A Review of the Literature on Design and Performance of Multi Lane Roundabouts in Canada: The Case for Turbo Roundabouts

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1 Introduction

Modern Canadian transportation is supported by a diverse road network; when these roads cross, intersections are needed. Single lane roundabouts (SLRs) have grown to become a standard intersection choice over the last two decades however, due to capacity their application is limited to small volume crossings. Roundabouts are preferred over traditional intersections (traffic lights or stop sign crossings) due to reducing collision and injury frequency over 35% and 75% respectively [3], and greatly increasing traffic flow. Multi lane roundabouts (MLRs) have been implemented for roughly two decades in North America however, their success does not include the sweeping safety benefits of SLRs. As time is lost within transportation systems due to 'clogging' of intersections and traffic backup, the need for solutions that offer better safety and traffic flow capacity exist.

Turbo roundabouts (TRs) are a relatively new intersection concept implemented in the Netherlands nearly twenty years ago; these MLRs include raised lane dividers, spiral circulating lanes, often shelter islands for pedestrians, and sometimes raised pedestrian crosswalks. While these roundabouts improve safety over existing MLR's [20], and capacity over SLRs, the relative impact of specific TR geometry and placement of appurtenances is still being researched. Approach angles influence speeds of entering or exiting vehicles [14], and consequently capacity and safety are functions of these angles. Crossing shelters assist pedestrians and cyclists by shortening road crossing distance [14], while raised crossings lower approaching vehicle speeds

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without disrupting two-way traffic flow. With rise of active transportation in municipal communities [1], inclusion of appurtenances in design guidelines cannot be overemphasized.

With Turbo Roundabouts only seemingly being actively applied in Europe, and somewhat addressed in the U.S. via the FWHA, there appears to be a knowledge gap for Canada to promote implementation; despite some MLRs that mimic turbo roundabout design, there are no ‘true’ TRs existing in Canada. Due to harsh winters and large snowfall, parts of Canada might create environmental challenges for snow removal. Additionally, there are various studies that somewhat conflict with the safety benefits purported. Finally, Appurtenances that make our intersections functional and desirable parts of the build environment seem to lack definition in existing design aids and research. This paper reviews the background of circular intersections, and illustrates most recent credible research outlining ideal Turbo Roundabout design guidelines in a Canadian context. Existing MLR projects are reviewed to give an idea of the lessons learned and provide insight towards ideal design guidelines. Appurtenance traffic calming and pedestrian aids are reviewed for insight into expected benefits and perceived best practices.

2 Background

This background serves to summarize the adoption of circular intersections from historical to modern transportation system improvements within a North American context.

2.1 Initial Circular Intersections

The first circular intersection utilized in North America was commissioned in 1905 in New York City—aptly named the Columbus Circle (Transportation Association of Canada [7]). A few decades followed where traffic circles and rotaries were used as an alternative road improvement. These ‘initial circular intersections’ (ICI) were different than ‘modern roundabouts’ (MR) due to their geometric design, entry/exit requirements, right of way procedures, circulating speed, and pedestrian allowances; particularly dangerous was the requirement for circulating vehicles to yield to entering vehicles, a large internal diameter, and high circulating vehicle speeds. Due to the various differences, ICI’s led to many high-speed collisions and congestion and were eventually phased out as a viable design improvement. During the 1960s the British varied rules of the road to require entering traffic to yield towards circulating traffic on all circular intersections. Around this same time, designs were being implemented using smaller internal diameters and slower circulating speeds. Due to these changes, safety and capacity of ICI’s improved drastically and led to the implementation and design of what are now called Modern Roundabouts.

2.1.1 Rotaries

Rotaries were installed within Canada prior to the 1960s and included large diameter central islands (sometimes larger than 100 m). These transportation improvements were designed to maintain high speeds while moving throughout the circle. Lane changes would be required to enter the circulating ring, contributing to large size. Implementation of these improvements was limited to Eastern Canada and United States. Rotaries are otherwise known as traffic circles in Western Canada [6].

2.1.2 Urban Traffic Circles

Traffic circles are circular intersections in urban settings. Traffic circles were often built around historical monuments or items of significant cultural value. Due to high volume pedestrian crossings at many of these urban sites, traffic signals were often used to control multiple modes of transportation (pedestrian, cycling, automotive, etc.) through the circles.

2.1.3 Neighbourhood Traffic Circles

Neighborhood traffic circles are residential improvements, often constructed within existing four-way intersections. These improvements may include yield signs at the entrance, however, are often minimalistic in design and include little more than a central island that forces one way circulating traffic.

2.2 Modern Roundabouts

Canada's first MR emerged in the 1990s. Since implementation, single lane MR's have been extended to interchanges around highways, intersections on highways, and have been given preference in policy as a first choice for highway intersections in British Columbia to support climate targets [2]. As mentioned, modern roundabouts utilize yielding to circulating traffic. Due to this characteristic, it's a commonly understood roundabouts hold advantages over intersections (especially signalized) in low volume situations [10].

2.2.1 Mini Roundabout

The smallest of modern roundabouts is the mini roundabout. The ICD for this type of roundabout is typically 13.5–27 m [12]. The central island is often traversable, and for four legs the maximum daily capacity is estimated at approximately 15,000 vehicles.

2.2.2 Single Lane Roundabout

The single lane roundabout typically has an inscribed circular diameter (ICD) of 27 m to 54 m, and as the name suggests, only supports movement of one lane of traffic. Depending on level of traffic and pedestrian / cyclist requirements, crossing signals may be used at entrance and exit of these roundabouts. Single lane roundabouts have demonstrated desirable safety metrics over traditional intersection design for severity and frequency of injury [5]; injury rate and collision frequency for SLRs are typically reduced by 73% and 51% respectively [16], in the United States.

2.2.3 Mixed Multi Lane Roundabout

Mixed Multi Lane Roundabouts are, by definition, multi lane roundabouts that allow driver lane changing. Mixed lane roundabouts were implemented to increase capacity over traditional roundabouts, however driver behavior (specifically the proclivity of drivers to change lanes multiple times within the roundabout), has led to a reduction in the efficiency of this intersection; specifically, it has been suggested that the reduced traffic safety of lane changing leads to more accidents, and in turn lowers the efficiency/capacity/robustness of this intersection [17].

2.2.4 Turbo Roundabout

The turbo roundabout was first designed by Dr. Lambertus Fortujin in 1996 while he was a senior lecturer at Delft University; the design was hypothesized to solve challenges towards multilane roundabout safety performance in the Netherlands. Key features of the TR include raised lane dividers separating inner and outer traffic lanes, spiral circulating roadway from inside to outside, and divergent entry lanes which restrict driver exit choices. The raised lane dividers eliminate lane weaving and reduce conflict points; the spiral roadway ensures that lane restricted vehicles may still access their desired exit point; the divergent entry lanes ensure any lane changes happen well before entering the TR. A depiction of the turbo roundabout and its' key features may be found in Fig. 1. It should be noted that typical turbo roundabout design give allowances for appurtenances that encourage more comfortable road passage and crossing for cyclists and pedestrians; these appurtenances include separated cycle track, crossing refuge, and sometimes raised crossings that encourage auto drivers to reduce speed.

3 Literature Review

The main literature used for this review comes from research papers and manuals produced in Europe; one of the main predecessors of these sources, while also being

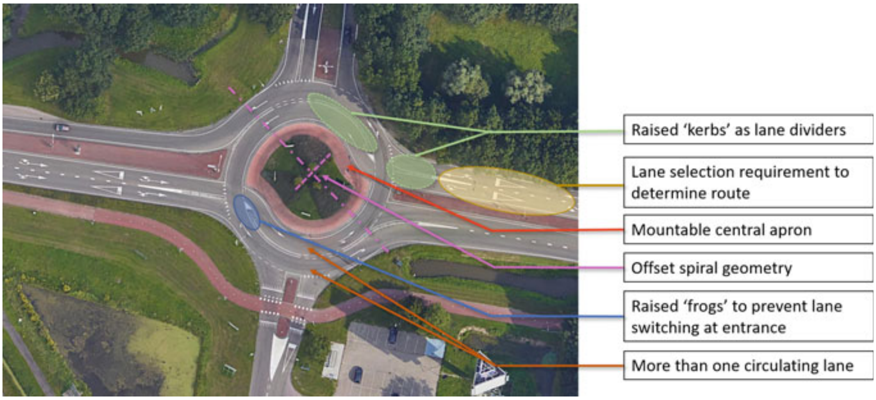

Fig. 1 Turbo roundabout key features. *Source* Google Maps; authors' labels

the most well defined, continues to be the Dutch Roundabout Design Manual. As a principle design source, much of the research created by others either supports or questions the assertions of the manual. This literature review serves to analyze the roundabout design manual by comparing it primarily with peer reviewed papers. For the purposes of analysis, this review will be limited to unsignalized or self regulating turbo and mixed multi lane roundabouts.

The first four subsections of this literature review will discuss features of a turbo roundabout that distinguish it from other similar intersection improvements. The final section will discuss how turbo roundabouts operate, their limitations, and opportunities within a transportation network.

3.1 Spiral Lane Geometry

There are seven types of lane geometry prescribed within the manual: basic, egg, knee, spiral, rotor, stretched knee and star [14]. The FWHA defines a turbo roundabout as having no more than two circulating lanes; and prescribed only the basic, egg, knee, spiral, and rotor geometries. The additional roundabout types in the Dutch catalogue (stretched knee and star) allowed for much higher capacity with additional lanes, which is something not recommended by FHWA [15].

Performance was mainly linked to safety statistics and not speed or volume for Dutch applications. The parameter found to be most closely correlated towards safety/speed was the radii of the inner curve and inner lane (R1); the ideal radii was found to be 12 m. The inside spiral R1 may be seen on the below figure and found highlighted in the below table. The below figure (turbo block detail) illustrates typical design geometry; four radii are used in laying out any two lane turbo roundabout geometry, and up to six radii are used if a three lane turbo roundabout is desirable. The radii are offset from center along a translational axis approximately half a lane distance. Using a smaller radii roundabout (as found in the turbo roundabout) ensures that vehicles will maintain a reasonable speed throughout the circulating lane; other research has confirmed has confirmed that lower vehicle speeds and drastically reduce the potential for serious injuries, however in 2012 some research lended credit to the roundabout design manual by suggesting 40 km/h as the optimal design speed for turbo roundabouts [8] (Fig. 2).

Czech researchers examining implementation of turbo roundabouts found the optimal lane width for turbo roundabouts was between 4.5 and 5.8 m in width [19]. This width coincides with widths pronounced in the Dutch Roundabout Design Manual, however this varied lane width allowed some flexibility to ensure that lanes were not too wide to encourage excessive speed, nor too narrow to encourage oversize vehicle lane encroachment.

Perhaps one of the most easily understood and well documented arguments for use of a turbo roundabout is from a conflict assessment approach; utilizing turbo roundabouts in place of multi lane roundabouts drastically reduces the amount of potential conflict points within an intersection design, as shown in Fig. 3.

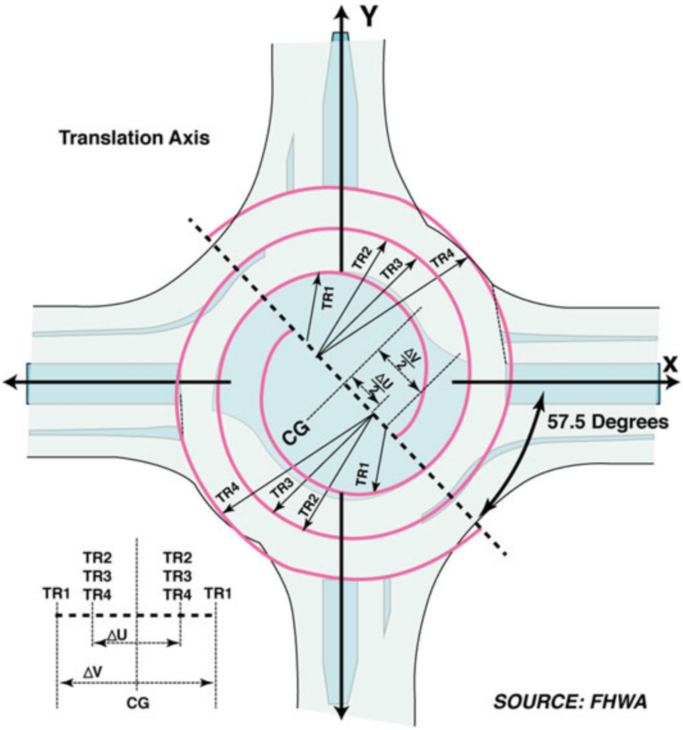

Fig. 2 Turbo block detail. Adapted from [13]

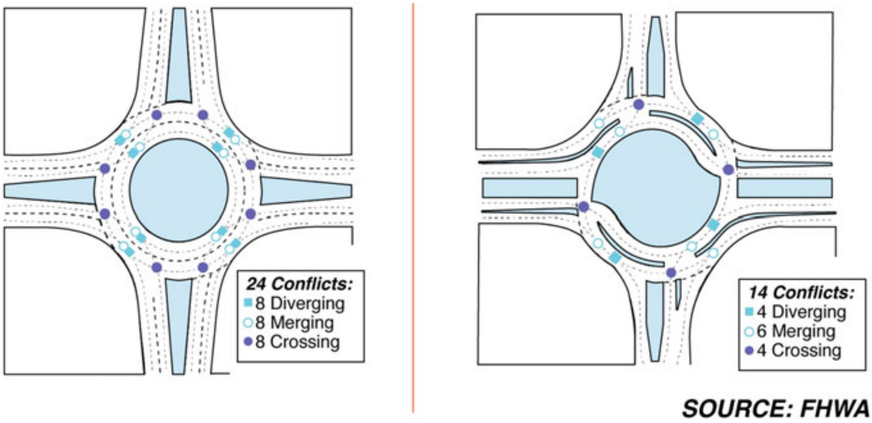

Fig. 3 Comparison of multi lane and turbo roundabout conflict points. Adapted from [13]

3.2 Physical Lane Dividers

Lane dividers are a necessary component of turbo roundabouts to prevent lane weaving, reduce speed of circulating vehicles, and reduce fear of being cut off while travelling in other lanes [14]. A large 'Frog' is placed near the start of the inner travel lane to allow higher visibility of the lane divider, and encourage entering the appropriate lane. Reflectors are advised and may be placed either on top of the lane divider, or on slopes. The original lane dividers had a 'soft' raised curb of approximately 1 inch, and then a sloped raise of another 2 more inches to the total height of barrier; the soft curb allowed vehicles to pass over if required however was a significant deterrent. To allow snowplowing the overall height of the divider was unchanged, but the soft curbs were removed, as shown in the below diagram. The overall width of divider in both diagrams is 1 foot wide, and a foundation or footing was suggested as a concrete structure embedded in the roadway (Fig. 4).

In 2015, a Polish research paper investigated the effect of raised lane dividers on reduction of certain types of collisions, as compared to multilane roundabouts with no raised lane dividers. At that time Poland had constructed both turbo roundabouts with and without physical lane dividers; the type and severity of collisions that occurred at the turbo roundabout with a physical lane divider were strikingly different; the collisions resulted in approximately 20% fewer serious injuries, and less than half the amount of vehicle side impacts when physical dividers were employed. The author concluded there was little difference between turbo roundabouts without a lane divider and a standard multi lane roundabout from a safety perspective [11], and suggested that multilane roundabouts without raised lane dividers are undesirable (Fig. 5).

Safety benefits of Turbo roundabouts with a raised lane divider cannot be overstated. Another group of Polish researchers analyzed collision data of nine multilane roundabouts (five of which were turbo roundabouts) over four years to prescribe

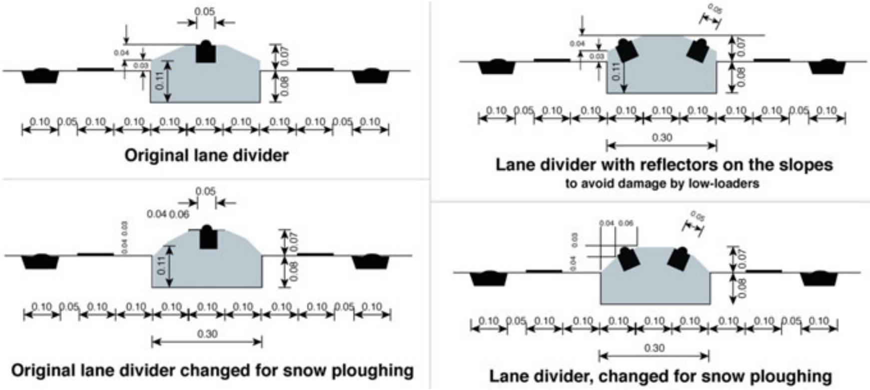

Fig. 4 Physical lane dividers. Adapted from [14]

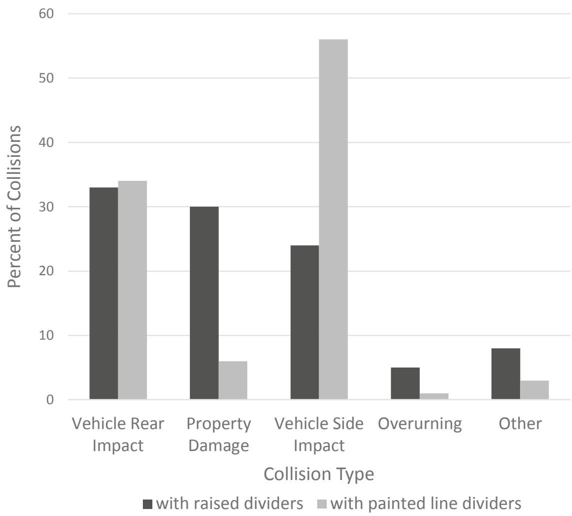

Fig. 5 Collisions type comparisons between turbo roundabouts with and without raised dividers [11]

predictive models of safety performance factor. The data and modelling suggested a 90 percent confidence that with given traffic volumes, a raised lane divider would result in up to 60 percent less collisions at a turbo roundabout site [9], most definitely in US applications where higher approach speeds are common. According to this team's research, the likelihood of drivers to follow a swept path was highly influenced by the presence of lane dividers; up to 40% of drivers using multilane and turbo roundabouts violated the selected lanes and changed lanes within the circulating lane. Having lane dividers reduces the potential conflict points significantly for circulating vehicles, and ensures that smaller radii geometry is followed, which induces lower speed and risk towards vehicles within the turbo roundabout.

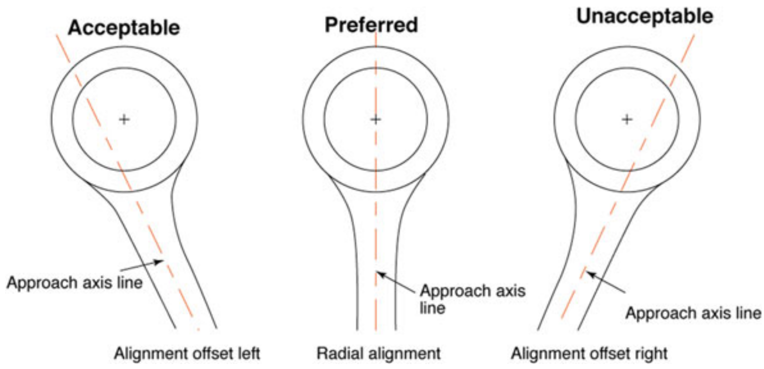

Fig. 6 Approach axis line [14]

Further, Italian research demonstrated that the physical lane dividers guarantee a reduced running speed throughout the circulating lane, by enforcing compliance to the smaller radii geometry [8]. This research suggested that physical lane dividers should be used in all circumstances when considering turbo roundabouts in an urban context.

3.3 Approach Lane Vectors

Alignment of the approach lane is a critical determinant of incoming speed. It is desirable to have drivers reduce speed when entering roundabouts for safety reasons. Due to this reason it's allowable to have offsets to the left of the center of the roundabout, but not to the right. Having an offset to the left is only advised if there are no cyclists and few pedestrians crossing the roadway, as higher vehicle exiting speed would be expected [14]. Ensuring vehicles approach roundabouts nearly perpendicular encourages reduction of speed due to the radius of curvature to enter the circulating lane; without a smaller radius curve to enter the lane, reduced speed (and therefore safety benefits) cannot be guaranteed (Fig. 6).

3.4 Pedestrian Crossings

Brilon summarized lessons learned with all types of roundabouts in Germany in 2011 at the TRB roundabout conference; particularly useful were the findings about effective placement of appurtenances. It was suggested that the only significant risk at compact roundabouts was with their connection to cyclists; Brilon suggested that cycle track crossings of entry and exit lanes should be placed at least 5 m from the circulating road, and might only be necessary when traffic carried at the roundabout exceeds 15,000 vehicles per day. While statistical information wasn't presented to support some of the lessons learned, it was suggested that cyclists suffer from poor visibility when their crossing distance is too close to the circulating lane [4]. Conclusions of this paper suggested that signalized intersection is still a well accepted solution for traffic amounts above 40,000 vehicles per day.

Brilon's findings were supported in a British case trial study where different cycle track and crossing schemes were tested to analyze how roundabouts affected the safety of cyclists and pedestrians and their proclivity towards active transportation in a network where roundabouts were constructed. Overall, the cyclists and pedestrians were supportive of the roundabout improvements towards an active transportation, and the designs most successful included segregation of all three modes, and separation from the circulating traffic ring [22].

It should be noted that pedestrian crossing locations and inclusion of appurtenances likely has significant effects on traffic capacity in urban context, if at grade crossings are included. Italian researchers estimating capacity of turbo roundabouts in urban context had contentious findings for capacity that did not agree with previous research and may warrant further investigation [8].

3.5 Placement Within Network and Capacity

Researchers in Spain analyzed the safety and capacity of Turbo Roundabouts using gap acceptance theory along with other complex capacity formulation techniques. Without getting into too much detail about this research, the findings indicated that turbo roundabouts had limited application in high capacity circumstances. The researchers concluded that previous authors used much too simplistic approaches for comparison of turbo roundabouts to mixed multi lane roundabouts (specifically for lane allocation and saturation); the circumstances where turbo roundabouts perform best are for locations where turns in the minor traffic flow direction are above sixty percent [18]. This point was further examined and agreed upon that in order for turbo roundabout capacity to exceed multi lane roundabouts, more than sixty percent of vehicles must be turning right [21].

Further research by Silva and others analyzed performance of turbo roundabouts compared to multilane roundabouts with microsimulation and real case study in corridor applications. The corridor analyzed had three roundabouts spaced at 400 and 470 m on a two lane road; the research was aimed at analyzing capacity of these turbo roundabouts at saturated or near saturated conditions. The findings by this research suggest capacity performance degrades rapidly as turbo roundabouts exceed capacity [17], as opposed to conventional multilane roundabouts; it appears the multilane roundabouts were less susceptible to clogging at saturated conditions.

4 Discussion

One of the main benefits recognized from numerous sources within the literature review was the safety benefits of turbo roundabouts (and roundabouts in general). Added safety via reduced frequency and severity of collisions has been attributed to radial curvature imposing a reduction of speed to under 40 km/h. Low radius curves require drivers to slow down to comfortably move throughout the circulating lanes. As shown in prior research, vehicles will take the fastest path through multi lane roundabouts where lane compliance is not enforced via raised lane dividers, making illegal movements commonplace throughout multilane roundabouts—thus undermining their purpose of improving road safety. Case studies have shown collision frequency reduction of at least 60% when converting a priority intersection to a turbo roundabout [19], however this amount varies based on country of implementation (expected speeds and rules of road vary).

One item differing between research papers was an agreed upon capacity formula, especially in urban context where pedestrian crossings are expected at grade. The method of calculating capacity with only vehicles wasn't necessarily agreed upon, and certainly the location of appurtenances and their affect on intersection capacity is not very well understood. It was however recognized that pedestrian and cyclist crossings should be kept back from these intersections; the appropriate distance from the circulating lane to place pedestrian crossings was not found in this literature review.

5 Conclusion

Turbo roundabouts seem to operate consistently, but not exclusively, at high capacity in locations with three intersecting legs. These roundabouts have the potential to replace many signalized intersections in three and four leg scenarios in urban applications however the likelihood of success is dependant on accurate modelling and understanding of how pedestrian flows affect the safety and function of the intersection itself. It seems reasonable that further research into modelling of the different types of these roundabouts in urban circumstances would be beneficial, so an analytical tool may be developed to adequately assess different locations for suitability of turbo roundabouts as a first choice.

One of the underlying program tenets for the Dutch roundabout design manual (referenced frequently in this paper) is a vision zero goal. The vision zero goal for transportation, as the name implies, is a goal of having zero fatal collisions; the goal places the onus on adequate design to reduce risks for road users. North American design manuals as recent as "Guidelines for the Planning and Design of Roundabouts" [12] seem to encourage multilane roundabout designs that focus on vehicles maintaining their directed path when entering roundabouts, with no physical lane controls. Research suggests up to 40% of road users ignore lane markings when using multi lane roundabouts for the fastest path; it seems redundant to design multi lane roundabouts for circumstances which aren't, in fact, observed or realistic. One conclusion is that opportunity for driver error isn't necessarily viewed as a designer's responsibility, and perhaps that is a fault of the road culture of North America. If safety is to be encouraged from a design perspective, it may be worth reviewing the program foundations supporting it.

Finally, it is apparent from the research reviewed that multi lane roundabouts are not desirable improvements from a safety perspective without raised lane dividers.

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