Journal of Safety Research 66 (2018) 151–159

Contents lists available at ScienceDirect

Journal of Safety Research

journal homepage: www.elsevier.com/locate/jsr

Whether conversion and weather matter to roundabout safety☆

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ARTICLE INFO

Article history:
Received 17 January 2018
Received in revised form 18 May 2018
Accepted 2 July 2018
Available online 17 July 2018

Keywords:
Roundabouts
Safety
Conversion
Inclement weather
Rainfall

ABSTRACT

Introduction: Roundabouts, as a form of intersection traffic control, are being constructed increasingly because of their promise to improve both efficiency and safety. However, roundabout performance varies from one context to another; and information on their performance during inclement weather is limited. *Methods:* To evaluate the safety effects of converting signal-controlled intersections to modern roundabouts in a region that historically was unfamiliar with this type of traffic control, an empirical Bayes approach was used to analyze. Second, to examine the potential effects of rainfall on roundabout safety, a matched-pair approach was used to compare risk estimates of collision occurrence at roundabouts and signalized intersections under inclement weather conditions. *Results:* Roundabout installation is shown as an effective safety intervention for serious collisions since conversion from signalized intersections to roundabouts translates into an overall 20% reduction in the occurrence of injury/fatal collisions. However, roundabouts witnessed more property-damage collisions than what would have been expected had the conversion not occurred. With respect to weather, there is no evidence of a statistically significant increase in crashes on days with rainfall relative to good weather conditions for roundabouts, whereas there is evidence of such an increase in crash risk estimated to be 4% to 22% for signalized intersections. *Conclusions:* While injury collisions are consistently found to be lower at intersections that have been converted from signalized intersections to roundabouts, the same is not always that case for property-damage collisions, suggesting that drivers need time to adjust. In terms of weather, the evidence in this paper shows that roundabouts show less sensitivity to rainy conditions than signalized intersections. *Practical applications:* The trade-offs between design, operation, and safety should be considered carefully when planning a new roundabout. More research is required on the specific problems users experience with roundabouts and the effectiveness of public education programs.

1. Introduction and research objectives

Globally, road collisions are a leading cause of death. A goal has been set in the recently adopted 2030 Agenda for Sustainable Development, which is to half the global number of deaths and injuries from road traffic crashes by 2020 (WHO, 2017). In order to achieve this ambitious target, organizations and nations from around the world are increasingly adopting a safe-systems approach to road transport, where systems are designed in ways that take into account human fallibility and vulnerability. Flowing from this thinking is the need to design infrastructure in ways that reduce the probability of collisions, as well as the severity of collisions when crashes do occur.

Roadway intersections are of particular importance in designing safe transport systems, especially in urban contexts. Intersections account for a large proportion of the total number of collisions worldwide, since they are the junctions of roads comprising the traffic network, where conflicts between traffic movements are most likely to happen (Antonucci, Hardy, Slack, Pfefer, & Neuman, 2004). For example, the U.S. Federal Highway Administration (2017) reports that more than 50% of collisions involving personal injury occur at or near intersections.

Movements at intersections are guided by intersection control mechanisms and rules (e.g., traffic signals, stop/yield signs, and right-of-way conventions for uncontrolled intersections). The most heavily traveled intersections typically are signalized. Other intersection designs, including displaced left-turn intersections, double crossover diamond interchanges, and roundabouts are also being used in efforts to address growing concerns over safety, while also maintaining or improving flow.

Roundabouts are of particular interest since, from a 'safe system' point-of-view, they are viewed as a preferred at-grade intersection option because of their ability to slow through-traffic and reduce the number of conflict points. Not surprisingly then, the vast majority of studies suggest that roundabouts are effective at reducing collisions that result in injury or death. The implications of roundabouts for more minor collisions are less clear, however, with variable results in

☆ Declarations of interest: none.

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https://doi.org/10.1016/j.jsr.2018.07.001
0022-4375/

different contexts. Some of the variation may be explained by a driver learning curve that translates into a lag effect in safety after roundabouts are introduced, although little empirical evidence exists to test this hypothesis. Other contextual factors that may dampen or accentuate safety benefits include weather, land use, and traffic mix and density. These too, have not been systematically examined.

This study addresses two of these gaps in the empirical research on road safety – the safety effect of conversion from signalized intersections to roundabouts in a region previously unfamiliar with roundabouts, and the ways in which inclement weather affects the safety outcomes associated with the conversion.

The specific objectives of this paper are:

1. To evaluate the safety effect of converting signal-controlled intersections to modern roundabouts in a region that historically was unfamiliar with this type of traffic control; and
2. To examine the potential effects of rainfall on roundabout safety.

2. Research context

In right-hand drive jurisdictions, a roundabout is a form of circular intersection in which the traffic circulates anticlockwise in the lanes around a central island (Highway Capacity Manual, 2010). The vehicles in the entry lanes are permitted to enter the intersection only if a sufficient gap in the circulating traffic is available (Highway Capacity Manual, 2010). Roundabouts have fewer potential vehicular conflict points than conventional intersections, which ameliorate or even eliminate some conflict types (e.g., head-on, high angles), particularly those associated with severe injuries (Gross, Lyon, Persaud, & Srinivasan, 2013). Compared with signalized intersections, roundabouts also eliminate red-light running situations and control intersection travel speeds (Rodegerdts et al., 2010).

Given the potential benefits of roundabouts for both safety and traffic flow, it is not surprising that they are increasingly being adopted around the world (e.g., Malloy, 2016). While circular intersections have a long history, modern roundabouts began being implemented only since the 1960s in the United Kingdom (Rodegerdts et al., 2010) and the 1990s in North America. In Canada, the experience is rather limited, with most roundabouts having been built only in the past 15 years (Bassi, Pearson, & Ledig, 2004). Also, the distribution of roundabouts in Canada is concentrated, with the majority located in a subset of urbanized areas of the most densely populated provinces (e.g., the provinces of Ontario and Quebec have about 100 of them).

Many previous studies have concluded that the implementation of roundabouts effectively reduces fatal and injury crashes (AASHTO, 2001; Daniels, Nuyts, & Wets, 2008; De Brabander & Vereeck, 2007; Gross et al., 2013; Jensen, 2013; Qin, Bill, Chitturi, & Noyce, 2013). However, the overall effects of conversion vary in magnitude, and sometimes even in direction. Consider the following three studies that estimate the effects of roundabout installation on total collisions. Persaud, Retting, Garder, and Lord (2001) studied 23 intersections located in seven states in the United States and concluded that roundabouts reduce total collisions by 35%, compared to intersections with traffic signal controls. Hu, McCartt, Jermakian, and Mandavilli (2014) summarized that, while the rate of injury and fatal crashes decreased near Bellingham, Washington, the rate of property-damage-only (PDO) crashes increased 36% in association with the installation of roundabouts. Third, a study of roundabouts in Arizona (Mamlouk & Souliman, 2016) also indicated that the installation of a roundabout at an existing signalized intersection led to a greatly elevated number of collisions. These studies suggest that more attention needs to be given to documenting and understanding the variable effects of conversion to roundabouts.

One factor that may affect the safety effect of roundabouts is inclement weather, particularly in the form of precipitation, which occurs frequently in most parts of the world, including Canada (Bonnin et al., 2006). In urban areas in Canada, rain or snow is observed almost 8% of the time, on average (Andrey, Mills, Leahy, & Suggett, 2003). For some major cities in Ontario, almost 40% of days receive some precipitation (Government of Canada, 2017). Additionally, most parts of Canada normally experience snow and ice during the winter season. Therefore, many road users are exposed to higher levels of risk associated with their driving during less-than-ideal weather conditions.

Currently, the analysis of traffic operations and performance, as well as the formulation of policy and standards for traffic, generally begin with a focus on clear conditions (Highway Capacity Manual, 2000). However, considerable attention has been paid to precipitation-related collision risks in previous studies. These empirical studies document significant increases in collisions frequency during rainfall and snowfall (Andreescu & Frost, 1998; Andrey et al., 2003; Andrey & Yagar, 1993; Brodsky & Hakkert, 1988; Caliendo, Guida, & Parisi, 2007; Edwards, 1996; Eisenberg, 2004; Hambly, Andrey, Mills, & Fletcher, 2013; Hermans, Brijs, Stiers, & Offermans, 2006; Koetse & Rietveld, 2009; Shankar et al., 2004). Most of these studies have focused on aggregate safety patterns for entire cities/regions or on particular highway networks. Little attention has been given to the effects of adverse weather on intersection safety. While it is commonly believed that intersection operations, on the whole, may perform worse under inclement weather conditions (Rodegerdts et al., 2010), it is important to ask "how much worse" and whether roundabouts are at all immune from this weather deterioration of safety.

3. Study area

The analysis is based on a case-study municipality in the province of Ontario, in Canada, the Region of Waterloo, which has among the densest distribution of roundabouts in Canada. Over a 13-year period from 2004 to 2017, 30 roundabouts were built on 'regional roads,' (i.e., those arterials under the jurisdiction of the Region of Waterloo), and numerous others were constructed on lower-volume city streets. Like some other urban areas of Canada, Waterloo has a two-tier municipal governance structure – the Region of Waterloo "is responsible for ambulance and police services, garbage collection, public health, public transit, taxis, social services," and 'regional roads,' and the cities/townships are responsible for other public services and for the extensive network of city streets and/or township roads. In total, there are about 700 km of regional roads in Waterloo Region (Region of Waterloo, 2015, para. 3).

The Region of Waterloo is located in southwestern Ontario, approximately 100 km southwest of Canada's largest city, Toronto. It has a humid continental climate with a clear seasonal temperature. According to the Canadian Climate Normals 1981–2010 Station Data, average temperature in the Region of Waterloo ranges from −6.5 °C in January to 20.0 °C in July (Government of Canada, 2017). On average, 45.5% of days receive precipitation, and almost one-third of precipitation days are snow days, which mostly occur from late autumn to mid-spring. Rainfall can occur through the year.

Provincial-level collision data indicate that the Region of Waterloo has a lower fatality and injury rate than the province of Ontario, as a whole. Since Ontario has a strong record of road safety, and has been consistently ranked in the top two among all North American jurisdictions from 1999 to 2014, it is clear that the Region of Waterloo has a good overall record of road safety (Ontario Ministry of Transportation, 2015).

Roundabouts have been a source of some concern in the Region since the first one was opened in 2004. A public survey conducted by the authors, as part of an omnibus survey orchestrated by the University of Waterloo Survey Research Centre in 2017, asked a series of questions about roundabouts to a random sample of residents aged 18 years or older ($n = 404$). Responses underscore the extent to which drivers and pedestrians are not yet comfortable with using roundabouts in Waterloo Region. More specifically, 37.9% of respondents indicated that, as a driver, they feel either 'somewhat less safe' or 'much less safe' at roundabouts as compared to intersections with traffic lights, while as