SURROGATE SAFETY STUDY OF QUÉBEC ROUNDABOUT MERGE ZONES

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Abstract

Implementation of roundabouts has been relatively new in North America, and especially so in Québec. As the original design of the roundabout originates from Europe, where a greater emphasis is placed on yielding behaviour and unsiganlized priority rules in intersection design, some degree of uncertainty remains regarding suitability of implementation of certain design features of the roundabout in a North American driving context.

This research aims to investigate the safety effects of various geometric design features, land uses, and traffic conditions on road safety for roundabouts in Québec. In order to achieve this, video data is collected at a large number of roundabouts across the major population centres of the province of Québec. The video data is analyzed automatically using computer vision to extract road user trajectories at various merging zones among the roundabouts sampled. Several dozen potential geometry, land use, and traffic factors are identified at each of these merging zones and 35 merging zones are instrumented and annotated in this way. Safety at each of these merging zone is quantified using surrogate safety methods, a proactive approach to road safety which makes use of road user trajectories to model potential collision courses from ordinary road user behaviour. Basic surrogate safety measures used in this work include driving speed and yielding post-encroachment time, but the more sophisticated time-to-collision measure, modelled using motion-pattern motion-prediction, is also included in this analysis.

Smaller roundabout aprons are found to be associated with higher speeds. Higher speed limits, are also associated with higher observed speeds, though only at a fraction of the posted increase. Irregular design of the merging zone, as well as presence of driveways on or immediately next to the merging zone is found to be associated with more serious conflicts (as measured by time-to-collision). Additionally, lane configuration and roundabout size is found to be less significant on the relevant safety factors than expected. Overall, geometric design and land use factors are found to be correlated with traffic conditions, which in turn are also found to be correlated with surrogate safety measures, suggesting some degree of interplay between all of these.

Résumé

La mise en œuvre des carrefours giratoires a été relativement récente en Amérique du Nord, et plus particulièrement au Québec. Comme la conception originale du carrefour giratoire provient de l'Europe, où l'accent est mis davantage sur le comportement de céder-le-passage et les règles de priorité, un certain degré d'incertitude subsiste quant à l'adéquation de certaines caractéristiques de conception du carrefour giratoire dans un contexte nord-américain.

Cette étude vise à étudier les effets sur la sécurité des diverses caractéristiques géométriques, des utilisations du sol et des conditions de circulation sur la sécurité routière des carrefours giratoires au Québec. Méthodes: Les données vidéo sont recueillies dans un grand nombre de carrefours giratoires dans les principaux centres de population de la province de Québec. Les données vidéo sont analysées automatiquement en utilisant la vision par ordinateur pour extraire les trajectoires des usagers de la route à différentes zones de fusion parmi les carrefours giratoire échantillonnés. Plusieurs douzaines de facteurs géométriques, d'utilisation du sol et de circulation potentielle sont identifiés à chacune de ces zones de fusion. 35 zones de fusion sont instrumentées et annotées de cette façon. La sécurité à chaque zone de fusion est quantifiée en utilisant des méthodes d'analyse substitutif de sécurité, une approche proactive de la sécurité routière qui utilise les trajectoires des comportements ordinaires des usagers de la route pour modéliser des collisions potentielles. Les mesures substitutives de sécurité utilisées pour cette étude incluent la vitesse, mesure de base, en plus de la mesure du temps-à-la-collision modélisée à l'aide du modèle de prédiction du mouvement basé sur les patrons de mouvements discrétisé

Une réduction de la taille des aménagements pour camions est associée à des vitesses observées plus élevées. De plus, une augmentation des limites de vitesse est également associée à des vitesses observées plus élevées, mais seulement à une fraction de l'augmentation affichée. La conception irrégulière de la zone de fusion ainsi que la présence d'allées sur la zone de fusion ou immédiatement à côté de celle-ci sont associées à une augmentation des conflits plus sérieuses (mesurés par le temps-à-la-collision). En outre, la configuration de la voie et la taille du carrefour sont moins importantes que prévu. Dans l'ensemble, la conception géométrique et l'utilisation des facteurs d'utilisation du sol sont corrélés avec les conditions de circulation, lesquelles sont également corrélées avec les mesures de sécurité de substitution. Il y a une forte interaction entre ces trois composantes.

1 Introduction

Roundabouts have been promoted as of late as a safer alternative to traditional traffic-light-controlled intersections, promising reductions in certain types of traffic conflicts, [specifically, fewer conflict points as per 26], citing accident history studies demonstrating reductions in serious vehicular collisions [12, 23, 10, 16], and reductions in observed speed [e.g. 12, 32]. However, since its inception in 1966 in the United Kingdom, roundabout adoption has been sporadic, primarily centred in Europe, almost ignored in North America until more recently. More importantly, the core design principle of the roundabout—yielding and implicit rules of priority—is virtually non-existent in the rest of North American road design: the traditional stop sign dominates intersection design philosophy. By contrast, European intersection design tends to favour yield signs or priority-to-the-right rules, though stop-sign implementation is not nearly as rare as yield signs are in North America. Given this large discrepancy in intersection design philosophy, and the driving habits that such differences foster, it begs the question if roundabouts are as beneficial in a North American driving context and if the benefits found in international roundabout safety studies can be fully replicated in North America, in either the short or long term.

In this paper, a microscopic study of road user behaviour and road safety is warranted of roundabouts involving North American drivers—who may not be familiar with either roundabouts or yielding at intersections in general. To this end, a surrogate safety study is devised. Surrogate safety analysis is a method of studying road user behaviour and road safety at a highly detailed level of analysis. The study of road user behaviour and collision mechanisms is a core component of the methodology [34], out of necessity, as it involves constructing highly detailed collision-course models between road users from ordinary road user observations in everyday traffic. Few, if any, studies have been attempted to examine the underlying collision mechanics at roundabouts at a microscopic level, except for possibly Sadeq, who examined a single roundabout extensively using automated trajectory data collection and a Traffic Conflict Technique-inspired analysis [28]. The method proposed in this paper uses a considerably more sophisticated method of modelling and predicting potential collisions and is also based on analysis of the "safety continuum" in place of discrete events.

1.1 Surrogate Safety

Surrogate safety is the study of road safety using alternative measures of safety to using historical accident records. This is desirable on the basis that real traffic accidents, especially serious ones, is not only undesirable but also on the basis that observing them as part of an experiment is of an ethically questionable nature. Furthermore, traffic accidents are rare events, often requiring years of data collection performed by third parties: this data comes with a host of practical issues with consistency, accuracy, and completeness. Surrogate safety is capable of compressing this data collection time into weeks, does not require accident observations at all, and can be conducted by the researchers themselves. The most widely-used surrogate safety measure is speed: it is widely accepted in the literature that as speed increases accident severity increases as well. In addition to speed, this paper will look at time-to-collision [11], one of the most popular surrogate measures of collision probability (as it describes speed-independent proximity of collision courses).

The study examines road user behaviour and road safety using measures of speed, yielding-specific post-encroachment time, and time-to-collision. These are chosen given their prevalence in the literature, and mostly context-independent nature. Time-to-collision is measured from modelled collision-courses, and so for this study, the Discretised Motion Pattern motion prediction model—created specifically for modelling collision courses in non-linear driving environments such as roundabouts—is used [31].

2 Literature Review

2.1 Roundabout Design

Roundabouts (not to be confused with traffic circles) are an example of a type of road infrastructure where traffic interactions are fully managed by the road users themselves [25], as opposed to stop sign or traffic light control. In fact, this—the road user-managed task of stopping and yielding at the approach of the intersection—is a distinguishing feature of the roundabout, especially in North America, where yield sign-controlled intersections or unsignalized intersections are exceptionally rare. Furthermore, the implementation of roundabouts in North America is a relatively recent phenomenon, unlike in Europe. For example, roundabouts in the province of Québec have only existed since 1998. Meanwhile, the first roundabout built in the United Kingdom, where the modern form of the roundabout was codified by the United Kingdom's Transport Research Laboratory, dates back to 1966.

In addition to alleged benefits regarding road safety, the most frequently cited operational benefits of roundabouts are [26]:

- fewer delays;
- offer better integration with existing traffic light coordination schemes;
- thus requireing fewer queuing lanes; and
- lack the complexity and maintenance required by installing traffic lights;

but also come with a number of disadvantages compared with traditional intersections [26]:

- for the same volume of traffic, besides a small reduction in necessary number of queueing lanes, roundabouts require a significantly larger footprint at the intersection proper;
- roundabouts have a maximum theoretical per-lane capacity smaller than that of ordinary traffic lights under certain circumstances; and
- multi-lane roundabouts have a number of road user and performance issues, and thus tend to scale poorly as the number of through lanes increases.

Given the small number of roundabouts and their relatively recent deployment in North America, and an overall different design philosophy with respect to intersection control in North America, issues with driver culture, driver education, and general road safety have been raised regarding roundabout adoption in North America. In response, several design guides have been published on the subject, including the National Coorperative Highway Research Program Report 572 [27] and Report 672 [26] and several localized guides including the Ministère des Transports du Québec's guide [19]. However, the number of North-America-specific studies remains small, especially in regards to understanding the underlying collision mechanisms that may be unique to North American driving behaviour and habits.

2.2 Roundabout Safety

In addition to the benefits outlined above, roundabouts are typically sold on alleged merits of safety. Reductions in accident severity have been widely reported in multiple studies investigating the effects of implementation of roundabouts [e.g. 12, 23, 10, 16] and it has been demonstrated in Swedish studies [12] that roundabouts might cause speed—a surrogate of accident severity—to be reduced (or at least normalised to 30 km/h). Furthermore, roundabouts have been proposed as a method for managing conflict points at intersections. Generally speaking, the design principle of the roundabout is to provide an at-grade intersection of two or more traffic corridors while minimizing the variety and locations of conflict generated [e.g. 26], especially the most problematic conflicts: left-turn conflicts, i.e. crossing an opposing stream of traffic head on. However, this type of qualitative analysis may be deceiving: while fewer *locations* ("points") and *types* of traffic conflicts are inherently derived from the roundabout design, it does not necessarily follow that fewer traffic conflict *events*—and thereby also collisions—occur overall (given the same volume of traffic).

In fact, arguably, more traffic conflicts are produced in the form of merging manoeuvres on the basis that road users must yield (interact) with one another, unlike at a traffic light, where interactions between road users are regulated by the traffic light explicitly. Stated more simply, the expected—and mostly predictable, but not perfect—behaviour of road users at a traffic light is to stop at the red light, resulting in fewer situations where right-of-way is contested. This is in contrast with yielding behaviour at the roundabout, where it is less explicit which road users have the right of way. The following design choice then arises: between two designs, one favouring a small but diverse number of (or serious) traffic conflicts, and another favouring a large number of similar (or less serious) traffic conflicts, which is more desirable? Many have argued in the literature that a greater number of low-severity events effectively *conditions* drivers to behave more cautiously overall. However, this then begs the question that if implementation is only partial (i.e. yielding behaviour at a small number of roundabouts amidst a landscape of stop signs and traffic lights) is the conditioning effect still effective? Such questions have yet to be addressed in further detail.

Some specific issues have been highlighted in the literature with roundabouts, particularly regarding vulnerable users: pedestrians and cyclists in general [12, 6, 5], and individuals with visual impairment more specifically, or regarding issues specific to crosswalk design [22]. These issues however are not a focus of this particular paper.

2.2.1 Accident Report-Based Studies

Despite eliminating left-turn conflicts [26] and generally reducing the rate of serious collisions [e.g. 12, 23, 10, 16, 27, 26], there is still some debate regarding the effectiveness in reducing the total number of collisions, both at the global and at the local level. A study by Jensen found a decrease in motor vehicle collisions but an increase in cyclist collisions [16]. Meanwhile, Daniels et al. found that accident rates differed from roundabout to roundabout for vulnerable users (pedestrians and cyclists) and that accident rate was highly correlated with traffic exposure in Flanders, Belgium [6]. Similar figures have been demonstrated in Victoria, Australia [5].

It's interesting to note that roundabout central island height has been cited as improving safety positively [17]. This result is counter-intuitive to classical safety models. Jensen argues that sight distances at the merging zone are sufficient, that the view of road users on the other side of the roundabout is superfluous information, and, if anything, acts as a distraction. Alternatively, if the view distances are not sufficient, it is argued that road users act more cautiously as a result.

Chen et al. [in 4] found that average approach speed was the most significant predictor of number of collisions and used a Bayesian Poisson-gamma and zero-inflated Poisson models to predict collisions (as a safety performance function). This study also found that roundabout diameter correlated with average approach speed, suggesting increases in expected collision probability (this inference is not entirely compatible with the safety framework presented earlier).

2.2.2 Surrogate Safety-Based Studies of Roundabouts

Usage of surrogate safety methods for roundabouts is more limited. Hydén and Várhelyi studied 21 roundabouts and found that speeds always reduced four months after implementation of the roundabout, although some gains in speed reduction were lost after four years [12]. Roundabout speeds tended to stabilize around 30 km/h; one roundabout approach with a before operating speed of 20 km/h saw its operating speed increase after implementation of the roundabout, suggesting that roundabouts might have a fixed influence on speed in their environment. This study suggested that these changes in speed had a negative impact on travel time and emissions for major streets, with gains on smaller streets. These observations have been confirmed at Quebec roundabouts in a preliminary manner as well [32].

The Swedish TCT was used by Sakshaug et al. to study traffic conflicts of cyclists and motorists in roundabouts. It was concluded that cycling within the roundabout caused issues with motorists exiting the roundabout when driving side-by-side with cyclist, while cyclist crossing the approach and exit next to the crosswalk caused yielding ambiguity.

An analysis of observed gap acceptance (e.g. acceptance of gap time, though used mostly in car following models) of a saturated multi-lane roundabout in Lund was performed using some manually-annotated video data to calibrate microsimulation software [13]. Although gap acceptance is to be revisited in this work in a derived form as an SSM of yielding primarily, gap acceptance also serves to calibrate flow models for basic traffic analysis purposes as it is a general purpose measure of traffic behaviour.

Al-Ghandour studied roundabout slip lanes using the Surrogate Safety Assesment Mdel along with Poisson regression to conclude that slip lanes reduce traffic conflict occurrence [1], though the question of whether this reduction in traffic conflicts leads to a reduction in collisions is not thoroughly addressed. It should be noted that the NCHRP design guide classifies roundabout slip lanes as non-standard, since they can induce conflicts with cyclists and pedestrians [26].

Of particular note is a thesis recently prepared [by 28] which studied a single roundabout extensively using video tracking and TCT. The methodology still relied heavily on manual interaction interpretation and a form of serious event comparison. Use of serious event comparison is problematic, but this thesis is still remarkable for exploring traffic violations at roundabouts in great detail.

The perceived safety of roundabouts is also mixed in the context of North America. Jacquemart and Pellecuer and St-Jacques cite issues of driver education, practical complaints with the design, and uncertainty regarding the safety benefit [15, 21]. However, Jacquemart argued that opinions would change upon implementation as users had an incomplete or incorrect understanding of what a roundabout is and how it works. Retting et al. studied the effects of various factors on perceived safety including signalization and design [24] and postured that the most prevalent problem was unsuitability of the design to the particular needs of the intersection. Meanwhile, Perdomo et al. performed stated preference surveys with vulnerable road users and concluded that presence of pedestrian-oriented design features, such as cross walks and crossing lights had a large effect on pedestrian preference [22], though it remains to be seen if this effect is large enough to effect a significant modal shift or trip re-routing.

3 Methodology

3.1 Merging Zone as a Unit of Analysis

At the macroscopic level, roundabouts operate in a similar fashion to ordinary intersections serving two or more traffic corridors. However, unlike traditional four-way intersections, instead of mixing all traffic movements from all approach within the same space by alternating the right of way of conflicting movements explicitly (either one road user at a time with stop signs or platoons of road users via traffic lights), roundabouts isolate conflicting movements physically, placing them into separate *merging zones*, effectively removing left-turn displacements across a conflicting movement. In this way, road users proceed counter-clockwise (in right-driving jurisdiction) around the ring, passing successive exits until they arrive at their desired exit. This effect is not only created physically [26]: it has also been demonstrated that central island height contributes positively to a reduction in the number of observed collisions on the basis that removing visual distractions and forcing the road user to pay attention when approaching the intersection reduces more serious conflicting interactions [17].

Given this,

- that the scope of analysis of individual merging zones is more relevant to investigating individual collision and collision course mechanisms than the roundabout in aggregate;
- that roundabouts are roughly symmetrical in design, incorporating a sequence of merging zones arranged in a ring, with one merging zone for every roundabout approach and exit pairing (usually);
- that despite apparent symmetry, a great deal of variability in potential contributing factors exist from one merging zone to the next, and that these differences are easily parametrized;
- that road user interactions are generally isolated between opposing sides of the roundabout; and
- a desire to study road user behaviour at a great level of detail,

merging zones are chosen as a unit of analysis for this study. The merging zone is defined, as it was in preliminary work [32], as: the segment of the road where approach and exit lanes overlap with ring roads, thereby forcing road users to interact (and yield) over limited physical space. A typical roundabout merging zone is illustrated in Figure 1. In the narrowest sense, the merging zone includes only that portion of space where the approach and exit lanes overlap with the ring lanes. However, in the general sense, the merging zone also includes sufficient distance upstream of the point of junction of the overlapping lanes to include any road users immediately intending to enter the roundabout.

3.2 Potential Contributing Factors

Given the purpose of this study—that is, to explain aspects of road safety from elements of geometric design and land use at roundabout—an inventory of design elements typical at roundabouts and roundabout merge zone and constituting potential contributing factors to road safety is produced. These factors were first identified in [32]. Some of these factors, particularly environmental

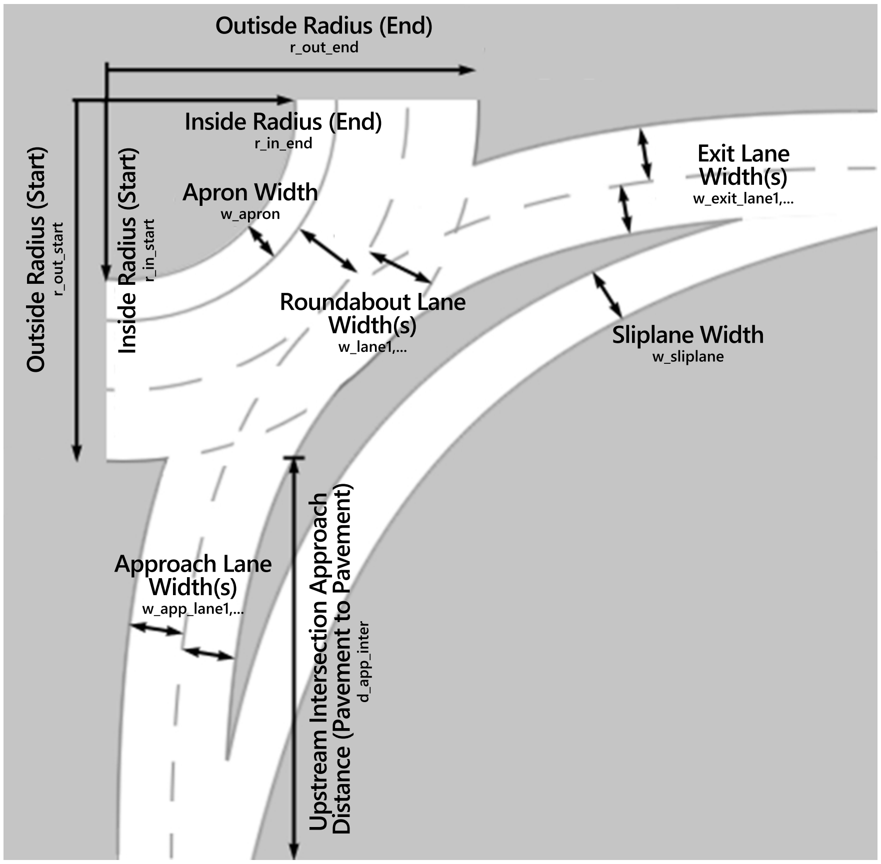

Figure 1: Typical design features of a roundabout merge zone.

factors are shared for all merging zones at the same roundabout, while others are unique to the merging zone.

Among potential environmental factors, land use, network classification, and urban density are identified and recorded. Land use is stratified into 6 basic land use types following the descriptions in Table 1

Table 1: Geometric Factors

Land Use Classification	Characterisation
lu1	Vacant land devoid of any use other than for transportation. This is typical of round
lu2	Residential land use of all types, including detached housing and multi-unit housing
lu3	Commercial land use of all types, including big-box stores, office space, and small,
lu4	Industrial land use of all types, from manufacturing to resource extraction.
lu5	Mixed land use. In practice, this typically means a roughly equal mix of residential a
lu6	Institutional land use, covering a range of public services building such as hospitals

Roundabout surrounding road networks are classified according to the designation of the primary traffic corridor passing through it (the corridor with the highest annual average daily traffic). Roundabouts can be found attached to the following types of road networks:

- Network classification type 1 (`nc1`) is the smallest and most basic road network: the roundabout is part of a road network with only collector roads.
- Roundabouts with a network classification type 2 (`nc2`) designation can be found attached to at least one arterial road, including avenues and boulevards.
- Roundabouts with a network classification type 3 (`nc3`) designation can be found attached to at least one regional, undivided highway (e.g. with speed limits of 70 to 90 kmh).
- By design of a limited-access-highway, roundabouts cannot be attached directly to a limited-access-highway. However, they can be found near limited-access-highways serving as interchanges with on-ramps and off-ramps feeding into them. These roundabouts are designated network classification type 4 (`nc4`).

For the purposes of this study, urban density is measured very roughly from the buildings in the vicinity of the roundabout (within a distance of about 1 km). In this manner, urban density can be classified into the following four classifications:

- Roundabouts with a density type 1 (`d1`) designation have no buildings at all in the vicinity. There is significant overlap of this type of roundabout with roundabouts with land use type 1 and type 4 designations (mostly composed of rural roads and inter-city roads, respectively).
- Density type 2 (`d2`) is characterized by detached housing; small, single-story businesses; or farms.
- Density type 3 (`d3`) is characterized by semi-detached housing; medium-sized businesses; heavy-industry; or institutional land use.
- Density type 4 (`d4`) is characterized by multi-story buildings (10 or more). Given the large footprints of roundabouts, these are exceedingly rare in very dense environments.

The geometry factors identify a number of characteristic roundabout features parameterizable at the merging-zone level, including lane configuration, lane and apron widths, approach distances and speed limits, various radii, and other special features. These are listed in Table 2 and illustrated in Figure 1.

Finally, a number of traffic flow parameters are obtained from the traffic data collected at each merging zone. This includes basic observations of traffic intensity as well as derived variables representing levels of traffic mixing at each approach. For example, the flow ratio Q_r is calculated using

$$Flowratio = \frac{Q_{app} - Q_{conf}}{Q_{app} + Q_{conf}} \tag{1}$$

where Q_{app} and Q_{conf} represent the observed approach and conflicting flows respectively. The absolute value of the flow ratio $|Q_r|$ thus indicates how polarised traffic demand is between the approach and the roundabout ring. Meanwhile, the approach flow dominance Q'_r, which normalises Q_r between 0 and 1, indicates to what degree traffic favours the merging zone approach lanes. A full list of potential factors are summarised in Table 3.

Table 2: Geometric Factors

Variable (merge zone)	Factor description	Type (Units)
b_quad_type	Merge zone only contains an exit	Categorical
n_start_lanes	Number of start (conflicting) lanes	Numerical
n_end_lanes	Number of end (conflicting) lanes	Numerical
n_app_lanes	Number of approach lanes	Numerical
n_exit_lanes	Number of exit lanes	Numerical
n_slip_lane	Number of slip lanes	Numerical
b_app_med_type	Median type (0=raised, 1=painted)	Categorical
b_driveway	Presence of a driveway on merging zone	Categorical
a_quad_size	Angular size of merge zone	Numerical (°)
r_out_start	Outside diameter at start of merge zone	Numerical (m)
r_in_start	Inside diameter at start of merge zone	Numerical (m)
r_out_end	Outside diameter at end of merge zone	Numerical (m)
r_in_end	Inside diameter at end of merge zone	Numerical (m)
w_apron	Width of apron	Numerical (m)
w_lane1	Width of lane 1	Numerical (m)
d_app_inter	Upstream distance to nearest intersection	Numerical (m)
app_speed_limit	Mandatory speed limit on approach	Numerical (km/h)

3.3 Behavioural Measures

The measures of performance used for this particular study are three of the most commonly used and generalizable surrogate safety measures: speed, post-encroachment time ($yPET$), time-to-collision (TTC) [11]. Note that $yPET$ is an ordinary PET measure [2] but is designated $yPET$ as, in the context of roundabouts, it is measured specifically at the merging zone yield line, where encroachment is prohibited by way of mandated yielding on the part of the approaching road user only. Other than this selection criterion, it is comparable to any other standard PET measure. Speed and $yPET$ are measured directly from the observed road user trajectories as they occur.

Speed is widely regarded in the literature as a useful predictor of collision severity [e.g. 9, 7] given the relationship between speed and kinetic energy carried by a road user in motion. Meanwhile, TTC, measured in units of time, is one of the most popular surrogate safety measures intended as a generalized predictor of collision probability as it models "near-miss" situations between any types of road users travelling anywhere, at any speed. It is most easily understood as remaining time before a potential collision ensues before a road user imitates evasive action (if at all). In its most basic form, constant velocity modelling [3], TTC is the distance between any two road users, at any time, divided by the differential speed between the two.

Like TTC, $yPET$ is measured in units of time and describes "near-miss" situations in a similar fashion to TTC. However, unlike TTC, this is performed without making any assumptions of motion, relying exclusively on observed behaviour It is thus less flexible in modelling as great a variety of potential outcomes without significantly larger quantities of observed data. Nevertheless, $yPET$ is of interest as a model of yielding behaviour and merging aggressivity as it is greatly

Table 3: Indicators Characterizing Demand and Traffic Ratios at Roundabouts

Variable (aggregated to the unit of analysis)	Factor description	Type (Units)
`flowratio`	Ratio Q_r of approaching and conflicting flow	Numerical $\in [-1, 1]$
`absflowratio`	Absolute value $\|Q_r\|$ of the ratio of approaching and conflicting flow	Numerical $\in [0, 1]$
`approach_dominance`	Approach flow dominance Q'_r	Numerical $\in [0, 1]$
`approach_flow_ph`	Hourly approach flow Q_{app}	Numerical (veh/h)
`conflicting_flow_ph`	Hourly conflicting flow Q_{conf}	Numerical (veh/h)
`inflow_phpl`	Hourly traffic volume Q normalized for number of lanes	Numerical (veh/h)

associated with gap time and gap acceptance. Note that $yPET$ values can be of any size, given that the only requirement is that the road users forming the crossing paths be successive in their arrival. If demand is low, some of these arrivals may be minutes apart and would thus obviously hold no value in interpreting interaction safety. To counter this a conservative minimum criteria of consideration $\zeta_{PET} < 5$ seconds on $yPET$ is used. This value is arbitrarily selected to reject those interactions where it is very clear that road users are not coexisting in time and space (the dwell time across each merging zone rarely surpasses 5 seconds).

In addition to the surrogate safety measures outlined above, additional measures of behaviour describing instantaneous collision-course conditions are stored alongside each collision-course model (i.e. each TTC measure). These include 15-second exposure, a micro-measure of exposure, which counts the number of road users present within the merging zone 7.5 seconds before and after the collision course is modelled, as well as intersection angle, which measures the angle of approach of the road users at the instant of the collision course in degrees. This angle is $0°$ when the road users are following each other and $180°$ when approaching others head on.

3.3.1 Advanced Time-to-collision Modelling and Aggregation

As stated previously, TTC makes use of collision-course prediction models. Typically, potential collisions are defined as collision-course events using constant velocity motion prediction, i.e. "with movement remaining unchanged" [3]. Given the non-linear driving required to navigate the deflection induced by roundabout central islands and approaches, a more sophisticated collision-course prediction model is used in this work instead: the discretized motion pattern motion prediction model developed specifically to address the issues of modelling movement in complex environments [31] i.e. TTC_{cmp}. It should be noted, however, that TTC_{cmp} is by no means specific to roundabouts.

Furthermore, as was discussed, collision-courses and TTC_{cmp} are modelled and measured continuously, unlike measures of yPET which result in a single measure between any two road users. Furthermore, multiple collision courses might be modelled at any one instant, resulting in multiple potential measures and collision points for any single instant of interaction between two road users. Probabilistic collision-course modelling, as in the case of discretized motion patterns, handle issues of multiple collision-courses by aggregating these measures of TTC_{cmp} via a weighted average of collision-course probability [31].

Regardless of prediction method, this still leaves continuous values of TTC over the time series of instantaneous interactions between any two road users. The general approach to handling this issue is to represent the entire timeseries with a single instant-aggregated value, typically the minimum (i.e. most severe) value at any instant in the timeseries [e.g. 18]. This however is somewhat sensitive to noisy data and outliers, and as such a n^{th}15-centile value, $TTC_{15^{th}cmp}$, might be used instead [30].

Table 4 lists a number of instantaneously measured parameters that further describe collision course factors to be analyzed in regression analysis along with ordinary contributing factors.

Table 4: Instantaneous Interaction (Traffic) Parameters Collected when measuring Collision Courses

Variable (instantaneous)	Factor description	Type (Units)
`fifteen_second_exposure`	Number of road users in the merging zone 7.5 seconds before and after the collision-course instant	Numerical (veh/15 s)
`interinst_angle`	Instantaneous angle between road users on a collision-course	Numerical (°)
`lower_inst_speed`	Instantaneous speed of the slower road user between two road users on a collision-course	Numerical (km/h)
`higher_inst_speed`	Instantaneous speed of the faster road user between two road users on a collision-course	Numerical (km/h)

3.4 Traffic Data Collection

Traffic data collection is performed using a video-based automated large-scale road user trajectory data collection system [14, 30]. This computer-vision based system collects the positions of all road users within the field of view of the camera continuously automatically. The system emphasizes mobility and affordability, aiming for rapid deployment over as many sites as possible instead of long-term deployment. In fact, data is typically collected at each site for no more than a single day, i.e. a workday between 6 A.M. and 8 P.M. Road users are tracked automatically in the video data using purpose-built computer vision as implemented in the Traffic-Intelligence project (specifically feature-based-tracking) and then projected into world space using a homography [29]. An example of the tracked positions of a sample of road users projected into world space is illustrated in Figure 2.

For this research, 23 roundabouts are visited, at each of which one or more merging zones is instrumented, resulting in 35 usable merging zones for this study. The roundabouts visited are located throughout the province of Québec, sampling various urban and rural environments and located on an even share of municipal and provincial jurisdictions.

The size of data used for this study are summarized in Table 5. Overall, 196,808 road users are captured as part of this study. Given the highly mobile and short-lived data collection at numerous geographically diverse locations, and assuming typical commuting habits, it is generally estimated that about half of these road user observations are unique.

Table 5: Québec Roundabout Data Inventory

Data collection		
Roundabouts visited	23	
Camera views	52	
Merge zones/analysis zones	35	
Total hours of video (pre-analysis)	534.2 h	
Disk space usage		
Video data	1,518,854 MB	(2,568 files)
Trajectory data	289,411 MB	(909 files)
Trajectory Data		
Unique road users	196,808	
Vehicle-kilometres travelled	11,519.1 veh-km	
Duration (analysis)	435.6 h	
Interaction Data		
User pairs	176,749	
User pairs with $TTC_{15^{th}cmp}$	32,650	

4 Experimental Results

Before a regression analysis is performed, a test of correlation is performed on each of the three (dependant) surrogate safety measures: speed, $yPET$, and $TTC_{15^{th}cmp}$. The premise in using all three parameters in a road safety study is that they should capturing different aspects of road safety, e.g. collision probability versus collision severity. A Spearman's correlation analysis is performed on the aggregated values at the site level and the results are presented in Table 6. The results do indeed suggest at the very least that these parameters are mostly independent from one another.

Table 6: Spearman's Correlation of Merging Zone-Aggregated Surrogate Safety Measure Indicators

	Mean speed	**Median Lag** $yPET_{\zeta<5}$	**Mean** $TTC_{15^{th}cmp}$
Mean speed	1.0000		
Median Lag $yPET_{\zeta<5}$	0.2640	1.0000	
Mean $TTC_{15^{th}cmp}$	-0.3242	-0.0769	1.0000

Next, an analysis of correlation is performed across all potentially contributing factors. Of the geometric factors, `r_in_start`, `r_out_end`, and `r_in_end` are removed, as they are ultimately very highly correlated (> 0.95) with `r_out_start`. Furthermore, `w_lane1` is found to be correlated with `n_start_lanes`, but not greatly so (-0.62). Indeed, at some of the roundabouts visited, many single-lane approaches had disproportionately large lane widths.

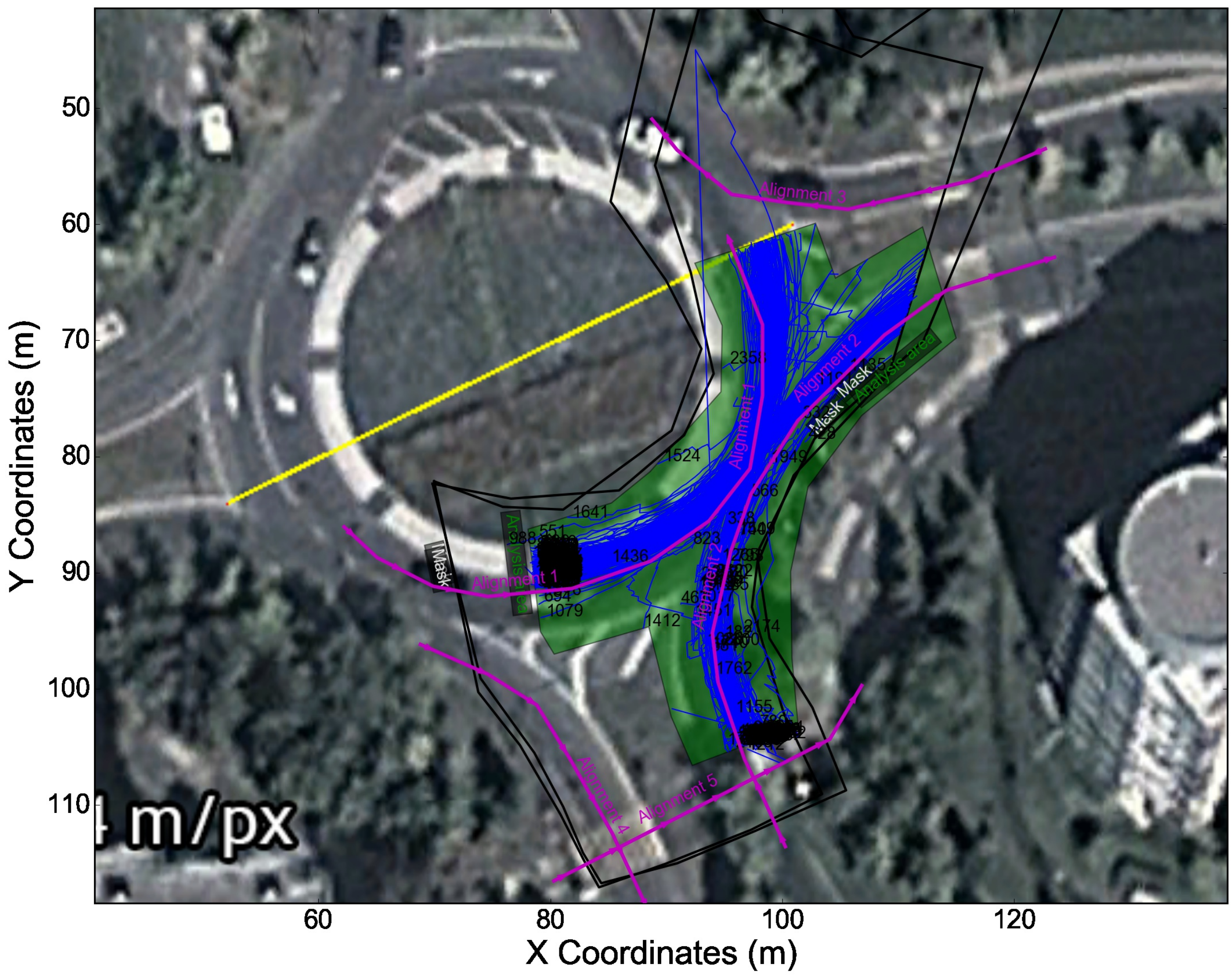

Figure 2: Trajectory data, image-space masks, and corresponding meta data coverage at a Swedish roundabout using two cameras.

Other significant correlations found include:

- `n_start_lanes` and `n_end_lanes`, which can be explained by the fact that adding or removing lanes is less frequent within the roundabout than at the approach and exit, but still not entirely uncommon.
- `nc3` and `app_speed_limit`, which is unsurprising given that the network class 3 designation is a speed limit of 70 to 90 km/h almost by design.
- `lu5` and `r_out_start`, which is a little surprising, although potentially coincidental and perhaps not explained by a causal relationship, given that the number of roundabouts classified as `lu5` is small (5) and contains a large share of converted traffic circle.
- `lu4` and `nc3`, which can easily be explained by the fact that a large share of the industrial sites are in resource extraction, and the sites are accessed predominantly via regional highways.

- nc2 and n_start_lanes, which can be explained by the fact that a large share of arterial roads host two lanes of traffic in either direction.
- nc3 and w_apron, which is a bit unexpected, but can be explained by the fact that almost all regional highways are managed by the provincial transportation agency and that implementation at these roundabouts appears to be templated (e.g. apron width is a feature implemented primarily to facilitate the movement of trucks, which are common on regional highways, for the same reason that heavy industry is associated with nc3).

4.1 Speed

A stepwise linear regression is performed on mean road user merging zone speed (measured in km/h) for all road users, against potential geometry, traffic, and land use parameters outlined earlier. Given observations regarding the relationship between built environment, traffic parameters, and road safety made in the literature [8, 20, 33], and repeated observation of this trend in the roundabout data, two models are attempted: a model focusing on geometry and land use, and a model focusing on traffic only. The coefficients of regression, adjusted R^2, Wald test score, and number of observations are provided in Table 7.

Table 7: Linear Regression Model for Mean Speed

Model	**Geometry-only model**		**Traffic model**	
	Coefficient	$P > \|t\|$	**Coefficient**	$P > \|t\|$
_cons	27.69	0.000	27.815	0.000
app_speed_limit	.1222	0.022	-	-
b_quad_type	20.02	0.000	-	-
d2	3.017	0.030	-	-
n_slip_lane	-9.135	0.024	-	-
w_appron	-1.196	0.005	-	-
approach_dominance	-	-	7.355	0.079
Adjusted R^2	0.5396		0.0629	
Wald Prob. $> F$	0.0000		0.0000	
Observations	35		35	

Regressing only for geometric and land use factors leads to a moderately predictive model, with an adjusted $R^2 = 0.540$. Significant factors associated with increases in mean merging zone speed include

- an increase in speed limit, though by only a tenth of the rate, corroborating the school of thought that holds that posted speed limits have only a marginal effect on modifying road user speeds;
- irregular merging zone shape, or more specifically, one approaches serving two exits;
- medium urban density;
- lack of a slip lane, though the speed on the slip lanes is not captured; it is possible that movement type (iv) road user travel faster and are simply not captured in this sample, and

furthermore, as stated earlier, caution is warranted when interpreting this factor, as the number of samples is very low; and

- shorter apron widths.

The traffic-parameters-only model provides poor predictive power, but it does suggest that approach dominance is positively correlated with mean speed road user merging zone, affecting up to just over 7 km/h.

Shorter apron widths are known, through experimental observations and inspection of trajectory maps, for causing issues with the reduced deflection of road user, and thus straighter and faster through-movements by road users.

4.2 Time-to-Collision

A random effects regression of the log of $TTC_{15^{th}cmp}$ is performed using two models: approach dominance along with non-collinear geometric factors, and a traffic parameters-only model (since most geometric parameters are captured by at least one of these traffic parameters and the remaining factors are not found to be significant). The random effects regression model takes the shape of

$$ln(TTC_{15_{ij}}) = \alpha + \sum_{k} \beta_k X_{kij} + u_{ij} + \epsilon_{ij} \quad (2)$$

for $j = 1, ..., m$ pairs of road users and for sites $i = 1, ..., n$ (merging zones), where α is the model intercept, β_k is the coefficient of factor X_{kij} for $k = 1, ..., m$ factors, u_{ij} is interaction-specific random error (also referred to as the *between* error), and ϵ_{ij} is the "ordinary" regression error (also refereed to as the *within* error). The random effects model adjusts the fixed-effects model with the between-effects model. It models the mean response from means calculated from the interaction for each group. In this way, the random effects model is a weighted average of the fixed-effects and between-effects models. Modelling results are shown in Table 8. Both models are reasonably good predictors of $TTC_{15^{th}cmp}$, especially between panels (merging zone factors). The within (individual road user) effects offer mediocre predictive power, but suggest that $TTC_{15^{th}cmp}$ increases—and therefore collision probability hypothetically decreases—with increased 15 second exposure (i.e. the "safety in numbers" effect).

Increased speed of the *slower* road user (`lower_inst_speed`) at the instant of the collision course is found to be associated with lower $TTC_{15^{th}cmp}$. The same cannot be said for the speed of the *faster* road user; however, this does not suggest that the differential velocity does not play a factor. It should be noted that the speed of either road user is found to be moderately correlated (0.695). This is not surprising, given that some degree of homogeneity should be expected of similar road users in the same environment, e.g. motorists in a roundabout with a single posted speed limit, but that some variation should exist too, e.g. variation in individual road user characteristics and different yielding rules between lanes.

The between effects are as follows:

- An increase in merging zone size (`a_quad_size`) and roundabout radius (`r_out_start`) is associated with increases in $TTC_{15^{th}cmp}$.

- Presence of a driveway (b_driveway), an irregular merging zone design (b_quad_type), and medium urban density (d2) are associated with a decrease of $TTC_{15^{th}cmp}$. The first two parameters are non-standard design features and should be avoided. Urban density may reflect generally increased road user activity and thus interaction complexity.
- In the traffic model, it can be seen that when traffic flow favours the approach, or, alternatively, when traffic flow is more balanced between the approach and merging zone start (absflowratio), $TTC_{15^{th}cmp}$ increases. It is possible that when traffic flow is very unbalanced towards the conflicting flow, approaching road users must wait longer (yield) for a gap and may take more risks. It is worth reminding that approach_dominance and absflowratio are modestly correlated (0.38), meaning that there is a small amount of overlap in the results between these two factors.

Table 8: Random Effects Regression Models for Motion Pattern-based n^{th}15 Centile Time-to-Collision

Model	Global model		Traffic model	
	Coefficient	$P > \|t\|$	**Coefficient**	$P > \|t\|$
_cons	-	-	0.8326	0.000
a_quad_size	0.0063	0.012	-	-
b_driveway	-0.6915	0.000	-	-
b_quad_type	-0.6868	0.033	-	-
d2	-0.1864	0.069	-	-
r_out_start	0.0132	0.022	-	-
approach_dominance	0.5006	0.028	0.8154	0.002
absflowratio	-	-	-0.5930	0.007
fifteen_second_exposure	0.0151	0.000	0.0151	0.000
interinst_angle	0.0029	0.000	0.0029	0.000
lower_inst_speed	-0.0179	0.000	-0.0179	0.000
Within R^2	0.1245		0.1245	
Between R^2	0.6709		0.4220	
Overall R^2	0.2515		0.1338	
Wald Prob. $> F$	0.0000		0.0000	
Observations	32111		32111	
Groups	35		35	

4.3 Yielding Post-Encroachment Time

A stepwise linear regression is performed on median lead and lag $yPET_{\zeta<5}$ at each site. Recall that $yPET_{\zeta<5}$ is not very normally distributed (it is at the very least a mixture model with a normal and some negative exponential components), so median aggregation is preferred.

Median lead $yPET_{\zeta<5}$ for approach road users could not be explained by any geometry, land use, or traffic parameter, except for hourly traffic volume, and only barely, with an adjusted $R^2 = 0.0780$, and a coefficient of 0.0027 with marginal statistical significance. It seems that the tendency for approaching road users to enter and follow conflicting flow road users at typical saturation headway (2 s) is unaffected by external factors.

Median lag $yPET_{\zeta<5}$ observations are a different story however. It seems that lag $yPET_{\zeta<5}$ can be explained by merging zone characteristics. A stepwise linear regression is performed on median lag $yPET_{\zeta<5}$ across all merging zones. The results are shown in Table 9. Recall that the smaller the $yPET_{\zeta<5}$ measure is, the closer road user interact with one another: more specifically, lag $yPET_{\zeta<5}$ is the time an approaching road user has before the next conflicting road user, which always has priority, enters the same space.

Table 9: Linear Regression Model for Median Lag Gap Below 5 seconds

	Coefficient	$P > \|t\|$
`_cons`	1.657	0.000
`app_speed_limit`	-0.0137	0.037
`b_driveway`	-1.022	0.003
`d4`	-1.276	0.037
`nc4`	-0.579	0.034
`w_lane1`	0.203	0.002
Adjusted R^2	0.4085	
Wald Prob. $> F$	0.0011	
Observations	35	

From these results, it can be deduced that significant reductions in $yPET_{\zeta<5}$, and hence hypothetical increases in collision probability, is associated with

- an increase in the speed limit (e.g. a 10 km/h increase yields a 0.1 s median $yPET_{\zeta<5}$, though it is interesting to note that the measured road user mean speed is *not* significantly associated with lag $yPET_{\zeta<5}$ (possibly explained as the speed limit being a proxy for other factors);
- presence of a driveway, within or in the immediate vicinity of the merging zone, a practice that should be avoided, even if only to reduce road user trajectory negotiations;
- high urban density;
- limited-access-highway ramps, possibly explained by road users exiting the highway and who have not quite transitioned into non-highway behaviour;
- a decrease in lane width. This is somewhat contradictory to what is expected: as lane width decreases, lane sharing, i.e. being within the same designated lane, is expected to decrease , resulting in more uniform arrivals. More investigation is needed with regards to this.

5 Conclusion

In this paper, a surrogate-safety study of Québec roundabouts is presented in an effort to investigate North American suitability of the roundabout design despite significant differences in roundabout design philosophy and traditional North American intersection design philosophy. It was demonstrated that roundabout geometry and land use are reflected in traffic parameters, and that these traffic parameters are in turn reflected in the various aspects of road safety via several measures of surrogate safety.

Regression models were prepared in order to explain surrogate safety measures from traffic factors (inflows, flow ratios, etc.) and geometry and land use factors. A number of factors were found to be associated with one or more elements of road safety. Generally speaking, it is found that small aprons (consequently generating poor road user deflection at the merging zone approach) result in higher observed road user speeds. Increasing posted speed limits is found to be associated with proportional increases in speed, though only at a rate of one tenth the posted speed limit. Designs which deviate from typical roundabout design, such as irregular merging zone configuration, are found to be associated with higher speeds and lower TTC measures, while the presence of driveways on or immediately near merging zones is associated with reduced yPET and TTC measures. Consequently, these designs should be avoided. In the case of one-way roads attached to a roundabout causing irregular merging zones, merging issues might be mitigated with larger merging zones and a more homogenized flow. The effect of lane width on yPET and presence of slip lanes is somewhat uncertain and will require further investigation.

Furthermore, while simple conversion of traffic circles into roundabouts (without effecting comprehensive geometry changes) was not parametrized in these models, this factor was found, through cluster analysis, to be associated with poor TTC measures. As a result, the recommendation of avoiding this practice in general is made, as the original physical dimensions of the traffic circle rarely meet the design requirements of the basic roundabout design.

Use of the merging zone as a unit of analysis for roundabouts is novel (besides precursory work), given the microscopic nature of the surrogate safety methods used. However, its use does increase complexity for comparison with non-roundabout intersections. In this work, conclusions about roundabout design were derived from a cross-sectional examination of existing roundabouts. A future study will implement the same methodology to a before-after study of a roundabout intersection conversion.

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