly reduce the risk of rollover accidents by automatically applying brakes and adjusting engine power to help maintain vehicle stability. In recent years, a significant change in the global automotive industry has increased interest in using Electric Vehicles (EVs) in the context of smart transportation systems. As a result of continuous research and development, the stability of EV's control has been significantly improved (Liu et al. 2020).

4 Considerations Within Individual State Supplements

Although this research does not cover the findings and techniques recommended to enhance road safety at roundabouts in Australia, providing a concise overview of the main approaches outlined in supplementary guidelines from various states is beneficial. A simple comparison of the supplementary guidance might help minimise the differences and develop new research ideas for future studies.

In general, state supplement guidelines allow for adaptation to local conditions, ensuring that road designs are suitable for the specific environment, climate, soil types, and traffic patterns. The key recommendations provided as supplements for roundabout design in each state and territory are listed below (Jedniuk 2024).

4.1 New South Wales

According to Transport for NSW (2023) roundabouts should not be used where the posted speed limit is greater than 80 km/h. In areas with a posted speed limit greater than 80 km/h the posted speed shall be lowered to 80 km/h on the approaches to the roundabout. At the minimum, greater consideration should be given to traffic volume, traffic mix, intersection visibility, crash history, and operating speed. In addition, reverse curve approaches are not practised. Reverse curve approaches should only be considered when the requirements of section 4.5.3: Maximum Entry Path Radius cannot be achieved (Transport for NSW 2023).

4.2 Victoria

VicRoads generally adopts Austroads design for roundabouts; however, they request that Aprons shall not be adopted on the outside of the circulating carriageways of roundabouts to assist larger vehicles making right turns, as this allows for higher speeds through the roundabout by cars. Other design changes should be made to ensure the vehicle can make this movement on the circulating pavement (VicRoads 2011).

4.3 South Australia

South Australia (SA) has requested that the central island radius be increased based on the largest operational vehicle (Department of Infrastructure and Transport 2022). SA also promotes the use of reverse curves for speeds greater than 80 km/h with a short straight to be provided for superelevation transition to reduce the risk of instability for Heavy vehicles. Simulation software is mandated to review the risk of truck instability for the following conditions: (i) approach speed 80 km/h or greater, (ii) roundabout located on a freight route, and (iii) The largest design vehicle is a Performance Based Standards (PBS) 2A or greater.

4.4 Queensland

The Queensland supplement suggests that the central island radius should be limited to a maximum of 75 m (desirably 50 m) to discourage high circulating speeds. TMR recommends that short horizontal straights between entry and circulating carriageway curves be included and that superelevation on approach curves may lead to poor driver perception, which is discouraged. TMR suggests "An alternative is to use adverse crossfall on one (or more) of the reverse approach curves and keep the crossfall in the same direction through the approach curves and entry curve" (TMR 2021).

4.5 Western Australia

Main Roads Western Australia (2019) requires rural and high-speed roundabouts (>80km/h) must provide supplementary geometric or traffic control device treatments to reduce vehicle speeds (more than 30km/h) on approach to the roundabout with the preferred treatment is incorporating successive reverse curves (MRWA 2019a). MRWA (2019b) has noted that heavy vehicles using smaller roundabouts may utilise raised encroachment areas; however, elevated aprons are not desired in roundabouts where vehicles transport animals or gasoline.

A Vehicle Stability Assessment Guideline (MRWA 2019b) has been developed for high-speed roundabout (≥ 80km/h) design, which proposed the mandatory use of simulation software (e.g., TruckSim) to allow the heavy vehicle movements not exceeding a load transfer ratio (LTR) of 0.6 at 30 km/h. The general process involves (1) Creating vehicle centreline alignments, (2) Creating 3D vehicle alignment and camber strings, (3) Carrying out the stability analysis using Universal Mechanism simulation software, and (4) Preparing analytical outcomes.

4.6 Tasmania

Tasmania generally adopts Austroads design for roundabouts; however, they request that "The adoption of reverse curve horizontal alignments on the approach to roundabouts in high speed (>80km/h) environments has not been adopted by State Roads" (Tasmanian Government 2020).

5 Literature Review Summary

5.1 Reasons for truck rollovers at roundabouts

This section summarises the factors influencing truck rollovers found in the literature review. Many factors contribute to truck rollovers, where high speed obviously comes first as they heavily contribute to excessive centrifugal force development. In addition, a small steering correction at high speed leads to directional forces (load transfer) changes that amplify the rollover outcomes. Other conditions for rollovers include small entry deflection, extraordinarily high visibility encouraging high speeds, No treatments at entry to reduce speed, a significant decrease in radius within the roundabout, and sudden superelevation changes, and raised kerbs or truck aprons. Table 1 shows an overview of the reasons why trucks flip over.

Table 1. Reasons for Truck Rollovers at Roundabouts

Reasons	Studies
High entry speed	Kennedy (2007); Rodegerdts et al. (2015); Chen et al. (2019); Hart (2020); Gertsh and Eichlhard (2003); VicRoads (2010); Kennedy, House & Ride (2008)
High visibility and stopping sight distance	Ahac, Dzambas & Drahcevic (2016); Kennedy, House & Ride (2008); Kennedy (2007); GDOT (2023); VicRoads (2010)
Superelevation and Cross-fall changes within roundabout approaches/reserve curves/circulating carriageway	Kennedy (2007); Ritchie and Lenters (2005); Tomorchio (2019); MRWA (2019a)
Excessive entry deflection	Kennedy (2007); Ahac, Dzambas & Drahcevic (2016)
Insufficient entry and circulating signage	Traffic Design Group (2000)
Tight turn on the circulatory carriageway	Kennedy (2007); VicRoads (2010)
Abrupt changes in cross fall on the circulatory carriageway	Chen et al. (2019); Kennedy (2007); Hou et al (2016)
Poor surface condition and side friction	Hart (2020); Gertsh & Eichlhard (2003); Hall (2014)
Heavier use of truck apron	Chen et al (2019); Chevuri (2018); Hart (2020)

When roundabouts are constructed to suit certain design vehicles, like trucks, there are seldom negative consequences for other users. So, the design feature simply allows drivers of passenger cars not to encounter speed interruptions.

5.2 Prevention Measures to Minimise Truck Rollovers

The reported practices include strategies to select appropriate design vehicle(s), introducing speed-reducing geometric elements and traffic control devices on approaches (curves, extended splitter island with curb), larger central island, truck apron, and wider lanes compared to urban/low-speed roundabouts, supplementary traffic control devices and lighting in advance of and at the intersection (Brewer et al. 2023a).

The review study suggests that improving high-speed rural roundabouts can be achieved through design enhancements like speed-reducing signage, using rumble strips to decrease approach speeds, yield treatments, exit treatments, and specific methods like the deflection angle method, effectively managing speed flow for enhanced roll stability.

Table 2 summarises various strategies that can be used to improve the roundabout design to avoid rollover outcomes. Strategies such as reducing approach speed, limiting visibility to minimum safe stopping distance, use of variable message signs/ flashing lights/vehicle activated signs/illumination, extending the splitter island upstream and creating tunnel effect were identified as notable to destabilise the larger trucks through roundabouts.

Table 2 Strategies to improve the roundabout design to avoid rollovers

Strategies	Resources
Introduce special speed reduction measures	Mndotresearch (2017); Rodegerdts et al. (2015); Tomarchio (2019); Xin et al (2021)
Introduce transverse rumble strips, coloured strips or coloured surface	TRL (2019); Department of Transport (2018); Brewer, Lindheimer, and Chrysler (2017)
Use of signs, variable messages, flashing lights, vehicle-activated signs, and markings to advise appropriate speed	Ritchie and Lenters (2005); Weber and Ritchie (2005); Lenters (2005); Traffic Design Group (2000); Hall (2014); Tomarchio (2019); Brewer, Lindheimer, and Chrysler (2017)
Enhance the landscaping of the splitter island to create a tunnel effect or provide illumination	Ritchie and Lenters (2005); Mndotresearch (2017); Tomarchio (2019)
Limit visibility to a minimum safe stopping distance at the entry	Ritchie and Lenters. (2005); Ahac, Dzambas & Drahcevic (2016);GDOT(2023)
Provide significant entry deflection/transition curve	Ritchie and Lenters (2005); GDOT (2023)
Central island with sight-blocking amenities	Ritchie and Lenters (2005); Ahac, Dzambas & Drahcevic (2016)
Introducing straight-trough lane	Chevuri (2018); Ahac et al (2022); Brewer at al (2023a)

In addition, some perceptual countermeasures can also be implemented, such as changing driver's perceptions to improve safety (e.g., creating an illusion that the drivers reduce their speed well before reaching roundabouts), signs and flashing warning lights at roundabout approaches (that require the driver's attention and ability to slow the vehicle from high speeds to low speeds), and narrow transverse raised or particularly textured strips on pavement or sealed shoulders (create noise and vibrations to notify drivers and slow them down TRL 2019).

High-speed roadways may need longer splitter islands or other cross-section or horizontal alignment changes far from the roundabout compared with lower-speed environments (Transportation Research Board 2023).

Winkler (1999) reported that low-stability vehicles for which rollover is such a great concern, relatively small improvements in their physical stability can yield rather large improvements in rollover accident rate (Winkler & Ervin 1999).

6 Discussion of Findings

This study's main objective is to investigate the geometric design requirements for improving heavy vehicle safety at rural roundabouts to avoid rollovers. This study first compares an international roundabout design standard, then highlights the theoretical background on truck rollover fundamentals, and finally explains safety audits and investigation tools to improve understanding of how geometric elements of roundabouts impact heavy vehicle rollover crashes, that is, providing an overall picture of the circumstances.

This study primarily reviewed findings from quantitative research linking geometric characteristics to truck rollover crash outcomes and computer simulation modelling of vehicle stability based on geometric features. The qualitative research outcomes showed evidence of the effect of visibility and stopping sight distance, crown lines, reverse horizontal curves, the amount of cross-fall and superelevation, rate-of-rotation, and so on. The reviewed quantitative research revealed the level of expected standards and requirements adopted to design and construct rural roundabouts. On the other hand, studies based on computer simulation of truck stability revealed that it is a good, cost-effective approach to visualise the effect of some specific geometric elements such as entry curve radii, circulation with and diameter, and entry deflection. In addition, simulation studies have significant advantages because they can be easily tailored to different roundabouts, truck designs, and traffic circumstances.

The report highlighted that several researchers worldwide have identified remedial actions for the issues with truck rollovers at roundabouts in high-speed areas, including limiting visibility, using variable message signs, extending splitter islands with illuminated transitions, using coloured approaches, and so on. This study also collected remedial measures for improving safety at rural roundabouts as best practices, but it is interesting to note that none appear to have a strong evidence basis.

After reviewing supplementary roundabout design guidelines within individual states, it was also discovered that two Australian states require computer simulation of vehicle stability at newly designed rural roundabouts.

Thus, this study suggests that in the future, simulation modelling should be done for different roundabout configurations to find out how different geometric elements and combinations of elements affect the dynamic rollover threshold (DRT). The Road Planning and Design Manual or Austroads Guide to Road Design can then incorporate the study results, ensuring that the initial roundabout design considers DRT considerations.

7 Future studies

This section discusses potential methods for investigating:

- The effect of geometric elements on the stability of trucks at rural roundabouts, and
- The effectiveness of speed control measures at rural roundabouts

7.1 Before-and-after studies

Before and after crash studies enable individual changes to geometric elements of roundabouts in rural areas to be analysed for the level of improvement. These studies can also be used to examine the effectiveness of introducing the various speed control measures. Although before and after studies can be an effective tool, they are usually costly and take considerable time.

7.2 Cross-sectional studies

Cross-sectional studies can be used to compare rural roundabouts with a specific speed control measure to those without any speed control measure. Arndt (1998) included this consideration but was unsuccessful in determining the effectiveness (or otherwise) of successive reverse curves. Further cross-sectional studies may also not be successful because of the many variables affecting crash rates that are not possible to measure.

7.3 Driver simulation

This project will develop a testing frame to examine the actual rate of rotation as vehicles pass through roundabouts. It will allow the study to determine how close a truck reaches the critical rollover threshold, especially in the context of roundabouts built on high-speed networks.

8 Recommendations

The results of this study make it quite evident that rural roundabouts need to have their design specifications updated. Therefore, it is recommended that driver simulation models be used to investigate the relationship between geometric elements and heavy vehicle stability. These models and their adaptability enable the development of various safety improvements applicable to multiple scenarios, including reviewing existing roundabout alignments and developing new ones. The ultimate goal is to create safer roundabouts in rural areas with improved road design guidance.

References

1. Ahac, S, Džambas, T & Dragčević, V 2016, 'Sight distance evaluation on suburban single-lane roundabouts', Journal of the Croatian Association of Civil Engineers, Gradevinar, vol. 68.
2. Ahac, S, Ahac, M, Džambas, T & Dragčević, V 2022, 'The Design Vehicle Steering Path Construction Based on the Hairpin Bend Geometry—Application in Roundabout Design', Applied Sciences (Switzerland), vol. 12, no. 21.
3. Alrejjal, A & Ksaibati, K 2023, 'Impact of crosswinds and truck weight on rollover propensity when negotiating combined curves', International Journal of Transportation Science and Technology, vol. 12, no. 1, pp. 86-102.
4. Arndt, Owen, 1994, ‘Relationship between roundabout geometry and accident rates’, Masters by Research thesis, Queensland University of Technology, Queensland, Australia.
5. Arndt, O & Troutbeck, R 1998, Relationship between roundabout geometry and accident rates', Transportation Research Circular E-C003, vol. 28, no. 1.
6. Arndt, Owen 2004, 'Relationship between unsignalised intersection geometry and accident rates', PhD thesis, Queensland University of Technology, Queensland, Australia.
7. Bao, W & Hu, S 2015, 'Vehicle rollover simulation analysis considering road excitation', Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering, vol. 31, no. 2, pp. 59-65.
8. Blue, DW & Kulakowski, BT 1991, 'Effects of horizontal-curve transition design on truck roll stability', Journal of Transportation Engineering, vol. 117, no. 1, pp. 91-102.

9. Boodlal, L, Donnell, ET, Porter, RJ, Garimella, D, Le, T, Croshaw, K, Himes, S, Kulis, PN & Wood, J 2015, 'Factors influencing operating speeds and safety on rural and suburban roads'.
10. Brewer, M, Lindheimer, T & Chrysler, S 2017, Strategies for Effective Roundabout Approach Speed Reduction, Texas A&M Transportation Institute, Minnesota Department of Transportation, Minnesota.
11. Brewer, MA, Zhou, HT, Tydlacka, J & Florence, D 2023b, 'Operational Performance of Roundabouts at High-Speed and Rural Locations', Transportation research record, vol. 2677, no. 12, pp. 144-57.
12. Brewer, MA, Fitzpatrick, K, Shirinzad, M, Zhou, H, Florence, D, Tydlacka, JM, Dadashova, B & Le, M 2023a, Research and Findings on Roundabouts and Innovative Intersections for High-Speed and Rural Locations, Texas A&M Transportation Institute.
13. Chen, Y, Zheng, X, Peterson, A & Ahmadian, M 2019, 'Simulation Evaluation on the Rollover Propensity of Multi-Trailer Trucks at Roundabouts', SAE Technical Paper: 2020-01-5005.
14. Chen, Y, Zheng, X, Peterson, A & Ahmadian, M 2020, 'Simulation Evaluation on the Rollover Propensity of Multi-Trailer Trucks at Roundabouts', SAE Technical Papers.
15. Chevuri, PK 2018, 'Trucks at roundabouts: a synthesis study', Journal of Transportation Technologies, vol. 8, no. 1, pp. 65-74.
16. Dahlberg, E 2001, 'Commercial vehicle stability-focusing on rollover', Report no: 2000-01-3492, Royal Institute of Technology, Stockholm, Sweden.
17. Department of Infrastructure and Transport 2022, Roads Master Specification, RD - GM - D1 Road Design , Version 4, Govenment of South Australia, Adelaide, SA.
18. Gaffney, T 2023, ARRB puts the spotlight on truck rollovers, https://www.arrb.com.au/latest-research/arrb-puts-the-spotlight-on-truck-rollovers>.
19. Gbologah, FE, Guin, A & Rodgers, MO 2019, 'Safety Evaluation of Roundabouts in Georgia', Transportation research record, vol. 2673, no. 7, pp. 641-51.
20. GDOT 2023, Roundabout Design Guide, Georgia Department of Transportation (GDOT), Georgia.
21. Germanchev, A, Eady, P & McKelvie, D 2011, 'The influence of speed on concrete agitator vehicle stability', Journal of the Australasian College of Road Safety, vol. 22, no. 3, pp. 45-50.
22. Gertsch, J & Eichlhard, O 2003, 'Simulation of Dynamic Rollover Threshold for Heavy Trucks', SEA Technical paper: 2003-01-3385.
23. Gkyrtis, K & Kokkalis, A 2024, 'An Overview of the Efficiency of Roundabouts: Design Aspects and Contribution toward Safer Vehicle Movement', Vehicles, vol. 6, no. 1, pp. 433-49.
24. Godavarthy, RP, Russell, E & Landman, D 2016, 'Using vehicle simulations to understand strategies for accommodating oversize, overweight vehicles at roundabouts', Transportation Research Part A: Policy and Practice, vol. 87, pp. 41-50.
25. Hall, TM 2014, 'Heavy vehicle rollover propensity at roundabouts on highspeed roads', Master Thesis. 329, Purdue University, <https://docs.lib.purdue.edu/open_access_theses/329>
26. Han, I 2023, 'Sensitivity analysis and improvement of the rollover propensity of large articulated vehicles on roundabouts using design of experiments', SAE International Journal of Commercial Vehicles, vol. 16, no. 02-16-02-0009, pp. 141-51.
27. Hart, P 2012, 'Rollover of Heavy Vehicles', ARTSA, <https://www.artsa.com.au/assets/articles/2012_06.pdf>.
28. Hart, P 2020, 'Rollover roundabouts', ARTSA Technical Column. <https://www.artsa.com.au/assets/articles/June2020.pdf>

29. Hou, Y & Ahmadian, M 2015, 'Effects of Commercial Truck Configuration on Roll Stability in Roundabouts', SAE Technical Paper: 2015-01-2741.
30. Hou, Y, Chen, Y & Ahmadian, M 2016, 'A Simulation-Based Study on the Improvement of Semi-Truck Roll Stability in Roundabouts', SAE Technical Paper: 2016-01-8038.
31. Jedniuk, A 2024, Heavy vehicle rollovers at High-speed roundabout, BE Dissertation, University of Southern Queensland, Toowoomba, Australia (not published).
32. Kennedy, J 2007, International comparision of roundabout design guidlines, TRL Limited, London, UK, https://trl.co.uk/uploads/trl/documents/PPR206_secure.PDF>.
33. Kennedy, JV, House, C & Ride, NM 2008, 'The uk standards for roundabouts and mini-roundabouts', National roundabout conference, TRB, Kansas City, Missouri, USA, pp. 18-21.
34. Liu, C, Chau, K, Lee, CH & Song, Z 2020, 'A critical review of advanced electric machines and control strategies for electric vehicles', Proceedings of the IEEE, vol. 109, no. 6, pp. 1004-28.
35. Mndotresearch 2017, Choosing effective speed reduction strategies for roundabouts, traffic and safety, https://mntransportationresearch.org/2017/08/02/choosing-effective-speed-reduction-strategies-for-roundabouts/>.
36. MRWA 2019a, MRWA Supplement to Austroads Guide to Road Design - Part 4B - Roundabouts , Version 3K., Main Roads Western Australia (MRWA), Perth, WA, https://www.mainroads.wa.gov.au/technical-commercial/technical-library/road-traffic-engineering/guide-to-road-design/mrwa-supplement-to-austroads-guide-to-road-design-part-4b/>.
37. MRWA 2019b, Guidelines for Vehicle Stability Analysis - Main Roads Internal Process, Main Roads Western Australia (MRWA), Perth, WA.
38. Park, L & Pierce, D 2013, 'Accommodation of Large Trucks in Roundabouts: Motor Carrier Perspective', Transportation research record, vol. 2388, no. 1, pp. 10-3.
39. Phanomchoeng, G & Rajamani, R 2012, 'Prediction and Prevention of Tripped Rollovers, Final Report', Intelligent Transportation Systems Institute, Department of Mechanical Engineering, University of Minnesota, CTS Project, vol. 2011019.
40. Pont, J 2004, 'Stability Effects of Sloshing Liquids and Hanging Meat', Transport Engineering Research New Zealand (TERNZ), Manakau City, New Zealand.
41. Ritchie, S & Lenters, M 2005, High Speed Approaches at Roundabouts, https://onlinepubs.trb.org/Onlinepubs/circulars/ec083/12_Ritchiepaper.pdf>.
42. Rodegerdts, L, Griffin, A, Steyn, H, Ahmadian, M, Hou, Y & Taheri, M 2015, 'Evaluation of Geometric Parameters that Affect Truck Maneuvering and Stability', No. FHWA-SA-15-073, Federal Highway Administration, Washington, DC.
43. Sullivan, J, Winkler, CB, Bogard, S & Hagan, M 2004, 'Influence of a roll-stability advisor on turning performance of truck driver', Proceedings of the Proceedings 8th International Symposium on Heavy Vehicle Weights and DimensionsMisty, Hills Conference Centre, 14-18 March 2004, Muldersdrift, Gauteng, South Africa
44. Tarko, A, Hall, T, Romero, M & Jiménez, CGL 2016, 'Evaluating the rollover propensity of trucks—A roundabout example', Accident Analysis & Prevention, vol. 91, pp. 127-34.
45. Tasmanian Government 2020, T3 – Road Design Guidelines & Standards INTERIM UPDATE, Department of State Growth Tasmania, Tasmania.
46. TMR 2021, Supplement to Austroads Guide to Road Design Part 4B: Roundabouts , 2: Volume 3, Department of Transport and Main Roads, Queensland.
47. Tomarchio, MD 2019, Improved theory for the design of high-speed roundabouts to suit heavy vehicles, BE Dissertation,, University of Southern Queensland, Toowoomba, Australia.

48. Traffic Design Group 2000, The Ins and Outs of Roundabouts, Traffic Design Group of Lower Hutt, Transfund, New Zealand.
49. Transport for NSW 2023, Supplement to Austroads Guide to Road Design (TS 02642:1.0), Transport for NSW, Sydney, NSW.
50. Transportation Research Board 2023, Guide for Roundabouts, National Academies of Sciences, Engineering, Medicine, The National Academies Press, Washington, DC.
51. TRL 2019, Safer Verges – Part 1: Use of Rumble Strips, Road Safety Knowledge Centre, Availalbe at, https://www.roadsafetyknowledgecentre.org.uk/rskc-1956/>.
52. VicRoads 2010, Understanding causes of rollover crashes, Information Bulletin, March 2010, VicRoads, Victoria, Australia
53. VicRoads 2011, VicRoads Supplement to the Austroads Guide to Road Design Part 4B – Roundabouts Department of Transport and Planning Victoria, Victoria, Australia
54. Weber, P & Ritchie, S 2005, 'Internationally recognised roundabout signs', Proceedings of the National Roundabout Conference, Transportation Research Board, Vail, Colorado.
55. Winkler, CB & Ervin, RD 1999, rollover of heavy commercial vehicles, Society of Automotive Engineers, Warrendale, PA.
56. Xin, T, Xu, J, Gao, C & Sun, Z 2021, 'Research on the speed thresholds of trucks in a sharp turn based on dynamic rollover risk levels', PloS one, vol. 16, no. 8, p. e0256301.
57. Young, L 2021, Analysis of the Suitability of Roundabouts for Heavy Vehicles driving at High Speeds in Queensland, Dissertation, University of Southern Queensland, Toowoomba, Australia.

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