Visual Approaches to Understanding Pedestrian Safety in Roundabouts

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SUMMARY

Although road safety research has traditionally considered driving as the central mode of interest, recent work has turned to non-motorized modes, particularly cycling and walking, to analyze their conditions within traffic flow, and their interaction with vehicles. “Visual Approaches to Understanding Pedestrian Safety in Roundabouts” is a thesis developed by Mario Perdomo where pedestrian safety is targeted as the main object of study. The research includes two separate studies. The first, based on a Stated Preference (SP) research tool, aims to describe the preferences of pedestrians towards design and operational features of roundabouts, an intersection whose construction has become more frequent in recent years in Quebec. This study describes the process of designing, administering and analyzing the SP survey, offering as its main outcome relevant conclusions regarding pedestrian preferences in terms of safety in roundabouts. The use of substitution rates, estimated from the analysis of the SP survey, are suggested as a means to help guide the design of roundabouts with pedestrians in mind. The second study examines pedestrian-vehicle interactions in roundabouts using automatic pedestrian and vehicle tracking with videos. These interactions were analyzed, making it possible to observe actual pedestrian behavior in such intersections. The core of the thesis relies on two scientific papers: one published in Accident Analysis and Prevention journal in 2014; and the other submitted to the Transportation Research Board the same year.

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1. INTRODUCTION

The construction of roundabouts appeared even before the automobile was invented: during their early stages, roundabouts were only an architectural component for monuments and fountains. Formal rules for their use had to be created as a result of the appearance of more sophisticated vehicles such as horse-drawn carriages, tramways, bicycles and cars. Initially successful with the right hand priority rule, roundabouts became unpopular as speed and traffic increased in the central circle. It was not until the mid-1960s, when England constructed smaller roundabouts and adopted the “give way” rule (priority to vehicles in the central circle), that modern roundabouts emerged as safer intersections (Marquis, Lacasse, & Guimond, 2002).

During the 1970s, roundabouts spread rapidly in many countries in Europe, Australia, New Zealand and the United States. France currently has the largest number of roundabouts (15,000), with a rate of approximately 1,000 new roundabouts built each year (Marquis et al., 2002). According to the Ministère des Transports du Québec (MTQ), there were 310 roundabouts in the United States and close to 100 in Canada in 2003. In Quebec, however, roundabouts have only been in use since 1998: the Abitibi-Témiscamingue region set up the first roundabout managed by the MTQ in 2001. The number of these intersections has increased rapidly since: the MTQ currently has over 50 roundabouts operating under its administration (Québec, 2014).

According to the MTQ, a roundabout “is an infrastructure development that considers one, two or three lanes of traffic around a central island in a counter-clockwise movement. In addition, users who want to engage in an intersection must yield to pedestrians and vehicles already circulating”. Roundabouts are one of four circular intersection types (roundabouts, rotaries, signalized traffic circles and neighbourhood traffic circles) where special control features such as yield control, channelized approach and geometric curvature produce desirable vehicle speeds and flow (Rodegerdts et al., 2010).

Moreover, roundabouts include additional features whose purpose is to enhance safety (or even capacity) in the intersection. Safety advantages of roundabouts are mainly due to their design: since vehicles travel in the same direction, right-angle and left turn conflicts present in regular intersections are eliminated; speed control is also present due to the intersection geometrical characteristics (Rodegerdts et al., 2010).

Report 672 of the National Cooperative Highway Research Program (Rodegerdts et al., 2010) points out how diverse studies in the United States, Europe and Australia show better performance of roundabouts in terms of capacity and safety compared to other intersections. The greatest reductions in injury crash frequency belong to motor vehicles, followed by pedestrians, cyclists and motorcyclists. In their report, Rodegerdts et al. (2010) also offer four main reasons to explain the higher level of safety in roundabouts: fewer vehicular conflict points; more time for driver reaction and lower crash severity, both due to lower speeds; and the reduction of pedestrian-vehicle conflict points. In this report, Rodegerdts et al. (2010) use the concept of conflict points (which exist in all at-grade intersections) to provide the factors to consider when approaching safety in roundabouts. The author defines conflict points as “the location where the paths of two motor vehicles, or a vehicle and a bicycle or pedestrian path, diverge, merge, or cross each other” (Rodegerdts et al. (2010), p.5-5), and argues that conflict point analysis in roundabouts should take into account at least their exposure, and the severity of the conflict and vulnerability.

Diverse approaches for analyzing safety levels in roundabouts are described in the literature review section of this paper. In general, existing literature shows that when addressing road safety, as in the case of roundabouts, most research has focused on driver safety (see Young, Sobhani, Lenne, and Sarvi (2014) for a review of a variety of methodologies to address road safety, including surrogate safety models, and crash data). In contrast, existing research reveals that vulnerable road users' safety (in particular pedestrians and cyclists) has not been as explored as the case of motorists.

Furthermore, user perception of safety is important for two reasons: if perceived safety is linked to actual safety, by improving perceived safety, actual safety can be expected to improve as well; if not, it may still be important to understand its causes since perceived safety will influence travel behaviour, in particular the choice of active modes of transportation which are promoted for diverse benefits. While diverse qualitative and quantitative methods exist to obtain user perceptions (Ryan et al., 2001), one powerful research tool for this purpose is the analysis of Stated Preference (SP) surveys.

Stated Preference surveys are questionnaires where respondents are asked to choose between two or more hypothetical alternatives specially designed for analysis. The statistical analysis of the choices made by respondents can describe the level of importance that each attribute has on people's preferences in a given choice context.

In addition, objective observation of vulnerable road user behavior and their interactions with other modes is a valuable complement for safety analysis. Existing literature provides different methodologies to study road user behaviour and interactions: the present research focuses on automated analysis techniques, using video recordings of roundabouts in order to track pedestrian behavior and investigate interactions with automobiles. This part of the project relies on previously collected video recordings and existing video analysis tools. Videos collected at different roundabouts in Quebec in which pedestrians were observed were automatically analyzed and pedestrian behaviour, including their interactions with automobiles, was studied. A detailed analysis of the types and frequency of different interactions was then conducted.

This technique represents an advantage for analyzing objective safety since recordings can be analyzed as many times as necessary using a variety of methods; moreover, existing literature shows that most road recording analyses have been done targeting motorists and their interactions.

This thesis is composed primarily of two research papers. The following section provides a comprehensive literature review. The review explores past and current scientific research that has addressed the safety of vulnerable road users, user behavior in roundabouts, pedestrian behavior, SP survey design, administration and analysis, as well as complementary research studies considering the means for obtaining and analyzing pedestrian behavior in intersections. The main goal of the literature review is to demonstrate the need for wider research regarding the safety of vulnerable road users in roundabouts and the need for more comprehensive means of studying pedestrian behavior analysis as well.

The literature review serves as background for the two papers: the first addresses pedestrian preferences and behavior in roundabouts in terms of road safety and was published in the journal Accident Analysis and Prevention in 2014; while the second is a report of the analysis of pedestrian trajectories obtained after analyzing video recordings of roundabouts in Quebec and was submitted for presentation at the Transportation Research Board Annual Meeting of 2015.

The thesis is concluded with some comments and observations about the entire research process, general conclusions from the papers, as well as ideas for future directions of research.

2. LITERATURE REVIEW

As a relatively new intersection design, research concerning roundabouts has been carried out all over the world in the last few decades. Its ancestor, the traffic circle, was constructed in various places starting in the 1900s and into the 1940s, without, however, providing significant traffic improvements (Bared, Prosser, & Tan Esse, 1997). Improvements to traffic circles in the United Kingdom led to the design of the modern roundabout and its subsequent construction in several European countries and Australia (Bared et al., 1997). The historical development and current research on roundabouts in different locations outside North America is described in publications such as Thai Van and Balmefrezol (2000) for roundabouts in France, Akcelik (2008) for Australia and Brilon (2005) in the case of Germany.

Research on roundabouts has taken place in North America as well. Comprehensive studies have been carried out through the National Cooperative Highway Research Program in the United States (Rodegerdts et al., 2010). This provided an extensive report on roundabouts that considered planning, operational analysis, safety analysis, geometric design parameters, the application of traffic control devices, illumination specifications, landscaping principles and recommendations for construction and maintenance. In general, tools for the prediction and analysis of the operation of roundabouts for North America can be found in the Highway Capacity Manual (2010) of the Transportation Research Board. Finally, research on roundabouts has also taken place in Canada. The Geometric Design Standing Committee of the Transportation Association of Canada has developed the Canadian Roundabout Design Guide as a companion document to the Geometric Design Guide for Canadian Roads. In the case of Quebec, Marquis et al. (2002) offer some roundabout functionality analysis in the province.

Existing literature has dealt with the impacts of roundabouts in three main areas: mobility improvement, environmental improvement, and safety improvements. An example of the first two areas is provided by Mandavilli, Rys, and Russell (2008). In this publication, the authors used videotapes, SIDRA software[1] and Measures of Effectiveness outputs[2] to evaluate mobility and environmental improvements in roundabouts. In this research, the authors found a significant decrease of vehicular emissions compared to regular intersections because vehicles are forced into an orderly flow by the geometrical characteristics of roundabouts. The influence of geometric and operational characteristics on mobility performance in roundabouts have also been studied by Bergman, Olstam, and Allström (2011) and Meneguzzer and Rossia (2011) in terms of capacity and operation in roundabout entries. The third area, safety, deserves special attention since it is the objective of this research.

De Brabander and Vereeck (2007) conduct an extensive literature review of the benefits of roundabouts in terms of road safety, concluding that these intersections are a sure way to reduce the amount of accident casualties. Hels and Orozova-Bekkevold (2007) also consider roundabouts to be better intersections than traditional intersections in two aspects: safety (fewer accidents) and mobility (higher capacity). Other authors such as Bared et al. (1997) provide a comprehensive review of state-of-the-art roundabouts, how roundabouts were conceived, and how they have been improving across many different regions. They also argue that roundabouts serve to enhance communities as well as reducing congestion and improving traffic flows.

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[1] http://www.sidrasolutions.com/Software/INTERSECTION/Overview

[2] http://www.dot.state.mn.us/trafficeng/modeling/resources/MOEcalcsD2.pdf

2.1. Safety in roundabouts

While discussing road safety in roundabouts, two main subjects of study can be found in the existing literature: driver safety and vulnerable user safety (mainly pedestrian and cyclists), although most research focuses on the former and very little has studied the interactions between different modes (motorized and not motorized) (Bared et al., 1997; and Sakshaug, Laureshyn, Svensson, & Hyden, 2010). In the case of motorized vehicles in roundabouts, a multitude of research purposes can be mentioned: comprehensive changes in pavement marks and lanes in roundabout safety (Bie, Lo, & Wong, 2008); the impact of roundabout design in terms of vehicles, flow, speed and sight distance on safety (Bared et al., 1997); the importance of driving experience on safety in roundabouts (Moller & Hels, 2008); the influence of crosswalk signal controls in roundabouts (Azhar & Svante, 2011); safety performance in terms of crash severity (Daniels, Brijs, Nuyts, & Wets, 2010b); and the relation between traffic volume and crash frequency (Daniels, Brijs, Nuyts, & Wets, 2010a).

According to Hydén and Várhelyi (2000), improvements in traffic safety in roundabouts is due to the following reasons: the reduction in the number of potential conflict points, vehicle speed reduction by forcing users entering the roundabout to give way to those in it, the discouragement of lane-changing in roundabouts, unidirectional traffic and the suppression of the left turn. The latter advantage is also highlighted by Moller and Hels (2008) who argue that in the case of Denmark, roundabouts represent an advantage since the second most common type of car accidents are those that involve a left turning vehicle.

Whereas the advantages of roundabouts in terms of driver safety is a constant in this research, it is worth keeping in mind that the design guidelines for roundabouts differ from one country to another, and therefore the results from one region might not be valid for another (Daniels et al., 2010a).

Papadimitriou, Theofilatos, and Yannis (2013); and Xi and Son (2012) are good examples of vulnerable user behavior analysis in regular intersections. However, when talking about vulnerable users in roundabouts, the majority of research deals with cyclist behavior and its relation to other modes; a useful general background for research about cyclists in roundabout is provided by Bared et al. (1997); Daniels, Brijs, Nuyts, and Wets (2009); and Macioszek, Sierpiński, and Czapkowski (2011b) who extensively review existing cycling facilities.

It is important to mention that it is not uncommon for researchers to find that roundabouts are not safer for cyclists than regular intersections. This observation is clearly outlined by Moller and Hels (2008) who showed that the most frequent types of accidents in roundabouts with cyclist presence were between cyclists and cars. Hydén and Várhelyi (2000) for instance, collected driver and cyclist opinions regarding roundabouts in order to observe the evolution of opinions across time, finding that car drivers are less positive than cyclists, in spite of the fact that they feel safer. Behavior interactions between these users, although on small one-lane roundabouts, has been studied by Macioszek (2011) and Sakshaug et al. (2010), who evaluated the importance yielding has in the interaction between drivers and cyclists. Hels and Orozova-Bekkevold (2007) on the other hand, studied the prevalence of cyclist accidents in roundabouts compared to conventional intersections, finding that the existence of a cycling facility did not meaningfully explain the variation in the number of cyclist accidents, which are more related to traffic speed in these intersections. However, Daniels et al. (2010a) highlighted that roundabouts with cyclist lanes clearly have inferior performance in terms of cyclist safety than roundabouts with cycling paths. This is supported further by Sakshaug et al. (2010), who demonstrated that separate cyclist lanes are the safest facilities for these users. Pedestrian behavior in intersections based on statistical analysis of observed behaviour.

Accidents and crash severity affecting cyclists in roundabouts are also issues addressed by existing research. Daniels et al. (2010b) found that cyclists represent almost half of all those killed or seriously injured in roundabouts. Moreover, it has also been demonstrated that roundabouts equipped with bicycle lanes were the worst with respect to crashes involving injuries (Daniels et al., 2009), in spite of the fact that more experienced cyclists are more likely to prefer endurance routes and unlikely to choose leisure ones (C. F. Chen & Chen, 2012).

While some authors consider pedestrians as part of a larger vulnerable user group (Daniels et al., 2010b), studies focusing solely on pedestrians in roundabouts are less numerous even though pedestrian behavior in different circumstances has been widely explored as described below. Perhaps the most representative research in this specific field has been done by Azhar and Svante (2011) who studied the relation between traffic and pedestrian flow and signal controlled crosswalks in roundabouts (traffic signals may be at the approach and in the direct vicinity of the roundabout, at the approach up and downstream of the roundabout, each crosswalk may be controlled by a traffic signal, or the roundabout may be fully controlled by signals, in which case it is typically not considered to be a roundabout, at least in North America).

The literature reviewed up to this point has mainly focused on describing road safety based on objective methods using crash data and direct observations of interactions (e.g. Clifton, Burnier, and Akar (2009); and Young et al. (2014)). There are, however, other means by which safety analysis can be complemented such as the analysis of user perception and preferences with respect to different types of intersections.

2.2. Stated Preference surveys as a tool to analyze perception and preferences

The existing literature offers different ways that perceptions and preferences towards different intersections can be studied. Ryan et al. (2001), for instance, produce a summary of qualitative (e.g., one-to-one interviews, dyadic interviews and case study analyses) and quantitative (e.g., ranking, rating and choice-based approaches) methods for this purpose. Nonetheless, in a transportation environment, perhaps the most frequently used tool to obtain this kind of information involves revealed preference (RP) and stated preference (SP) techniques. According to Hensher and Bradley (1993), whereas RP data describe actual choices that people make, SP data record choices that people report they would make in hypothetical choice situations. Hensher (1994) defines a stated preference experiment as one where an individual chooses from among fixed or varying choice sets, enabling the estimation of a discrete choice model for direct behavior prediction of market share. Overall, it's possible to define an SP survey as a research tool in a questionnaire form where respondents have to choose between defined alternatives in each of the questions known as 'choice tasks'. Choices made across the total choice task set are analyzed through discrete choice models and specific attributes are ranked according to levels of importance.

In the case of road safety, SP surveys are used in two contexts that have been discussed thus far: driver safety, and vulnerable user safety. There are many examples of driver safety analyses through SP surveys considering a variety of objectives: understanding the relative weightings of different driver behaviors to establish thresholds, above (or below) which changes to the behavioural parameters (such as speed, lane keeping measures, headway, overtaking and gap acceptance) had minimal impact on safety (Jamson, Wardman, Batley, & Carsten, 2008), precautionary behavior (Andersson, 2013), driver response to signs

(Wardman, Bonsall, & Shires, 1997), willingness to pay for reducing accidents (Iragüen & Ortúzar, 2004) and interurban road safety (Rizzi & Ortúzar, 2003), to name a few.

There also exists some research targeting vulnerable user perceptions related to different types of road and cycling infrastructure through SP surveys. Caulfield, Brick, and McCarthy (2012) for instance outline the infrastructure features that affect the decision of whether to cycle or not. Hunt and Abraham (2006) consider not only cycling facilities but also cyclist characteristics such as the amount of time spent cycling under different conditions. Larger surveys with more attributes have also been conducted for this purpose: Stinson and Bhat (2003) use an SP survey where 11 attributes (divided into link-level and route-level factors) were used for analyzing cycling route choice decisions, finding that cyclists preferred residential to non-residential streets, a conclusion also supported by Krizek (2006). Cyclists avoided routes where parking was permitted and preferred routes designed for bicycle use. Other research has shown that the best incentive to promote cycling was the provision of bicycle lockers or similar options, while the second best incentive was the provision of bike lanes, mainly for inexperienced cyclists (Taylor & Mahmassani, 1996). Other interesting findings are brought forward by authors like Ehrgott, Wang, Raith, and van Houtte (2012), who based their model on the common observation that travel time seems to have the most significant influence on route choice decisions for commuting cyclists as well as safety and comfort. C.F. Chen & P.C. Chen (2012) on the other hand found that recreational cyclists were more likely to choose challenging routes, while Caulfield et al. (2012) concluded that cyclists had a greater preference for lower adjacent traffic speeds and exclusive off-road cycling lanes.

In the case of pedestrians, SP surveys have been used for understanding their behavior via approaches generally divided into route choice and intersection crossing behavior. Papadimitriou, Yannis, and Golias (2009); and Sisiopiku and Akin (2003) for instance reported that most pedestrians prefer crosswalks that give preference to pedestrians. At the same time, Kaparias, Bell, Miri, Chan, and Mount (2012) used two web-based stated-preference surveys to collect two sets of responses from pedestrians and drivers, in order to determine preferences in intersections, demonstrating that shared spaces work better when drivers are encouraged to reduce speed and yield to pedestrians and vulnerable users.

Although there exists diverse research related to vulnerable user preferences for different types of road facilities, there is very little research that has focused on cyclists and even less on pedestrians in roundabouts (a fact highlighted by Wall, Long, Guth, Ashmead, and Ponchillia (2005)). While vulnerable user safety in roundabouts (e.g. Daniels et al. (2009); De Brabander and Vereeck (2007); and Moller and Hels (2008)) and pedestrian behavior in such intersections (e.g. Meneguzzer and Rossia (2011)) have been studied, there is no research that addresses pedestrian safety using stated preference approaches in roundabouts.

2.3. Stated preference survey design, administering and analysis

Considering that SP surveys have been used for a wide variety of purposes, although not used to characterize pedestrian preference in roundabouts, it is pertinent to also study how this approach has been developed in other contexts in order to explain how an SP study can be designed to understand pedestrian preferences with respect to roundabouts. While there are many examples of how SP surveys are designed, administered and analyzed, a very commonly cited and referred to reference on the subject is Louviere, Hensher and Swaite (2000). As such, this section draws the description of the main steps of a stated preference study from this source. The details of the application of these steps for the SP survey administered in the context of this thesis are explained in the manuscript itself.

SP survey design

The very first step in SP survey design is defining the behavior to be studied and modeled. Once the purpose of the study has been defined, it is necessary to analyze related research that has already been carried out to build upon existing results and to adapt the approach to the context of interest. Table 1 shows a summary of attributes and levels found in existing research where safety was evaluated. As shown, a distinction is made between research that has considered roundabouts and that which has not.

Table 1. Attributes and levels found in existing pedestrian safety literature

Attribute	Possible levels	Evaluation of safety and infrastructure	Evaluation of safety and infrastructure in Roundabouts
Traffic volume	Low, medium, high	(Chu et al., 2004; Guo et al., 2012; Kaparias et al., 2012; Kelly et al., 2011; Papadimitriou et al., 2009; Sisiopiku & Akin, 2003)	(Daniels et al., 2010a, 2010b; Hels & Orozova-Bekkevold, 2007; Macioszek, Sierpiński, & Czapkowski, 2011a; Moller & Hels, 2008; Schroeder et al., 2011)
Traffic speed	Low, medium, high	(Chu et al., 2004; Guo et al., 2012; Kaparias et al., 2012; Kelly et al., 2011; Papadimitriou et al., 2009, 2013; Sisiopiku & Akin, 2003)	(Daniels et al., 2010a, 2010b; Hels & Orozova-Bekkevold, 2007; Macioszek et al., 2011a; Moller & Hels, 2008; Schroeder et al., 2011)
Signalization	No signalization, yield, speed limit, pedestrians	(Chaurand & Delhomme, 2013; Chu et al., 2004; Kelly et al., 2011; Sisiopiku & Akin, 2003; Papadimitriou et al., 2009)	(De Brabander & Vereeck, 2007; Moller & Hels, 2008; Schroeder et al., 2011)
Pedestrian crossing location	In the entrance of the intersection, near the entrance, away from the entrance	(Chu et al., 2004; Kelly et al., 2011; Papadimitriou et al., 2009; Sisiopiku & Akin, 2003)	(Meneguzzer & Rossia, 2011; Schroeder et al., 2011)
Cycling facility	Mixed traffic, cycling lane within the roundabout, cycling separated path, grade-separated paths	(Chen & Chen, 2012; Caufield et al., 2012)	(Daniels et al., 2009, 2010), (Macioszek et al., 2011), (Moller & Hels, 2008)
Yield Signal	No yield signal, yield signal in entrance for drivers, yield signal for cyclists	(Chaurand & Delhomme, 2013; Sisiopiku et al., 2003)	(Sakshaug et al., 2010)
Entering/Exit lanes	2, 3, more than 3	-	(Daniels et al., 2010; Macioszek, 2011)
Circulatory Markings	Concentric marking, "Alberta" marking	-	(Bie & Wong, 2008)

Attribute	Possible levels	Evaluation of safety and infrastructure	Evaluation of safety and infrastructure in Roundabouts
Cyclist volume	Few cyclists, considerable number, congested	-	(Daniels et al., 2010; Moller & Hels, 2008)
Number of legs in roundabouts	3, 4, 5 or more	-	(Daniels et al., 2010; Macioszek et al., 2011b)
Diameter of central island	Small (5-15 m), medium (15-25 m), large (more than 25 m)	-	(Hels & Orozova-Bekkevold, 2007; Macioszek et al., 2011b; Moller & Hels, 2008)
Width of bicycle facility	1.5 m, 1.5-2.0 m, more than 2.0 m	-	(Moller & Hels, 2008)
Sidewalk around central island	No, yes	-	(Daniels et al., 2010)
Priority to the cyclist	No priority specified, priority to cyclists, priority to cars	-	(Macioszek et al., 2011; Sakshaug et al., 2010)
Visibility of movements in legs of roundabout	Always visible, somehow visible, not visible in some points	-	(Daniels et al., 2010; Wall et al., 2005)
Drive curve length	-	-	(Hels & Orozova-Bekkevold, 2007)
Lateral displacement	-	-	(Hydén & Várhelyi, 2000)
Yielding rates	-	-	(Sakshaug et al., 2010)
Pedestrian volume	Low, medium, high	(Asano, Iryo, & Kuwahara, 2010; Guo et al., 2012; Kaparias et al., 2012; Sisiopiku et al., 2003; Papadimitriou et al., 2009)	-
Physical barriers	Vegetation, median, non-barriers	(Chu et al., 2004; Papadimitriou et al., 2013; Sisiopiku & Akin, 2003)	-

Further steps need to take place in order to prioritize potential attributes: the first is called a focus group. A focus group is a recommended exploratory practice where a group of potential respondents is asked to identify attributes of importance regarding a specific issue, in this case road safety (Louviere, Hensher, & Swait, 2000).

The final result of the focus group in combination with literature review is the selection of attributes to be included in the final survey instrument. Some of the attributes in the final survey, however, may change, depending on how effectively differences between them and their levels could be delivered to potential respondents. This is generally observed through a pilot survey.

A pilot survey is a pre-test of the survey that aids to identify strong and weak points in the research tool, whether respondents understand the survey, or whether there is sufficient information provided in the survey so that respondents can make their choices. Once the final selection of attributes and levels is defined, it is necessary to design the combination of attribute levels in the choice tasks of the final survey instrument. This is known as 'design of experiments'.

The design of experiments (DoE) refers to the arrangement and control of information presented in a research experiment. In the case of SP surveys, the DoE is the definition of what attribute levels will characterize each alternative of each choice task presented to respondents (Louviere et al., 2000), and its importance lies in the fact that an optimal arrangement allows researchers to get significant effects of the attributes and their interaction. Most designs consider three main principles: minimal overlap (each attribute level is shown as few times as possible in the same choice task), balance (each attribute is shown the same number of times), and orthogonality (attribute levels are picked independently of other levels). In SP surveys there are two kinds of DoE commonly used:

orthogonal designs (employing a single version of a questionnaire, with the advantage of having high efficiency measuring main effects and particular interactions), and random designs (which are less efficient, but all interactions can be measured) (Sawtooth Software, 2013). For this specific research, a method known as Balanced Overlap was used; it considers half as much overlap as a random method, but keeping track of the all pairs of attribute levels.

Critical also to a successful survey is to ensure the survey tool is presented in such a way that is easily understandable to respondents. This is why survey developers have to consider how to tailor a survey to its context (Behrens, Diaz-Olvera, Plat, and Pochet (2006) look, for instance, at the impact of survey-specific design in a bilingual context), as well as how to present the choice tasks (Rizzi, Limonado, & Steimetz, 2011).

Elements like visual aids may help to overcome difficult to communicate attributes. Recently explored mechanisms for presenting choice tasks is the use of videos: Krizek (2006) for example, used 10-second clips to let respondents know the characteristics of the alternative cycling routes. Research by Taylor and Mahmassani (1996), Krizek (2006) and Arentze, Borgers, Timmermans, and DelMistro (2003) can be observed as evidence of the positive results that visual aids have had in SP surveys. The impact of visual aids on SP surveys (in the case of travel time evaluation) is studied by L. I. Rizzi, Limonado, and Steimetz (2011).

Additional considerations on factors that might affect the quality of responses to SP surveys are also important in their design. For instance, user fatigue when responding to surveys (Arentze et al., 2003), design strategies of the survey that might influence answers (Patil, Burris, & Douglass Shaw, 2011) and additional information from revealed preference (Hensher & Rose, 2005; and Hensher, Rose, & Bertoia, 2007).

The idea of using a simulation video for the presentation of choice tasks is based on the fact that some of the attributes, specifically traffic speed and volume, are difficult to transmit through text or images. In addition, existing research has demonstrated that the use of visual aids in SP surveys can imply a significant difference in results (Krizek (2006); Taylor and Mahmassani (1996)).

SP survey administration

Once survey design is completed, administration alternatives have to be studied in order to get as many targeted respondents as possible. One effective way to reach these respondents is through the careful definition of a sample. Although diverse sampling methodologies can be found in existing literature (and C. F. Chen & Chen, 2012; Hunt & Abraham, 2006; Meneguzzer & Rossia, 2011; Rose, Hensher, Caussade, Ortúzar, & Jou, 2009; Sisiopiku & Akin, 2003; Weinstein Agrawal, Schlossberg, & Irvin, 2008), it is particularly useful in terms of this research to recall what Goudie (2002), Kelly, Tight, Hodgson, and Page (2011), and Krizek (2006) did. In their research, only respondents located within a specific buffer of evaluated urban elements (i.e. cycling paths) were considered for the survey. In addition, there are different alternatives to reach respondents who were identified in the sample. Talking about existing differences between mail-based and web-based surveys, the research of Fleming and Bowden (2009) describes how web based surveys can be more controlled, keeping similar response rates and socio-demographic characteristics among respondents as regular surveys.

SP survey analysis

The stage of analysis and interpretation of SP surveys is typically done with discrete choice models that are mostly common variations of Logit or Probit models, although in some cases, researchers have used additional tools as well. The purpose of a discrete choice model is to understand the behavioural process that causes an agent (person, firm, etc.) to make specific choices when known alternatives are presented to him/her, assuming this set of choices can be seen as a discrete outcome. The following description of discrete choice models draws heavily on Train (2009).

In general terms, discrete choice models are based on the Random Utility Theory, where a decision maker (n) chooses the alternative (i) that provides him/her the highest utility amongst all possible alternatives. Based on observed choices, the researcher estimates a utility function that is typically represented as:

$$U_{ni} = V_{ni} + \varepsilon_{ni} \qquad \forall \quad i \tag{1}$$

where U_{ni} is the utility individual n obtains from alternative i, V_{ni} is the systematic (measurable) portion of the utility, and ε_{ni} is the random error. V_{ni} can be expressed as a linear combination of coefficients and attributes of the alternatives and decision/maker, as follows:

$$V_{ni} = \alpha_{ni} + \beta x_{ni} \qquad \forall \quad i = 1, \dots, n \tag{2}$$

where α and β are coefficients either known or estimated by the researcher. Thus, the probability that the decision maker n chooses alternative i would be denoted by:

$$P_{ni} = Prob\left(V_{ni} + \varepsilon_{ni} > V_{nj} + \varepsilon_{nj}\right) \qquad \forall \quad j \neq i \tag{3}$$

Since ε_{ni} is not given, the choice probability is the integral of the cumulative distributions $P_{ni}|\varepsilon_{ni}$ over all values of ε_{ni} weighted by its density function $f(\varepsilon_{ni})$:

$$P_{ni} = \int \left(\prod_{j \neq i} e^{-e^{-(\varepsilon_{ni}+V_{ni}-V_{nj})}} \right) f(\varepsilon_{ni}) d\varepsilon_{ni} \tag{4}$$

where the cumulative distributions are:

$$P_{ni}|\varepsilon_{ni} = \prod_{j \neq i} e^{-e^{-(\varepsilon_{ni}+V_{ni}-V_{nj})}} \tag{5}$$

and its density function is:

$$f(\varepsilon_{ni}) = e^{-\varepsilon_{ni}} e^{-e^{-\varepsilon_{ni}}} \tag{6}$$

Although the error remains unobserved and unknown, its distribution is in fact what determines the specific model used to estimate the utility function.

If the error is assumed to be independently and identically extreme value distributed (iid), then the probability that the individual n chooses alternative i can be expressed with the closed-form expression of the Multinomial Logit (MNL) model:

$$P_{ni} = \frac{e^{V_{ni}}}{\sum_{j=1}^{J} e^{V_{nj}}} \tag{7}$$

Although this form of the MNL model makes it straightforward to estimate, interpret and use, the assumptions related to the error in this model are questionable in many choice contexts, such as when observations involve more than one choice per respondent, as in the case of an SP experiment.

In the MNL model, the coefficients for β are fixed across users. In contrast, the Mixed Multinomial Logit Model (MMNL) allows having a vector of random coefficients. Assuming utility as varying over people, but being constant over choice situations for each person, the utility for alternative j in choice situation t by respondent n is $U_{njt} = \beta_n x_{njt} + \varepsilon_{njt}$, with ε_{njt} being independently and identically distributed (iid) extreme values over time, people and alternatives. Considering a sequence of alternatives for each time period (or choice task) $i = \{i_1, \ldots, i_T\}$, the probability that a respondent makes this sequence of choice is defined as the product of logit formulas (see equation 8), since the ε_{njt}'s are independent over time.

$$L_{ni}(\beta) = \prod_{i=1}^{T} \left[\frac{e^{\beta'_n x_{nit}}}{\sum_{j=1}^{J} e^{\beta'_n x_{nit}}} \right] \tag{8}$$

The integral of this product over all values of β, is the unconditional probability:

$$P_{ni} = \int L_{ni}(\beta) f(\beta) d\beta \tag{9}$$

By integrating the product of logit formulas over all values of β, the correlation of errors across the choices of a given individual are captured. As such, this is an appropriate discrete choice model for the case of repeated choice task data, as used in this project.

Examples of the use of different versions of the logit model can be found in existing literature: from simple logit models (Hunt & Abraham, 2006), to Mixed Generalized Ordered Response Logit Model (Eluru, Bhat, & Hensher, 2008), and nested logit models (Taylor & Mahmassani, 1996). Similar to the present research, Caulfield et al. (2012) evaluates vulnerable users (cyclists) choices towards six choice tasks where attribute levels were varying (different routes with different attributes are compared for the same individual). For their analysis the authors consider a Mixed Multinomial Logit Model (MNL) as well.

Coefficients of Logit models can be also useful for other interpretations. By using the concept of substitution rates, coefficients can tell us the willingness to trade-off attributes. A substitution rate is an economic concept defined as “the amount of a particular item that must be given to an agent in order to exactly compensate that agent for the loss of one unit of another item” (Hensher, Rose, & Greene, 2005). In the case of Logit models, substitution rates can be obtained by dividing the coefficient of one variable with that of another. Willingness to pay (WTP), for instance, is a particular form of substitution rate that is commonly used in transportation research.

2.4. Observed pedestrian behavior and safety analysis

While SP surveys and the logit models are useful to understand people’s preferences (for example, towards safety elements in roundabouts); actual safety levels need to be analyzed using different methods. In this case, road user behavior research has mainly focused on drivers (Fuller (2005); Noyce and Elango (2004); and Sathyanarayana, Boyraz, and Hansen (2008)), although there is relevant research related to vulnerable user behavior and safety in roads.

In the case of pedestrians, different approaches have been used to address their safety. Clifton et al. (2009), for instance, examine the influence of personal and environmental characteristics on crash severity and injuries in pedestrian-vehicle interaction; Miranda-Moreno, Morency, and El-Geneidy (2011) also study the influence of the built environment, including land use type, connectivity, transit supply and demographic characteristics on pedestrian activity and pedestrian-vehicle collisions; Xi and Son (2012) developed a model to understand pedestrian decision-making processes when crossing; while Pedestrian perceptions toward traffic characteristics is addressed by Papadimitriou et al. (2013). Complementarily, a comprehensive literature and methodology review of pedestrian safety study is offered by Harwood, Torbic, Gilmore, Bokenkroger, and Dunn (2008) in the Report 17-26 of the NCHRP.

Alternative methods to study pedestrian behavior and safety have been also developed. Ismail, Sayed, Saunier, and Lim (2009) offers, for instance, an innovative approach based on the automated analysis of pedestrian behavior using video recordings. This research begins from the assumption that relatively small quantities of data on collisions typically make statistical analysis in this field difficult. As such, the authors propose as a complement to collision data, the use of surrogate safety measures. The automated video analysis proposed by the authors is capable of detecting, tracking and classifying road users in a scene: identifying potential collisions and calculating conflict indicators. In this research they present the basis and development of an entire process for video tracking and analysis, from camera calibration and video formatting to feature tracking and grouping, as well as object processing. The authors also obtain, validate and analyze data from a signalized intersection in Vancouver, British Columbia, Canada (Ismail et al., 2009).

While promising for the present research, automated video analysis has followed the same trend as the rest of road safety research: it focuses mainly on drivers, either through traffic surveillance systems (Hsieh, Shih-Hao, Yung-Sheng, & Wen-Fong, 2006), real time traffic parameters extraction and occlusion detection (Rad & Jamzad, 2005), or through real time vehicles location through active contour models (Tai, Tseng, Lin, & Song, 2004).

An interesting approach, however, is presented by Jackson, Miranda-Moreno, St-Aubin, and Saunier (2013), who offer a comprehensive description of an analysis system based on camera recordings and automated video analysis. It is shown this system can be used to identify, track and analyse not only motorists but also cyclists and pedestrians. The authors propose a flexible system for video data collection, automated feature tracking, and surrogate safety analysis available in an open source project called “Traffic Intelligence”. These techniques and algorithms have been used in complementary work for vehicle interactions (Saunier, Sayed, & Ismail, 2010) as well as roundabouts (St-Aubin, Saunier, Miranda-Moreno, & Ismail, 2013), although in the latter only driver behavior is analyzed (considering trajectory interpretation and conflict measures).

2.5. Weaknesses of existing literature

It is convenient, as a summary, to point out the limitations that existing literature shows, and how these limitations are related to the present work. Although works like Bared et al. (1997) show an analysis of the advantages and disadvantages of roundabouts, they do not offer a quantitative analysis of pedestrian and cyclist behavior or interactions based on empirical data. In fact, in most roundabout guidelines, the protection of pedestrians or cyclists is assumed and justified primarily through theoretical arguments. The work of Hels and Orozova-Bekkevold (2007) can be considered as a good reference for evaluating cycling facilities (not for roundabouts, though); nonetheless, as the authors mention, the results are only preliminary since more comprehensive models require better observation data.

The case of cyclists, their perception and behavior in roundabouts has been studied in two projects: one is Moller and Hels (2008) who studied risk perception of cyclists by comparing different roundabout attributes and the relation between specific cyclist facilities to the increases or decreases of risk perception. As the authors conclude, a relevant next step of their work would be research that combines perceived risk and behavior. Sakshaug et al. (2010) evaluate a single roundabout to observe the interaction behavior between drivers and cyclists. In this work, as well as in Moller and Hels (2008), the preference of cyclists is not stated, although the authors make a comprehensive analysis of cyclist and driver interactions and conflicts. As demonstrated earlier in this section, the case of pedestrian preferences with respect to roundabouts has not been studied so far.

When considering objective safety analysis for pedestrians in roundabouts based on direct observations, the literature review showed that there are no works addressing this topic. However, there are recent techniques involving video analysis that have been used to study driver behavior under different circumstances, including roundabouts (see St-Aubin, Saunier, et al. (2013)). Although these techniques have not been used to understand pedestrian behavior, their capacity and feasibility make them interesting and relevant to use in such situations.

Through the study of existing literature, it is possible to highlight the absence of vulnerable user preferences in much of the research on safety in roundabouts. Moreover, as seen, most of research focusing on user behavior in roundabouts is based on the statistical analysis of historical events based on crash records.

Considering existing weaknesses in the literature as well as the increase in roundabout construction and operation in Quebec, the main research question of this research is to identify which physical and operational attributes of roundabouts are more significant in terms of safety perception for vulnerable users and pedestrians in particular. This is done through the administration of a Stated Preference survey of pedestrian preferences to roundabouts.

Since pedestrian preferences with respect to roundabouts can only provide us insight into how pedestrians perceive these intersections, a remaining question is how these intersections actually perform with respect to safety for these users.

Overall, these research questions lead to the general objective of the present work: to identify and quantify pedestrian perception and preferences in terms of road safety towards selected operational and geometrical attributes in roundabouts in Quebec. Related to this main purpose, there are other more specific objectives of the research: to identify which attributes can be traded-off to improve pedestrian safety perception in roundabouts; to provide specific recommendations or policies for pedestrian safety perception improvement; and to observe the difference between these perceptions and actual pedestrian behavior.

The section above aims to identify particular issues that have not been addressed in existing literature, but which the research reported here seeks to contribute to. This review suggests that pedestrian behavior and preferences towards safety items in roundabouts have not been approached through SP surveys so far. Likewise, the observed behavior of pedestrians and their interactions with drivers have not been analyzed using automated video processing.

3. INTRODUCTION TO MANUSCRIPTS (CONTRIBUTION BY AUTHORS)

Considering the review of existing literature related to pedestrian road safety in roundabouts, safety perception, actual safety analysis, as well as the methodology provided in the previous section, the following manuscript papers were produced to describe the research towards characterizing pedestrian preferences in roundabouts in Quebec, as well as observed pedestrian behavior in these sites.

Sections 4 and 5 contain two manuscripts, the first one is a copy of the paper entitled “Pedestrian Preferences with respect to Roundabouts – A Video-Based Stated Preference Survey” published in Accident Analysis and Prevention journal in 2014. This publication is the result of constant improvements to a first paper submitted and accepted for Transportation Research Board (TRB) meeting in 2014, and describes the development analysis, and results of an SP survey administered to know pedestrian preference towards roundabouts safety elements in the region of Quebec.

The second manuscript is a copy of the paper entitled “Obtaining Pedestrian Safety Indicators in Roundabouts through Automated Video Data Collection –A Case Study in Quebec”, which describes the methodology, and results of pedestrian crossing video analysis using “Traffic Intelligence” software.

My role in both papers was lead author. In the first paper, I put together a Stated Preference survey by creating numerous micro-simulation scenarios according to a defined experimental design. This process required me to generate simulation backgrounds, and transit simulations in VISSIM. In addition I structured the survey body for its upload. Collecting, cleaning, and modelling data were also my duties in this research.

For the second paper my role depended on previously collected information (intersection recordings). Using this data I could identify all pedestrian–motorist interactions. Using existing code for tracking and analyzing road users, I obtained the safety indicators presented in this paper. Both papers represent a proven contribution to research in the field as discussed in the concluding section of each one.

4. PEDESTRIAN PREFERENCES WITH RESPECT TO ROUNDABOUTS – A VIDEO-BASED STATED PREFERENCE SURVEY

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4.1. Abstract

Research on user behavior and preferences has been a helpful tool in improving road safety and accident prevention in recent years. At the same time, there remain some important areas of road safety and accident prevention for which user preferences, despite their importance, have not been explored. Most road safety research has not explicitly addressed vulnerable user (pedestrians and cyclists) preferences with respect to roundabouts, despite their increasing construction around the world. The present research stems from the fact that studies related to roundabout safety have generally focused on drivers, while overlooking the importance of safety as it relates to vulnerable users, especially pedestrians. Moreover, it handles this particular issue through an approach that has not been used so far in this context; the Stated Preference (SP) survey. As such, there are two main goals (and contributions) of this work. First, to show how SP surveys can be used to investigate the importance of different design and operational features to pedestrian perceptions of safety in roundabouts. This allows us, for example, to quantify how some features of roundabouts (e.g. high traffic volume) can be compensated for by design features such as pedestrian islands. This is useful in helping to design roundabouts that pedestrians prefer and will hopefully use, to help encourage active transport. Second, to demonstrate how traffic simulation software can be successfully used to include difficult-to-communicate attributes in SP surveys.

***Keywords**: Roundabouts, pedestrians, stated preference methods, vulnerable user safety*

4.2. Introduction

Developed initially in the UK in the 1960s, roundabouts have become increasingly popular in the last two decades in North America. Roundabouts are circular intersections where traffic flows counter-clockwise around a central island, preventing vehicles from crossing in a straight, and therefore faster, path. These intersections work based on the principle that vehicles entering the roundabout must yield to those already traveling within the central circle (Rodegerdts et al. (2010, pp. 3-5), pp. 3-5).

There are several commonly identified benefits of roundabouts compared to regular intersections that have been documented in the significant body of research on the topic. These benefits can be divided into different categories including environmental (e.g. reduced emissions because of increased fluidity of traffic flow, in particular fewer stops), mobility (increased fluidity of traffic flow compared with regular intersections), and safety (fewer accidents) improvements - the former of which can be further classified between driver and vulnerable user safety benefits.

How roundabouts improve driver safety is an issue addressed in the majority of the studies on the topic, although in some cases vulnerable road users (cyclists and pedestrians) are also considered. In the literature focusing mainly on motorists it has been shown that for these users, roundabouts are safer than other types of intersections, both in terms of frequency of accidents and their severity (Bared et al., 1997; Bie et al., 2008; Y. Chen, Persaud, Sacchi, & Bassani, 2013; and Gross, Lyon, Persaud, & Srinivasan, 2013). On the other hand, Daniels et al. (2010a); (2010b) found that vulnerable road users have a higher probability of being injured in roundabouts than expected based on their share of occupancy in traffic. Daniels et al. (2010a) also found that some geometric elements such as the presence of bicycle lanes inside roundabouts are a significant risk factor. At the same time there is a bit of literature that has touched on the question of vulnerable road users in roundabouts, according to Wall et al. (2005) there are simply not enough studies related to the safety of this type of roundabout user, despite the importance of the subject.

While there has not been much research on the safety of vulnerable road users in roundabouts, pedestrian safety has attracted increased attention recently. Different approaches have been proposed to map injury risk and/or identify factors associated to injury frequency or severity of pedestrians using traditional methods based on historical crash data, but many of these have been focused on intersections or crosswalks (Clifton et al., 2009; Harwood et al., 2008; and Miranda-Moreno et al., 2011). To address some of the issues of traditional crash-based methods, surrogate safety methods have also been proposed to investigate pedestrian safety using field observations such as video data (Ismail et al., 2009). While there is an important body of literature on objective safety using crash-risk or surrogate measures, the literature on safety perception is limited, in particular at roundabouts (Brosseau, Zangenehpour, Saunier, & Miranda-Moreno, 2013; C. Li, 2006; Lipovac, Vujanic, Maric, & Nesic, 2013; and Ren, Zhang, Wang, Zhou, & Wang, 2011). Papadimitriou et al. (2013) focuses on pedestrian perceptions of intersection safety with respect to traffic characteristics such as vehicle volume and vehicle speeds.De Brabander and Vereeck (2007); and Xi and Son (2012) on the other hand concentrate on statistical analyses of pedestrian accidents and injuries, but do not consider pedestrian preferences or behavior explicitly. Finally, Meneguzzer and Rossia (2011) examine the empirical relationships between pedestrian occupancy of crosswalks and impedance to vehicle flow in roundabouts. Despite there being a literature on roundabouts, and there being a literature on pedestrian safety, there is little research that focuses exclusively on pedestrian safety in roundabouts, especially when compared with how much literature there is for drivers. Perhaps the most comprehensive research focused on pedestrian safety in roundabouts is Report 674 of the National Cooperative Highway Research Program (see Schroeder et al. (2011), pp. 34-61), which gathers various studies of the National Research Council of America on roundabouts. In the report, different roundabout attributes are studied in order to provide specific recommendations for their construction. While some of the research surveyed in the report looks at pedestrian preferences with respect to roundabouts, none of that research broached the question by means of an Stated Preference (SP) survey.

SP surveys have been used in a limited number of situations to understand vulnerable road user preferences and behavior. The method has been used for example to better understand cyclist preferences, although never in the context of roundabouts (see e.g. Krizek (2006)). Furthermore, pedestrian preferences and behavioral analyses have been confined to: route choice and behavior at intersections (Papadimitriou et al., 2009); the influence of perceived level of safety at an intersection and where pedestrians cross (C. Li, 2006); preferences with respect to pedestrian crossing facilities (Sisiopiku & Akin, 2003) and pedestrian-motorist interactions at intersections (Kaparias et al., 2012).

Another field related to this research is that on the use of visual aids in transportation SP surveys. Studies by Taylor and Mahmassani (1996), Krizek (2006) and Arentze et al. (2003) can be observed as evidence of the good results that visual aids can produce in SP surveys. Particularly interesting is the work of Krizek (2006), where the use of visual aids (10-second video clips of bicycle paths) was reported to improve survey performance markedly.

In summary, the existing literature on roundabouts has focused on motorists and has mostly ignored vulnerable road users, despite an explosion in research and interest of this subject recently. Moreover, despite being used to successfully understand user preferences in other branches of transportation research, there has been no research to have explored the use of SP surveys to understand pedestrian preferences with respect to safety in roundabouts.

Understanding pedestrian preferences and behavior is an important goal in order to help encourage the use of active modes of transportation (see e.g. NCHRP report 674 (Schroeder et al., 2011)). Also, the use of visual aids in SP surveys to understand preferences, especially those that are difficult to communicate in words – and particularly in the context of vulnerable road users – is in its infancy.

As such, this research contributes to existing literature along these dimensions through the use of a video-based stated preference survey of pedestrian preferences in terms of safety with respect to roundabouts. There are two main goals of this work. First, to show how SP surveys can be used to quantify the importance of different design and operational features to pedestrian perceptions of safety in roundabouts. This allows us to quantify how some factors such as high traffic volume can be compensated for, by design features such as pedestrian islands. Second, to demonstrate how traffic simulation software can be successfully used to include difficult-to-communicate attributes in SP surveys.

The paper continues with a description of the development and administration of the survey. This is followed by a description of the statistical model used to analyze the data, model results and interpretation. The paper is finished with a discussion and conclusion of the results as well as a few notes on future work.

4.3. Methodology

An SP study typically involves a long process that includes: the design, administration and analysis of collected data (Arentze et al., 2003; Chu, Guttenplan, & Baltes, 2004; Kaparias et al., 2012; Kelly et al., 2011; Louviere et al., 2000; and Papadimitriou et al., 2009). In the present research, the purpose of the survey was to understand what factors (and to what degree those factors) influence vulnerable user preferences with respect to roundabouts in terms of safety. The first step in the development of an SP survey is an examination of the existing literature to understand what characteristics and attributes have been considered important in previous relevant studies. Table 2provides a summary of relevant work for pedestrian safety where vulnerable road user safety has been considered, focusing on the attributes (geometrical and operational) and their levels that have been used and evaluated in them. The literature is categorized by the type of intersection considered (traditional or roundabout) and the methodological approach adopted (SP or Other). This organization of the existing research allowed us to know which attributes (and their levels) have been found to be important in previous vulnerable user safety studies.

Table 2. Attributes and Levels Used in Existing Literature for analyzing Vulnerable Road User Safety of Regular Infrastructure and Roundabouts

Attribute	Levels	Vulnerable Road User safety analysis for traditional infrastructure		Vulnerable Road User safety analysis in roundabouts	
		By other methods	Using Stated Preference	By other methods	Using Stated Preference
Traffic volume	Low, Medium, High.	(Guo, Wang, Guo, Jiang, & Bubb, 2012; Papadimitriou et al., 2013; Sisiopiku & Akin, 2003)	(Chu et al., 2004; Kaparias et al., 2012; Kelly et al., 2011; Papadimitriou et al., 2009)	(Daniels et al., 2010a, 2010b; Hels & Orozova-Bekkevold, 2007; Macioszek, Sierpiński, & Czapkowski, 2011a; Moller & Hels, 2008; Schroeder et al., 2011)	-
Traffic speed	Low, Medium, High.	(Guo et al., 2012; Papadimitriou et al., 2013; Sisiopiku & Akin, 2003)	(Chu et al., 2004; Kaparias et al., 2012; Kelly et al., 2011; Papadimitriou et al., 2009)	(Daniels et al., 2010a, 2010b; Hels & Orozova-Bekkevold, 2007; Macioszek et al., 2011a; Moller & Hels, 2008; Schroeder et al., 2011)	-
Pedestrian volume	Low, Medium, High.	(Asano, Iryo, & Kuwahara, 2010; Guo et al., 2012; Sisiopiku & Akin, 2003)	(Kaparias et al., 2012; Papadimitriou et al., 2009)	-	-
Signalization	No signalization, Yield, Speed limit, Pedestrian crossing.	(Chaurand & Delhomme, 2013; Sisiopiku & Akin, 2003)	(Chu et al., 2004; Kelly et al., 2011; Papadimitriou et al., 2009)	(De Brabander & Vereeck, 2007; Moller & Hels, 2008; Schroeder et al., 2011)	-
Pedestrian crossing location	In the entrance of intersection, Near the entrance, Far from the entrance	(Sisiopiku & Akin, 2003)	(Chu et al., 2004; Kelly et al., 2011; Papadimitriou et al., 2009)	(Meneguzzer & Rossia, 2011; Schroeder et al., 2011)	-
Physical barriers	Vegetation, Median, Non barriers	(Papadimitriou et al., 2013; Sisiopiku & Akin, 2003)	(Chu et al., 2004)	-	-

(-) Nonexistent related work

As can be seen, most of the research has considered the following attributes: traffic volume, traffic speed, pedestrian volume, signalization, pedestrian crossing location and the presence of physical barriers (e.g. pedestrian islands).

While the first step provides an idea of the attributes that are likely to be included in the survey instrument, further complementary studies, such as focus groups and pilot tests are necessary to establish which attributes should be included in the final survey instrument. This constitutes a second step in survey development. A focus group is an exploratory research tool where a group of potential respondents are asked to identify which attributes they consider to be important in the question (choice) of interest. While being asked what attributes are important, respondents are also asked what appropriate ranges and/or levels of those attributes are (see Louviere et al. (2000), pp. 257-258). In this study, a focus group of eight individuals was convened. The focus group participants were contacted by a survey company specializing in the recruiting and administering of surveys. They were contacted if they lived within 1km of roundabouts in the region of Montreal and were asked to participate if they had accessed a roundabout by foot in the past three months. Gender and age diversity were sought in the formation of the focus group. Participants were asked at the beginning to simply share what they thought about roundabouts. Afterwards, they were asked to share their perceptions in terms of particular roundabout attributes and their relation with safety perception. While previous literature served as a backdrop of what to expect, the particular attributes to be addressed were left open to the focus group participants to discuss.

Based on these discussions, five attributes from the literature review were confirmed to be important for potential respondents: Signs; Pedestrian crossing position – i.e. distance from the intersection (although a particular preference for this attribute was not predominant); Traffic volume (less traffic preferred); Traffic speed (slower traffic preferred) and Pedestrian volume (more volume preferred).

These preferences with respect to roundabout characteristics were consistent with what has been found in previous literature (see e.g. Daniels et al. (2010a); and Hels and Orozova-Bekkevold (2007)). In addition, participants brought up two new attributes: Number of lanes (fewer lanes preferred), and the presence of a pedestrian island (presence of a pedestrian island preferred). They also suggested a new level for the Signs attribute: "Flashing signs" (presence of signs preferred over no signs). Thus, the very first version of the survey to be tested – the Pilot Survey – included all of these seven attributes.

Pilot Survey

A pilot survey is a tool that aids in identifying the strengths and weaknesses of the survey instrument. In this case, it was conducted online in order to test not only the instrument itself, but also to test the administration and data collection procedures to be implemented in the final survey. The pilot version had essentially the same structure as the final version of the survey.

Six choice tasks with two alternative roundabouts for each were shown to 48 participants in the pilot survey. As a result of the pilot survey, Traffic Speed and Traffic Volume were redefined so that differences between low and high values of these attributes were easily discernible without being unrealistic. These values were tested once again through a simpler online survey. In addition, this test showed Pedestrian volume did not seem to affect respondent choices with respect to preferred roundabouts.

Final Survey Administration

The definitive version of the survey instrument was divided into the same four sections as the pilot version of the survey. As such, it was structured as follows:

- First section (six questions). Respondent and household general information.

- Second section (two questions). Transportation mode going through a roundabout and frequency with which they accessed roundabouts by each mode (driving, by car but not driving, by transit, cycling and walking) in the past three months.
- Third section (three questions). Safety perception and knowledge of roundabout functionality.
- Fourth section (six choice tasks).

Based on what focus group and pilot test analyses revealed, the final survey included the following attributes and their respective levels:

- Signs: Absence of signalization, presence of standard pedestrian and cyclist crossing signs, and flashing pedestrian and cyclist crossing signs. According to previous literature and the focus group, it was expected that pedestrians would prefer the presence of signs, and flashing signs in particular.
- Number of lanes: One or two lanes per direction. In this case it was expected that pedestrians would prefer a shorter crossing distance (one lane).
- Presence of a pedestrian island: With and without an island. It was expected that pedestrians would prefer the presence of an island.
- Distance of pedestrian crossing from the entrance of the roundabout: Absence of pedestrian crossing, crossing at the entrance of the roundabout, and crossing 5 meters from the entrance. In this case there was not a clear preference in focus groups, although existing literature and the pilot survey point to a preference for a crossing far from the entrance over other options.

- Traffic volume: Low and high volume (100 and 500 vehicles/h). These values were proposed after the results observed in the pilot survey. The main objective was to make the difference easy to perceive for respondents while at the same time ensuring realistic volumes. It was expected that pedestrians would prefer lower traffic volumes.
- Traffic speed: Low and high speed (22 and 65 km/h on average). As in the case of traffic volume, the intention in the simulations was to establish a clear difference between high and low speed levels, while at the same time ensuring realistic speeds. It was expected that pedestrians would prefer lower traffic speeds.

The alternatives of the individual choice task videos were created with VISSIM, a microscopic simulation tool developed by PTV Group for modeling multimodal traffic flows. The attributes of each of the alternatives of the choice tasks were pre-determined by experimental design (explained further below) and programmed in VISSIM so that each choice task was unique. A constant pedestrian volume was used in all simulations, based on findings from the pilot survey (i.e. respondents could not distinguish different realistic levels of pedestrian volume). Figure 1shows a screen shot of one of the choice tasks that were viewed as embedded YouTube videos with the VISSIM simulations.

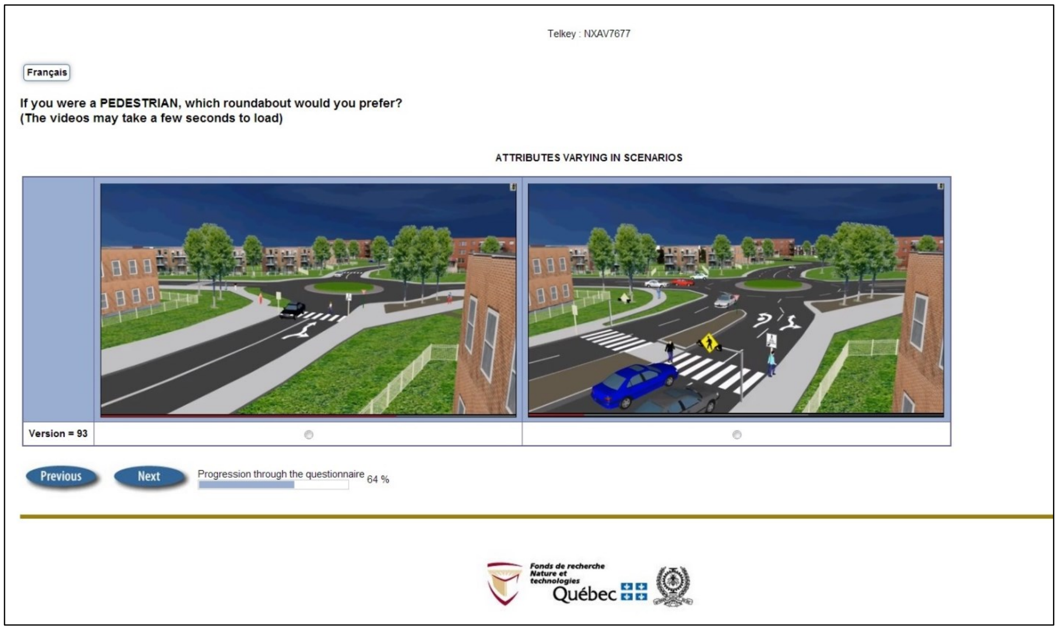

Figure 1. Example of a choice task in the on-line survey.

The first option shows a roundabout with one-lane roads, no island, regular signs, and a pedestrian crossing at the entrance of the roundabout. The second shows a roundabout with two-lane roads, pedestrian flashing signs, a pedestrian island and a pedestrian crossing far from the entrance of the roundabouts. While it is possible to distinguish the low (left choice task) and high (right choice task) traffic levels in this static photo, it is not possible to distinguish traffic speed, without watching the videos.

In Stated Preference surveys, the choice of levels of attributes characterizing choice alternatives must be done with great care. The determination of what attribute levels will characterize the alternatives in the choice tasks in a SP survey is referred to as the “experimental design” (see Louviere et al. (2000), pp. 83-131). For the final version of the survey our aim was to recruit 500 respondents. As such, we used an experimental design of 500 different versions of the survey. Each version was composed of six choice tasks involving two alternative hypothetical roundabouts (see Figure 1 for an example of one of the choice tasks). The versions themselves were obtained from Sawtooth Software, a software specialized in the development of SP surveys. Sawtooth offers different approaches (or strategies) to select experimental designs from the set of all possible choice task combinations, known as the full factorial design.

In this research we used the "balanced-overlap strategy". This strategy represents a trade-off between the random strategy and the complete enumeration strategy. The random strategy employs random sampling with replacement for characterizing concepts (or alternatives within the choice task), allowing an attribute to have identical levels across concepts, but not identical concepts in all attributes within the same task. With the complete enumeration strategy, all possible concepts are considered, while ensuring the most nearly orthogonal design for each respondent in terms of main effects. The balanced overlap strategy allows roughly half as much overlap within the same task as the random method. With respect to design efficiency (the minimization of the standard error of coefficient estimates), the balanced overlap strategy is less efficient than designs with minimal overlap, however it can result in more thoughtful responses by encouraging respondents to trade-off between more alternatives (Sawtooth Software, 2013). The design in this study was 24 % less efficient than the most efficient design, but it allowed us to capture all attribute interactions.

For the final survey, a company specialized in web-based surveys and the administration of online research tools (Groupe Altus) was hired in order to recruit the 500 respondents qualifying for the survey. In order to qualify, respondents needed to: be 18 years old or older; live within a buffer of 1 km from a roundabout (as was done in the work by Goudie (2002), Kelly et al. (2011) and Krizek (2006) where only respondents located within a specific buffer were considered for the survey); and have walked through a roundabout in the past three months. In order to select possible respondents within a 1 km buffer, the company administering the survey was provided with coordinates of all roundabouts in Quebec.

The survey was conducted during the first week of July, 2013, finishing with 501 completed online surveys. Before proceeding to the estimation of the final models presented below, some data cleaning was done. Data cleaning is considered to be a critical and necessary step of stated choice analysis. Guidance and examples of data cleaning by leaders in stated preference analysis can be found in Hensher et al. (2005) , as well as in Hess, Rose, and Polak (2010). The approach we used was similar to Hess et al. (2010). In particular, all of the choice tasks were examined and respondents who chose choice tasks that were dominated (i.e. the alternative had at least one better attribute and no worse attributes – based on preferences found in the literature and confirmed in focus groups, see last paragraph of section 5.2) were removed from the analysis. Altogether this represented 14 % of the respondents.

The Multinomial Logit Model and the Mixed Logit Model

The last stage of a Stated Preference survey is the statistical analysis of respondent choices. This is most typically done through the use of discrete choice statistics. This section describes the statistical model used.

This description of the multinomial logit (MNL) and mixed multinomial logit models draws primarily on Kenneth Train's book Discrete Choice Methods with Simulation (Train, 2009). It is kept brief since comprehensive explanations can be found in many other references.

The logit model is used when trying to explain discrete choices; choices among several mutually exclusive alternatives.

According to random utility theory, a decision maker (n) will choose the alternative (i) that provides them the highest utility. It is important, nonetheless, to understand that: only the decision-maker knows (intuitively) the utility of each alternative; whereas the researcher can only observe the choices made by, and some of the characteristics of, the decision maker. By analyzing the decision maker's choices, the researcher can estimate a representative utility function (the deterministic portion of the utility). This is typically represented as in equation (4).

$$U_{ni} = V_{ni} + \varepsilon_{ni} \qquad \forall i \tag{10}$$

Here, U_{ni} is the utility individual $n$obtains from alternative i. V_{ni} is the systematic portion of utility and ε_{ni} is the random error. V_{ni} can be re-expressed as in equation (2) where it is a linear combination of the model coefficients and alternative and decision-maker characteristics.

$$V_{ni} = \alpha_{ni} + \beta x_{ni} \qquad \forall i = 1, \dots, n \tag{11}$$

The error is unobserved and unknown and in fact, it is the assumption about its distribution that determines the model used to estimate the utility function. If the error is assumed to be independently and identically extreme value distributed, then the probability that the individual n chooses alternative i will be defined by the closed-form expression of the MNL:

$$P_{ni} = \frac{e^{V_{ni}}}{\sum_{j=1}^{J} e^{V_{nj}}} \tag{12}$$

Although this form of the MNL model makes it straightforward to estimate, interpret and use, the assumptions related to the error in this model are questionable in many choice contexts, such as when observations involve more than one response from the same person. The relaxation of such assumptions can be allowed by the use of models that require numerical integration, such as the Mixed Logit Model.

In the MNL model the coefficients for $\beta$are fixed across users. In contrast, the Mixed Multinomial Logit Model (MMNL) allows having a vector of random coefficients. Assuming the utility as varying over people, but being constant over choice situations for each person, the utility for alternative j in choice situation t by respondent n is $U_{njt} = \beta_n x_{njt} + \varepsilon_{njt}$, with ε_{njt} being independently and identically distributed (iid) extreme values over time, people and alternatives. Considering a sequence of alternatives for each time period $i = \{i_1, \dots, i_T\}$, the probability that a respondent makes this sequence of choice is defined as the product of logit formulas (see equation 4), since the ε_{njt}'s are independent over time.

$$L_{ni}(\beta) = \prod_{i=1}^{T} \left[\frac{e^{\beta'_n x_{nit}}}{\sum_{j=1}^{J} e^{\beta'_n x_{nit}}} \right] \qquad (13)$$

The integral of this product over all values of β, is the unconditional probability:

$$P_{ni} = \int L_{ni}(\beta) f(\beta) d\beta \qquad (14)$$

By integrating the product of logit formulas over all values of β, the correlation of errors across the choices of a given individual are captured. As with the MNL, the MMNL is also capable of identifying random sources of heterogeneity, making these choice models less restrictive than models that assume fixed βs.

4.4. Results

Table 3shows the results for the MMNL model estimated with the survey data. Since we used stated choice data with multiple responses from each respondent, we estimated a panel MMNL to account for correlation across respondents. The model has right-signed coefficients (signs of the coefficients are consistent with our expectations based on the existing literature and focus group), that are all significant at the 90% confidence level. The presence of a pedestrian crossing far from the entrance of the roundabout was found to be the attribute that would increase the odds of an alternative roundabout being chosen the most. The segmentations shown in this model suggest that those users not living in Greater Montreal are less sensitive to the number of lanes than those living in Montreal. This is likely explained by the fact that those living in Montreal are more accustomed to roundabouts with more lanes, and as result are less sensitive to this design feature. Those who live outside of Montreal but frequently access roundabouts by foot are more sensitive to speed than the rest of respondents. This is likely explained by the fact that higher speeds are more expected in suburban and rural areas. The model also shows that four variables (pedestrian crossing at the entrance of the roundabouts, pedestrian crossing 5 m from the entrance, number of lanes and presence of island) are specified to have normally distributed random coefficients.

Table 3.Multinomial Mixed Logit Model Results for Pedestrian Preferences with Respect to Roundabouts in Quebec

Attributes	**Segmented MMNL**			
	Coefficient		***t*-Statistic**	**exp (*b*)**
Presence of regular signs	0.422	*	1.67	1.526
Presence of flashing signs	1.117	***	4.29	3.055
Number of Lanes	-0.997	***	-6.25	0.369
Interacted with not in Great Montreal area dummy variable	0.370	*	1.88	1.448
Presence of island	0.737	***	6.78	2.091
Pedestrian crossing at the entrance	2.689	***	8.45	14.710
Pedestrian crossing 5 m from entrance	4.273	***	10.67	71.736
Traffic volume (veh/h)	-0.163	***	-6.64	0.849
Traffic speed (10 km/h)	-0.648	***	-2.72	0.523
Interacted with pedestrain who mainly walk through a roundabout not in Great Montreal area dummy variable	-1.190	**	-2.00	0.304
Number of random coefficients	4			
Number of lanes Standard Deviation	0.686	***	2.96	-
Presence of Island Standard Deviation	0.716	***	3.50	-
Pedestrian crossing at the entrance Standard Deviation	1.373	***	5.38	-
Pedestrian crossing 5 m from entrance Standard Deviation	2.129	***	6.91	-
Final Log Likelihood	-961.57			
Pseudo R^2	0.4623			
Number of parameters	14			
Degree of freedom (above base MNL model)	6			
$\chi^2_{(observed)} = -2[LL_{(base\ model)} - LL_{(new\ model)}]$	106.56			
* = Significant at 90% Confidence Interval (C.I.),				
** = Significant at 95% C.I.				
*** = Significant at 99% C.I.				

The model suggests that there is taste variation across respondents with respect to these four attributes, especially with respect to the coefficient for having a pedestrian crossing 5 m from the entrance. For this attribute, such variation was also observed in focus groups – while some pedestrians appear to prefer the safer feeling of being further from the intersection, others prefer a more direct route. It is also interesting to observe that taste variations across respondents are only identified in infrastructure attributes and not in operational characteristics, showing that the perception of speed and volume (operational attributes) is more uniform across respondents. In addition, the log likelihood ratio test (Train, 2009)in the MMNL model indicates that this model also offers better explanatory power than the base model at the 99% confidence level.

While these models are instructive, to better understand the results, it is helpful to get a sense of just how important each of the design and operational characteristics are with respect to each other. In order to do so, a substitution rates analysis was done. A substitution rate is an economic concept defined as “the amount of a particular item that must be given to an agent in order to exactly compensate that agent for the loss of one unit of another item” (Hensher et al., 2005). In the case of logit models, substitution rates can be obtained by dividing the coefficient of one variable with that of another. The most common substitution rate to be derived from Logit models is the money substitution rate, or the willingness to pay (WTP). This is obtained by dividing the coefficient for a given variable by the coefficient for price (see e.g. Train (2009), pp. 39). If the survey were about vehicle choice, for example, it would be possible to estimate WTP for vehicle fuel efficiency by dividing the coefficient of fuel efficiency by price. Although there is no price attribute in our case, we have estimated other non-monetary substitution rates, as shown in Table 4.

Table 4. Substitution rates for segmented MMNL model

	Number of lanes	Number of lanes Outside Greater Montreal	Traffic Volume (veh/h)	Traffic Speed (10 km/h)	Traffic Speed - Frequent Pedestrians Outside Greater Montreal
Presence of regular signs	0.42	0.67	2.59	0.65	0.23
Presence of flashing signs	1.12	1.78	6.85	1.72	0.61
Presence of Island	0.74	1.18	4.52	1.14	0.4
Crossing at the entrance	2.7	4.3	16.5	4.15	1.46
5 m crossing	4.29	6.82	26.21	6.59	2.32

Table 4 shows, for instance, that the negative effect of going from one lane to two lanes in a roundabout can be compensated by the presence of flashing signs (coefficient of flashing signs divided by coefficient of number of lanes = 1.12 – the substitution rate between these attributes). Substitution rates can also be calculated for changes in operational attributes. For example the presence of a pedestrian crossing at the entrance has the same effect on pedestrian preferences as decreasing traffic speed by ~41 km/h (substitution rate in Table 3 of 4.15, with the speed variable unit being multiples of 10 km/hr).

Such substitution rates can be helpful by suggesting how different elements could be traded off in the design of a particular roundabout in order to maintain the same degree of satisfaction that pedestrians feel towards them. It is useful to observe that, in general, the impact of those attributes that are difficult to control in practice (such as traffic speed and volume) in pedestrian safety perception, can be compensated through geometrical attributes easy to implement (e.g. by providing a pedestrian crossing).

Although the results confirm what we might expect by intuition (apart possibly from the location of crossings), the interest in using an SP analysis and estimating a discrete choice model lies in the ability to quantify the effect of each of the attributes, while controlling for the effects of all the other attributes.

4.5. Discussions and conclusions

Both the administration of the SP survey and the analysis of its results provide a rich field for discussion. First, this research shows how Stated Preference methods are relevant (and as yet unused) in trying to better understand pedestrian preferences with respect to safety in roundabouts. As mentioned in the literature review, while SP methods have been used to understand pedestrian preferences at traditional intersections (Kaparias et al., 2012; Kelly et al., 2011) they have not been in roundabouts. Second, the modeling results and marginal substitution rates derived from them can be interpreted as recommendations of how to improve roundabout design in the eyes of vulnerable users in terms of safety, an application of these models that has not been explored before. Third, it is necessary to highlight the methods used for presenting choice tasks to respondents. As explained in the literature review, there is little research where videos (simulated or recorded) are used in Stated Preference surveys, apart from a few studies in other branches of transportation research (e.g. Arentze et al. (2003); Krizek (2006); and Taylor and Mahmassani (1996)). These studies demonstrated the advantages of using recorded videos to communicate variables difficult to describe by text. Our study contributes to this by providing evidence for the advantages of using traffic micro-simulation videos to communicate operational features of roundabouts, i.e. traffic speed and volume.

A variety of pedestrian crossing positions can be found in roundabouts across Quebec, regardless of land use, levels of service of the road or neighborhood type where they are located. Our research shows that vulnerable users are more likely to prefer roundabouts in terms of safety perception if they have pedestrian crossings, confirming what other authors found for regular intersections (e.g. Chu et al. (2004); Kelly et al. (2011); and Sisiopiku and Akin (2003)). Although many operational attributes are difficult to control in the field, respondents have demonstrated through the survey that they feel safer when traffic volume and speed are low. This is also consistent with previous research that has come to similar conclusions using other methods (see e.g. Daniels et al. (2010a, 2010b); Hels and Orozova-Bekkevold (2007); and Moller and Hels (2008)). Moreover, our research has found that vulnerable users consider flashing pedestrian crossing signs to be preferable than other (or no) signs – a result not found in the existing literature.

Evidently, it is difficult to imagine that all roundabouts could be designed according to pedestrian preferences: pedestrian crossing flashing signs, one-lane intersections, presence of an island, pedestrian crossings far from the entrance and low traffic speed and volume; but it is well worth taking them into account when implementing this type of intersection in the region, encouraging, at the same time, the use of active modes of transportation. Moreover, through the substitution rate analysis it is possible to understand how to compensate vulnerable user safety perceptions for negative operational attributes that are difficult to control. In particular, the results show that negative attributes (such as an increase in speed, volume or number of lanes) can be compensated with different roundabout design features. It’s particularly interesting to observe how safety perception from vulnerable users in roundabouts can be increased by relatively small changes, such as moving pedestrian crossings. Thus, the substitution rates obtained in this research can be a useful tool in the decision and policy making process related to roundabouts by providing guidance on how to trade-off different design and operational characteristics of roundabouts. The approach, for example, could be used to evaluate the effect on pedestrian perceptions of safety of roundabouts design guidelines such as those in TRB Report NCHRP Report 674: Crossing solutions at roundabouts and channelized turn lanes for pedestrians with vision disabilities (see e.g. Schroeder et al. (2011)).

4.6. Future work

The innovative aspects of this current research suggest that there is plenty of room for testing findings and improving procedures. First, it would be interesting to compare the method presented here to a traditional text-based survey to evaluate which type of instrument would be better to use in this context.

More important, however, is the validation of these findings through the comparison between safety perception and actual safety and user behavior (such as the research based on direct behavior observation data funded by the FRQNT in the same larger project as this study). Although perceived safety is important for the acceptability of the design, the direct observation of user behavior and accident analysis relating to roundabouts and pedestrians (or vulnerable road users) would allow future research to propose well-defined recommendations in terms of safety regarding this type of intersection for these users.

4.7. Acknowledgements

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5. OBTAINING PEDESTRIAN SAFETY INDICATORS IN ROUNDABOUTS THROUGH AUTOMATED VIDEO DATA COLLECTION –A CASE STUDY IN QUEBEC

TRB paper 15-4780

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5.1. Abstract

Existing literature shows that in the case of road safety, motorists have been privileged in terms of research, being studied through a variety of approaches, from traditional accident statistics to surrogate safety methods. The latter has recently seen a renewed interest, in particular using automated video analysis. The present case study departs from previous automated video analysis applications under different circumstances, using the technique to characterize the actual safety of pedestrians in roundabouts, something that has not been studied with this kind of tool before. The purpose of the paper is to study pedestrian behavior in these intersections. The paper describes the background and the process of obtaining the required information. Four interaction cases are studied, depending on which road user yields (decelerating or stopping). Results show that in most motorist-pedestrian interactions (88 %), the road users comply with the priority rule (for the pedestrian). Yet, some interactions seem unsafe based on measured the time to collision, with a higher proportion of less safe interactions when the pedestrian yields. Based on the results of this case study and the small sample size, the paper highlights the need of getting recordings in more optimal settings in order to obtain useful behavior and safety parameters for a particular type of road user.

Key words: *pedestrians, roundabouts, road safety.*

5.2. Introduction

Roundabouts are considered as a means to improve safety and mobility at intersections. This is why this geometric arrangement, initially developed in the UK in the 1960s, has become increasingly popular in the last decades in North America. As St-Aubin, Saunier, et al. (2013) mention, it is important to distinguish between roundabouts and rotaries: while roundabouts are circular intersections where traffic flows counter-clockwise around a central island and where incoming traffic yields to traffic already in the roundabout; rotaries (or traffic circles) are generally much larger and can be signalized. A comprehensive study of roundabout design, operation, control, and maintenance was recently produced by the National Cooperative Highway Research Program in its report 672 (Rodegerdts et al., 2010).

In existing literature, roundabouts have been studied in three main ways: mobility advantages (e.g. Bergman et al. (2011); and Meneguzzer and Rossia (2011)); environmental advantages(e.g. Mandavilli et al. (2008)); and safety advantages with this last stream commonly divided between motorist safety and vulnerable road user safety.

An extensive literature review of roundabout benefits in terms of safety is offered by De Brabander and Vereeck (2007). This paper supports the idea that the majority of road safety research on roundabouts has been focused on motorists (e.g. Bared et al. (1997); Bie et al. (2008); Y. Chen et al. (2013); and Gross et al. (2013)), while only very few address vulnerable users, despite the recognized importance of the study of vulnerable users, as described by Wall et al. (2005).

Among the research dealing with vulnerable users' safety in roundabouts, the majority is focused on cyclist behaviour and its interaction with other modes (e.g. Daniels et al. (2009); Hels and Orozova-Bekkevold (2007); Hydén and Várhelyi

(2000); Macioszek et al. (2011a, 2011b)). Research focusing on pedestrians would be inexistent, were it not for the few studies like Azhar and Svante (2011) or Schroeder et al. (2011) –Report 674 of the NCHRP. This report is probably the most comprehensive research on pedestrian safety where roundabout accessibility, signals, and crossings are analyzed.

Although not related to roundabouts, there is a relatively large amount of research addressing road safety issues for pedestrians: traditional methods based on historical crash data at crosswalks (Clifton et al. (2009); Harwood et al. (2008); and Miranda-Moreno et al. (2011)), statistical analysis of pedestrian accidents and injuries (De Brabander and Vereeck (2007); and Xi and Son (2012)), or pedestrian perception of traffic characteristics (Papadimitriou et al. (2013)). More innovative approaches to studying pedestrian safety have also been used: Ismail et al. (2009) present the results of an automated analysis of pedestrian behavior using video recordings. In this research the authors present a video analysis system capable of detecting and tracking road users for later classification into pedestrians or motorists, identifying possible collisions and calculating the severity of conflicts in a signalized intersection in Vancouver, British Columbia, Canada (Ismail et al. (2009)).

Video recording technology has also been used to study road safety, with the majority focusing on motorists as well (e.g. Hsieh et al. (2006); Rad and Jamzad (2005); and Tai et al. (2004)). Jackson et al. (2013) present, for instance, a comprehensive description of a system based on video camera recordings and automated video analysis for road safety. They describe a flexible system for video data collection, as well as the analysis of this data through an open source project called “Traffic Intelligence” that includes an automated tracker and tools for behavior and surrogate safety analysis, illustrated by three case studies (Jackson et al. (2013)). The use of these same algorithms has been tested in other works such as Saunier et al. (2010), or, in the case of roundabouts, St-Aubin, Saunier, et al. (2013).

As explained above, video recording and tracking analysis have been used so far to study driver behaviour and safety under different circumstances (including roundabouts (St-Aubin, Saunier, et al., 2013)), as well as pedestrian behaviour in regular intersections (Ismail et al., 2009). However, so far these approaches have not been combined to study and understand pedestrian behavior in roundabouts. This reinforces the observation that there is a lack of significant research into pedestrian safety in this kind of intersection.

The purpose of this research is to present a case study where video recordings of roundabouts have been analyzed focusing solely on pedestrians and their interaction with motorists, in order to achieve two main objectives: to characterize pedestrian behavior in these intersections and to evaluate this technique when used specifically for pedestrians. The paper starts with a description of previous work where the need for more attention to pedestrian research was identified, as well as a general background of video analysis methods and their application to safety analysis. A description of the methodology used to obtain and analyze pedestrian behavior in specific roundabouts in Quebec is presented afterwards. The paper finishes with a discussion of the results along with conclusions and avenues for future work.

5.3. Methodology

The following section provides a description of the methodology used to study pedestrians' behavior and safety at roundabout crossings in the province of Quebec, Canada. The starting point for this paper is previous research on pedestrian preferences and safety perception of roundabouts. The research presented here was intended to obtain actual safety indicators for pedestrians in roundabouts to complement our findings on pedestrian perceptions of safety at these intersections. This methodology section therefore starts with a brief description of the research where perceived pedestrian safety in roundabouts was obtained. It continues with a description of previous work where safety indicators (for other kinds of users) have been successfully obtained in roundabouts, and an explanation on how methods employed in such papers can be applied to pedestrians. This section sets the basis for the case study developed afterwards in the paper.

Pedestrian Perceptions of Roundabouts

During the summer of 2013 Perdomo, Rezaei, Patterson, Saunier, and Miranda-Moreno (2014) designed and administered a Stated Preference (SP) survey addressed to pedestrian users of roundabout in Quebec, Canada. The main goal of this study was to understand pedestrian preferences in terms of road safety towards a variety of design and operational attributes of roundabouts. This research found that, when talking about road safety in roundabouts, pedestrians are more likely to prefer roundabouts with: pedestrian crossings away from roundabout entrances, pedestrian crossings with flashing signs, pedestrian islands, low traffic volumes, and low traffic speeds. Although this research provided general recommendations regarding roundabout improvement, its conclusions are based on respondent choices under hypothetical circumstances, a feature of all SP surveys (Louviere et al. (2000)).

Recognizing this limitation in their research, Perdomo et al. (2014) suggest that an important future addition to this research would be the analysis of actual pedestrian safety in these intersections, something that would allow the comparison of user perceptions to revealed user behavior. The comparison between perceived and actual safety is important since risk perception is quite subjective, whereas objective safety analysis is based on crash statistics measuring crash frequency and severity, or on the observation of non-collision events and the development of surrogate measures of safety (Winters et al. (2012)). Work like that of Hakkert, Gitelman, and Ben-Shabat (2002); Sjöberg, Elin Moen, and Rundmo (2004); and Winters et al. (2012) can be considered as examples of such comparisons, although not for the case of pedestrians in roundabouts.

Data collection

Data used for this case study comes from the large video dataset collected for the analysis of road user behaviour and safety at roundabouts using surrogate measures of safety (St-Aubin, Saunier, and Miranda-Moreno (2014)). Data was collected at 20 roundabouts around Quebec. A purpose-built mobile video camera system was installed at these sites to record road user movements at 40 analysis zones. The analysis zones are centered on merging zones (defined as the portion of the ring intersected by an approach and an exit) during mild weekdays under regular traffic conditions from 6am to 7pm and in some cases to 10pm. The reader is referred to St-Aubin, Saunier, et al. (2013) for more details about the data collection, and to Jackson et al. (2013) for a more detailed description of the system requirements, components, equipment, and steps to go from data collection to analysis.

Although this data collection campaign yielded 600 hours of video data, the focus was on vehicle interactions in merging zones and not on pedestrian crossings. Added to the fact that most roundabouts are located in suburban or rural locations, this means that only few pedestrians were observed at these sites. Recordings from St-Aubin et al. (2014) at 5 sites were manually studied, identifying and putting aside 387 cases where a pedestrian made use of one of the crossing approaches in the observed roundabouts. Among them, only 164 cases of an interaction between pedestrians and vehicles were identified, where an interaction is defined as the event when a pedestrian has the intention to cross the road and needs to be aware of at least one vehicle approaching the crossing.

Pedestrian tracking, behaviour and safety analysis

Forsyth, Arikan, Ikemoto, O'Brien, and Ramanan (2005) offer a comprehensive illustration of approaches and techniques used for tracking pedestrians. To summarize their findings, the authors differentiate three main approaches: tracking by detection (subtraction of the current image from a background or using object classifiers), tracking using flow (matching distinctive feature points between successive images), and tracking with probability (treating tracking as a probabilistic inference problem). However, Ismail et al. (2009) state that there is no fully functional video-based pedestrian conflict analysis system. For their case study, feature-based tracking was preferred since it can deal with partial occlusion. Feature-based tracking consists of two steps:

1. Detecting distinctive features in the whole video image and filtering out stationary features, as well as features with irregular behavior, unexpected from the road users under study;
2. Grouping features that belong to the same road user, using common motion constraints.

An implementation of the feature-based tracker used in Ismail et al. (2009) is available in the open source “Traffic Intelligence” project started and maintained by Saunier (2014), that also provides other tools and libraries for the interpretation of road user behaviour and surrogate safety analysis. For more details on the tracker, the reader is referred to Saunier and Sayed (2006) as well as Jackson et al. (2013), while the tools have been successfully applied to surrogate safety analysis in various environments (highways by St-Aubin, Miranda-Moreno, and Saunier (2013), roundabouts by St-Aubin, Saunier, et al. (2013), and urban intersections by Mohamed and Saunier (2013)) as well as for various types of road users (vehicles by Mohamed and Saunier (2013), vulnerable road users and mixed traffic by Zangenehpour, Miranda-Moreno, and Saunier (2014)).

As such, Traffic Intelligence is used in this study to obtain the trajectories of pedestrian-vehicle interactions at roundabout crossings from the videos in which pedestrian-vehicle interactions are present. Once the trajectories are extracted and the velocities derived, behavior and safety analysis is performed by computing a series of indicators for all instants where two interacting road users are tracked. The indicators computed include: simple kinematic indicators such as distance and speed differential; and surrogate measures of safety such as time to collision (TTC) and post-encroachment time (PET) (see Saunier et al. (2010) for more details). TTC, defined as the time required for two vehicles to collide if their movement were to remain unchanged, is the most commonly used surrogate measure of safety. In simple situations of rear-end or head-on interactions, it is simply the distance between the two road users divided by their speed differential. The overall safety of an interaction is often summarized by one value of the series of measures of the safety indicator, typically the most extreme value or a centile of the time series.

5.4. Case study

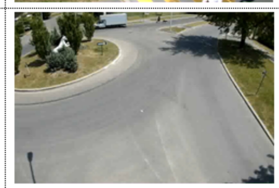
The following section describes how pedestrians were identified and tracked with the tracking software. This section begins with a description of the sites where the recordings were made, followed by a brief description of the feature-tracking procedure and validation, finishing with the results and conclusions.

Roundabout Sites

This study includes five roundabouts where pedestrian-motorist interactions were examined. Although 12 roundabouts were available from the videos collected for

St-Aubin, Saunier, et al. (2013), five of them were located in suburban areas where pedestrian flow was basically non-existent. Two others had pedestrian flows, but the camera was located too far from any pedestrian crossing to track any pedestrian. Table 5 shows a summary of the roundabouts included in this study. It shows the amount of video available for each site, as well as the number of crossing events (when a pedestrian or a group of pedestrians cross the intersection) manually identified, the geometry of the roundabout (considering the same attributes and levels as Perdomo et al. (2014) for comparative purposes) and a video frame from the recording at the sites.

Table 5. Studied Roundabouts

Site	Recorded time	Crossing events	Geometry	Sample view
Des Soeurs – du Golf	6 hours	112	One lane per direction Pedestrian crossing 5 m far from entrance Presence of island Regular signs No bike path	
Des Soeurs – Rene Levesque	12 hours	227	One lane per direction Pedestrian crossing 5 m far from entrance Presence of island Regular signs No bike path	
Des Soeurs – Riverdale	6 hours	6	One lane per direction Pedestrian crossing at the entrance Presence of island No signs No bike path	
Frechette – Anne le Seigneur	8 hours	18	One lane per direction Pedestrian crossing at the entrance Presence of island Regular signs No bike path	
Nobel Curie	11 hours	24	Two lanes per direction Pedestrian crossing 5 m far from entrance Presence of island Regular signs No bike path	

As shown in Table 5, in 43 hours of recording only 387 crossing events were identified. This rate (about 9 pedestrians an hour) can be seen as low compared with other research on pedestrian analysis works are considered (e.g. S. Li et al. (2012) used 2,206 cases, while Ismail et al. (2009) found 2,100 pedestrians in 20 hours of recording).

Data Analysis and Validation

For the behavior and safety analysis of pedestrian-motorist interactions in roundabouts, different characteristics of each interaction event recognized in the recordings were registered in a database. These characteristics are divided as follows:

- Geometric characteristics of the site. Based on the levels and attributes used by Perdomo et al. (2014) to characterize pedestrian safety perception in roundabouts, the following attributes were collected: number of lanes per direction, position of pedestrian crossing, presence of island, pedestrian signalization, and the presence of bike path. As stated before, the purpose of these specifications was to be able to compare pedestrian perceived safety to actual safety.
- Pedestrian characteristics. Characteristics such as gender, age (adult or child), and if the pedestrian crossed as part of a group, were visually assessed for each crossing event.
- Tracking characteristics. The trajectories, including velocities, and indicators (TTC, in particular) were obtained using Traffic Intelligence.

In addition, each interaction was classified according to the observed interaction between pedestrian and motorist in the recordings. Thus, each interaction was in one of the following four categories:

1. The driver reduced speed or stopped completely to yield to the pedestrian(s) at the crossing.
2. The driver waited. In this case, the driver was already stopped (because of a queue or pedestrians already crossing) and waited for the pedestrian(s) to cross.
3. The pedestrian reduced his/her speed or stopped completely, yielding to a vehicle at the crossing.
4. The pedestrian waited. In this case, the pedestrian(s) had to wait for a vehicle to pass the crossing. This happened in cases of high motorized

traffic volume or when motorists did not yield to the pedestrian(s) deliberately.

This classification allows analyzing waiting times (for motorists and pedestrians) as well as gap measurements (accepted/rejected by drivers and pedestrians). Although all interactions could be analyzed based on the above classification and characteristics; many of them presented diverse issues that reduced the number of interesting events for analysis. First, among the 387 crossing events, only 164 (42 %) represented an interaction between a pedestrian and a driver: the details of the interactions split across cases are presented in Table 6. The location of Des Soeurs – Riverdale had to be discarded, since none of its crossing coincided with the presence of motorized vehicles. Second, some of the crossing events could not be tracked. This was due partly to the position of the cameras, which, as stated before, were chosen to study vehicle interactions in merging zones, not pedestrians or their interactions with vehicles. If not tracked, safety indicators such as gaps or TTC could not be objectively estimated. Other factors, like shadows from the nearby buildings or trees, or the combined tracking of different road users could also make the tracking output unusable. Because of all these issues, some interactions had to be discarded. All the interactions that could not be tracked are presented in detail in Table 7). Finally, only a minor proportion of all the interactions, 19 out of 164 (corresponding to cases 3 and 4), represented a crossing where pedestrians had to yield to vehicles (contrary to what signalization in these roundabouts requires).

Table 6. Number of interactions of each case (whether tracked or not)

Location	Case					Total
	1	2	3	4	Error	
Des Soeurs – du Golf	37	9	5	3	3	54
Des Soeurs – Rene Levesque	66	19	0	1	27	86
Frechette – Anne le Seigneur	8	1	2	0	11	11
Nobel Curie	5	0	7	1	5	13
Total	116	29	14	5	46	164

Case 1 – Motorist stopped

Case 2 – Motorist waited

Case 3 – Pedestrian stopped

Case 4 – Pedestrian waited

Error – Objects could not be tracked or there was an error while tracking

It is worth mentioning that 38 of the 46 events classified as ‘not tracked’ belong to case 1 (motorists stopped), while 7 of them belong to case 3 (pedestrians stopped). It is also interesting to observe that the Nobel Curie roundabout had the highest number of ‘case 3’ interactions (7 considering tracked and not tracked cases); this can be explained by the geometry of the intersection: since it has two lanes per direction, pedestrians have to walk further to cross the road, making it possible for drivers to cross first by increasing their speed.

Table 7. Number of interactions of each case that could not be tracked

Location	Case				Total
	1	2	3	4	
Des Soeurs – du Golf	1	1	1	0	3
Des Souers – Rene Levesque	27	0	0	0	27
Frechette – Anne le Seigneur	8	1	2	0	11
Nobel Curie	1	0	4	0	5
Total	38	2	7	0	46

Case 1 – Motorist stopped

Case 2 – Motorist waited

Case 3 – Pedestrian stopped

Case 4 – Pedestrian waited

Because of the position of the camera, it was difficult to obtain accurate safety indicators when a vehicle stopped or reduced its speed far from the pedestrian crossing (case 1). It should also be noted that the measured vehicle speed represent in general only the speed shortly before and after the crossing given the limited field of view for pedestrian tracking.

For all the 114 interactions where a vehicle-pedestrian interaction was observed and the road users could be tracked, six basic indicators were computed: pedestrian positions, pedestrian speed, vehicle positions, vehicle speed and TTC.

Discussion of results

One of the basic outputs of Traffic-Intelligence software is the speed of objects. One interesting result based on this is that pedestrian speed at a crossing is lower when a vehicle is yielding: when a vehicle reduces its speed or stops completely (case 1), average pedestrian speed is 4.1 km/h; whereas when a pedestrian is yielding (case 3), average pedestrian speed is 5.4 km/h when crossing once the vehicle has passed. In those cases when vehicles or pedestrians wait for other users to cross, average pedestrian speeds are similar: 3.7 km/h for case 2, and 3.1 km/h when the vehicle has crossed for case 4.

Figure 2 shows the distribution of pedestrian and vehicle speeds across cases: in the case of pedestrians, the great majority of speeds are located between 3 and 6 km/h. Higher speeds in the case of pedestrians correspond to case 3 (pedestrian stops), where 25 % of speeds are higher than 9 km/h, which is considered a high speed for pedestrians.

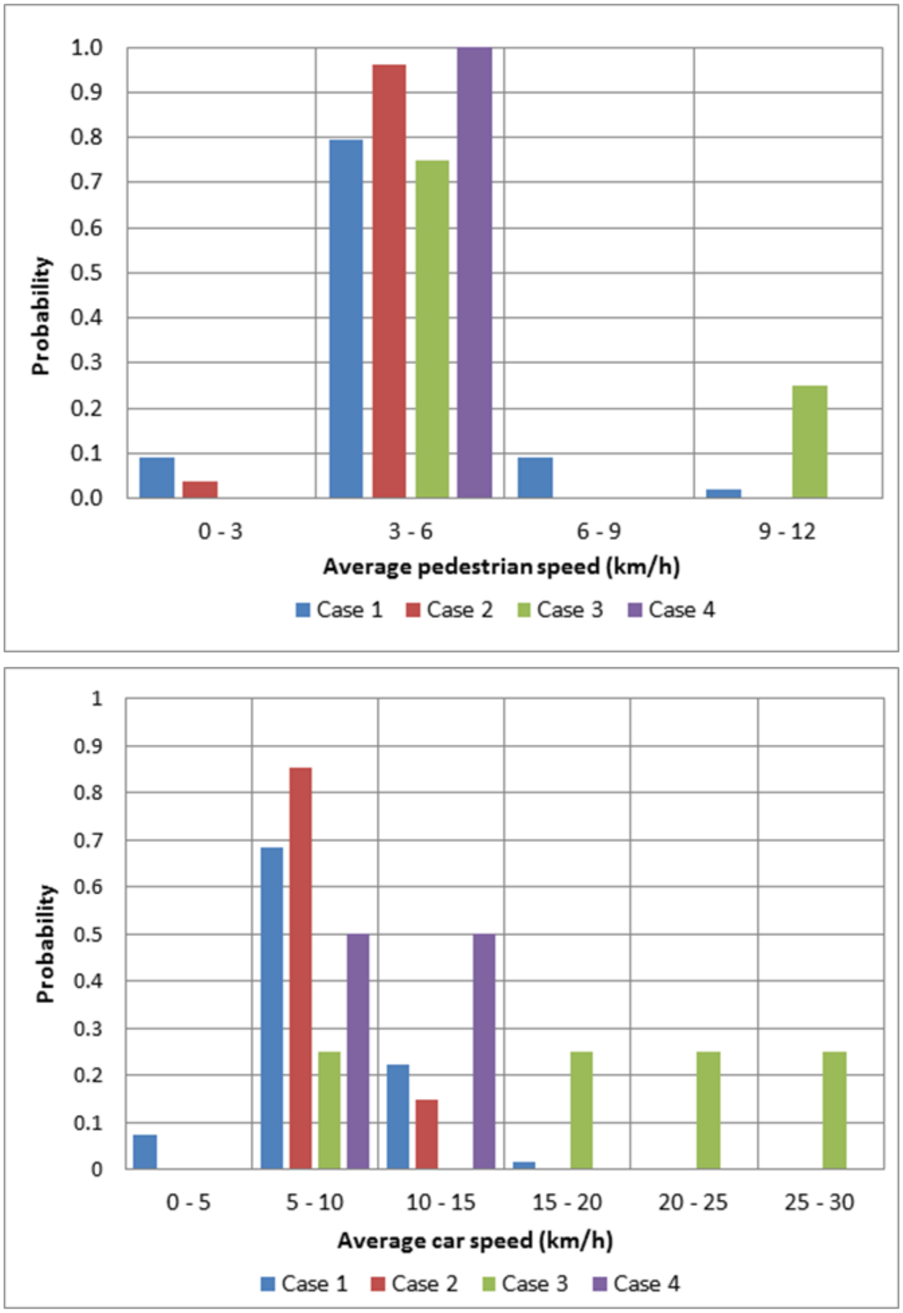


Figure 2. a) Distribution of average pedestrian speed per case; b) Distribution of average car speed per case

In the case of vehicles, most of their speeds in all cases are between 5 and 10 km/h; it is interesting to observe, in addition, that for case 3 (pedestrian stops), vehicle speed varies from 5 to 30 km/h. When vehicles yield to pedestrians (cases 1 and 2), average vehicle speed approaching the crossing is 7.9 km/h; whereas their average speed when pedestrians yield (cases 3 and 4) is 13 km/h. It is possible that faster vehicles make pedestrians stop and yield, or the other way around; under this circumstance the difference in speeds may explain why pedestrians tend to increase their speed at crossings when they had to yield to fast vehicles before. Such differences are more evident in Figure 3, which shows the distribution of average speed differential between vehicles and pedestrians across cases.

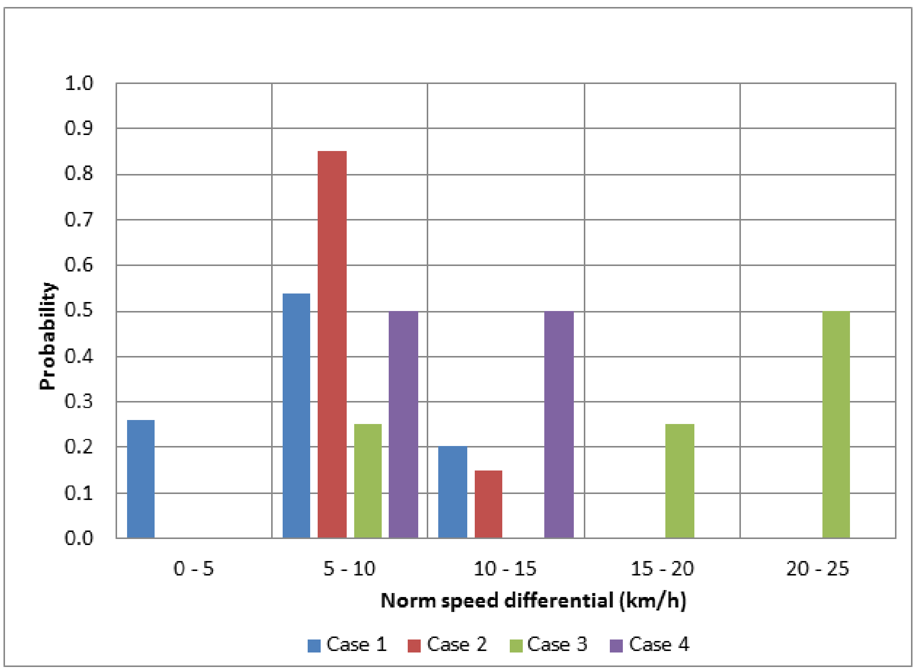


Figure 3. Distribution of average speed differential between pedestrian and vehicle per case

As shown, higher differences in speed correspond to cases 3 and 4; considering most pedestrian speeds are between 3 and 6 km/h (according to Figure 2,a), the speed differential is obviously dominated by the vehicle speed and it seems higher vehicle speeds make pedestrians yield. Nonetheless, it is difficult to be sure if pedestrians yield to fast vehicles, or if vehicles accelerate because drivers are aware pedestrians are yielding to them, even though this behavior is against road signalization that gives priority to pedestrians. Speed differential is also particularly relevant to the estimation of potential accident severity, which would increase for higher speed differentials, i.e. when pedestrian yields.

TTC could be computed in only four cases among the 114 interaction when using simple motion prediction methods, but could be computed for 83 cases using more robust methods taking into account the various paths that may lead road users to a collision (*40*). The distribution of the 15th centile of TTC, TTC15, for each interaction per case is presented in Figure 4. Although TTC could be computed for only 3 of the 5 interactions in case 4 could be tracked, it is obvious that they are by far the most dangerous. There are also few interactions with computed TTC15 in cases 2 and 3 which are safer. The largest share is in case 1, which is also the most common type of interaction. The distribution of TTC15 in case 1 is almost uniform in fact, but does also show some very close interactions with TTC15 well below 1.5 s.

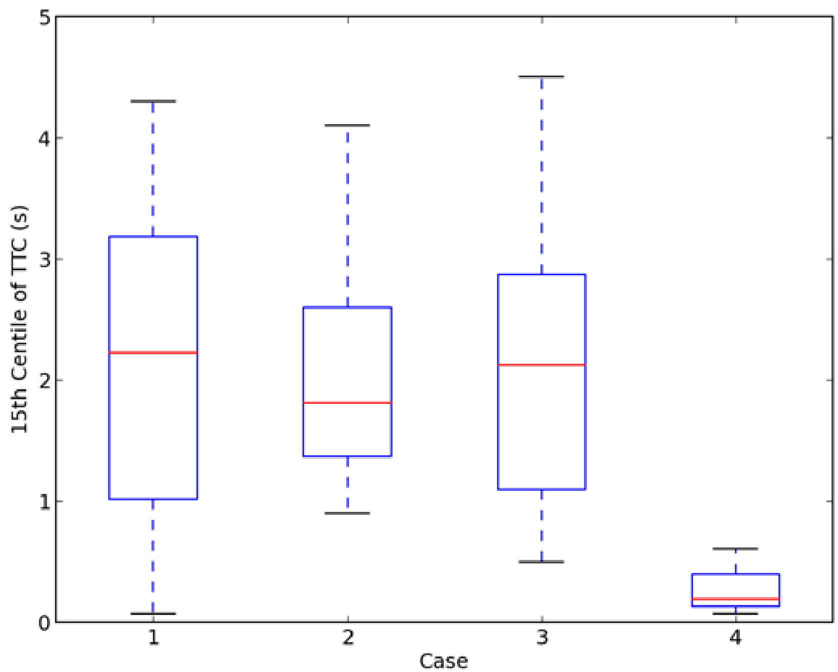


Figure 4. Distribution of 15th centile of TTC per interaction for each case

5.5. Conclusions and discussion

In general, it was observed that motorists tend to comply with roundabout signalization, which requires them to yield to pedestrians. Again, this observation has to be considered carefully, since the sample size is small in terms of motorist-pedestrian interactions, and because analyzed roundabouts are located in areas where pedestrian flow was not high. Yet, considering the total recording time, the distribution of events (tracked and not-tracked) when classified into cases demonstrates that the great majority of observed users (88 % considering cases 1 and 2) obey roundabout signalization (giving priority to pedestrians).

In addition to these findings about pedestrian and driver behaviour, this case study also provides important conclusions related to the use of automated video analysis software. First, it is necessary to keep in mind the kind of users the research is targeting through video recordings. As specified before, this study considered as input video recordings used in St-Aubin, Saunier, et al. (2013), which focused on motorized vehicles. Pedestrian analysis requires specific camera locations capable to get, at least, five main items:

- Pedestrian and vehicle movements when approaching the crossing
- Pedestrian movement when crossing
- Pedestrian and vehicle movement when leaving the crossing

Although automated video analysis and Traffic Intelligence have been successfully applied under different conditions as shown in the literature review, new recordings targeting pedestrians in roundabouts are needed to better characterize actual pedestrian safety and behavior in this kind of intersection. It is however difficult as roundabouts are still currently built in areas with limited pedestrian activity. In addition, considering that the starting point of this research was the work by Perdomo et al. (2014), a further step will be a comparison between perceived and actual safety of pedestrians and their factors in these intersections.

5.6. Acknowledgements

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6. CONCLUSIONS

Although each paper presented here contains its own results and discussion, it is worth mentioning some general conclusions considering the thesis document as a whole. This section presents such conclusions divided into three main parts: a discussion of the results obtained from both studies, the limitations found in each one, and perspectives for new research.

6.1. Summary of results

As observed in the literature review, the SP approach has not been used before to understand pedestrian preference with respect to roundabouts. The results from this study demonstrated that SP techniques cannot only be applied for this purpose, but their analysis can also produce valuable conclusions. Moreover, in terms of specific actions and policy making, marginal substitution rates can provide useful recommendations for improving safety perception in this kind of intersection. In addition, the survey demonstrates the use of 3D traffic simulations in the presentation of choice tasks and how they can be used to include difficult-to-communicate variables to respondents of these surveys.

Specific outcomes of the survey relate to preferences of pedestrian respondents towards low traffic volume and speed as well as the presence of flashing pedestrian crossing signs in roundabouts. Some of the outcomes (as seen in the manuscripts) confirm previous research findings. Although it is difficult to design roundabouts with all the characteristics preferred by respondents, it is well worth knowing which design features make these users feel safer. In addition, marginal substitution rates can be a priceless aid to know how to trade-off design features.

In the case of the observation of safety in roundabouts for pedestrians, this research suggests that motorists appear to comply with roundabout signalization, although the analyzed data was obtained from roundabouts with small numbers of motorist-pedestrian interactions. Richer conclusions might be available if specific research limitations are overcome in the future.

6.2. Research limitations

Research improvements can be achieved by studying the limitations of the two studies presented here. To be sure, the use of visual tools in presenting difficult-to-communicate variables in SP surveys is a field still in development, therefore the representation of more complex attribute (like pedestrian flow) were limited by the resources.

In the case of objective safety observation, it is necessary to keep in mind that the analyzed recordings originally focused on motorists, and not on pedestrian-vehicle interactions. This represented a limitation to the research, since not many pedestrian-motorists were identified. A greater number of this interaction would have yielded to the development of more detailed models.

6.3. Future Research Directions

There are different outcomes for this research that can provide useful ideas for future research. Firstly, the use of video generated from traffic micro-simulation software as a visual aid in choice task delivery showed the potential of such tools in SP survey development. Existing literature shows that these sorts of aids have been poorly explored, despite their potential. In this sense, future research can be done in terms of the development and the impact of such aids. Considering the comparison between the results of an SP survey with visual aids, to a traditional text survey under the same conditions and environment would be a first step to better understanding the advantages and disadvantages of these tools. Considering more complex attributes and including them in surveys with better techniques could also result in a better comprehension of user preferences.

In addition, a better understanding of pedestrian safety and behavior in roundabouts requires the collection of additional data. This could be done, for example, by undertaking new video data collection targeting pedestrian crossings at roundabouts. Pedestrian analysis requires specific camera locations capable of observing, at least, the pedestrian and vehicle movements when approaching the crossing, pedestrian movement when crossing, and pedestrian and vehicle movements when leaving the crossing. A wider sample of roundabouts would provide more inputs for analysis. Better recordings combined with the power of video and surrogate safety analysis can lead to a better knowledge of pedestrian safety in roundabouts; in addition, such knowledge can be useful to make a proper comparison between perceived and observed safety in roundabouts.

Although this research showed the level of importance and preference some safety elements have in roundabouts, it would be useful to evaluate if features that pedestrians prefer would, if implemented, really improve safety in the intersections. At this point it is only possible to assure that such changes would improve safety perception.

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