Large-Scale Microscopic Traffic Behaviour and Safety Analysis of Québec Roundabout Design

Paul St-Aubin, ing. jr, Ph.D. Candidate (Corresponding author)
Department of civil, geological and mining engineering
École Polytechnique de Montréal, C.P. 6079, succ. Centre-Ville
Montréal (Québec) Canada H3C 3A7
Phone: +1 (514) 885-7285
Email: paul.st-aubin@mail.mcgill.ca

Nicolas Saunier, ing., Ph.D., Assistant Professor
Department of civil, geological and mining engineering
École Polytechnique de Montréal, C.P. 6079, succ. Centre-Ville
Montréal (Québec) Canada H3C 3A7
Phone: +1 (514) 340-4711 ext. 4962
Email: nicolas.saunier@polymtl.ca

Luis F. Miranda-Moreno, Ph.D., Assistant Professor
Department of Civil Engineering and Applied Mechanics
McGill University, Macdonald Engineering Building
817 Sherbrooke Street West, Montréal, QC, H3A 2K6 CANADA
Phone: +1 (514)-398-6589
E-mail: luis.miranda-moreno@mcgill.ca

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ABSTRACT

Roundabouts are a staple of European road design with many international studies demonstrating important reductions in collision severity and, to a lesser extent, frequency, among other benefits. With the promise of better safety, roundabouts have recently proliferated across across North America as well. However, regional adoption has not been smooth and questions still remain regarding roundabout design and suitability in the context of North American driving culture. Indeed, driving behaviour is a vital component of a well functioning roundabout as all movements within are managed entirely by driving etiquette.

To obtain a better understanding of how roundabout design affects driving behaviour at Québec roundabouts, a study of 37 instrumented weaving zones across 20 roundabouts throughout the province of Québec was conducted. The instrumentation captured continuous, high-resolution, microscopic movements and speeds fifteen times per second (trajectories) of over 80,000 individual vehicles over a combined 9,500 veh-km, one of the largest studies of its kind to date. This study looks at the effects of several geometric design and built-environment factors on the behaviour and safety indicators of speed and time-to-collision.

Among the major findings, roundabout conversions from traffic circles consistently scored the highest speeds and lowest (most dangerous) time-to-collisions, the number of roundabout lanes was negatively correlated with speed in the weaving zone, and mixed flow ratios between the roundabout lanes and the approach lanes produced the lowest time-to-collisions.

INTRODUCTION

Roundabouts are a relatively new design for intersection traffic management in North America. With great promises from abroad in terms of safety, as well as capacity—roundabouts are a staple of European road design—roundabouts have only recently proliferated in parts of North America, including the province of Québec. However, questions still remain regarding the feasibility of introducing the roundabout to regions where driving culture and road design philosophy differ and where drivers are not habituated to their use. This aspect of road user behaviour integration is crucial for their implementation, for roundabouts manage traffic conflicts passively. In roundabouts, road user interactions and driving conflicts are handled entirely by way of driving etiquette between road users: lane merging, right-of-way, yielding behaviour, and eye contact in the case of vulnerable road users are all at play for successful passage negotiation at a roundabout. This is in contrast with typical North American intersections managed by computer-controlled traffic-light controllers (or on occasion police officers) and traffic circles (1) of all kinds which are also signalized. And while roundabouts share much in common with 4 and 2-way stops, they are frequently used for high-capacity, even high-speed, intersections where 4 and 2-way stops would normally not be justified. Resistance to adoption in some areas is still important, notably on the part of vulnerable road users such as pedestrians and cyclists (2, 3, 4, 5) but also by some drivers too.

While a number of European studies cite reductions in accident probability and accident severity, particularly for the Netherlands (6), Denmark (7), and Sweden (2, 8), research on roundabouts in North America is still limited, and even fewer attempts at microscopic behaviour analysis exist anywhere in the world. The latter is important because it provides insight over the inner mechanics of driving behaviour which might be key to tailoring roundabout design for regional adoption and implementation efforts.

Fortunately, more systematic and data-rich analysis techniques are being made available today. This paper proposes the application of a novel, video-based, semi-automated trajectory analysis approach for large-scale microscopic behavioural analysis of 20 of 100 available roundabouts in Québec, investigating 37 different roundabout weaving zones. The objectives of this paper are to explore the impact of Québec roundabout design characteristics, their geometry and built environment on driver behaviour and safety through microscopic, video-based trajectory analysis. Driver behaviour is characterized by merging speed and time-to-collision (9), a maturing indicator of surrogate safety and behaviour analysis in the field of transportation safety. In addition, this work represents one of the largest applications of surrogate safety analysis to date.

LITERATURE REVIEW

Roundabout Safety Studies in Europe

A number of roundabout safety studies have been performed throughout Europe. In the Netherlands, for example, one study found a decrease in casualty rate across 46 roundabout conversions of up to 74% (6) (though admittedly the rates were small to begin with). A more recent example in Denmark shows important reductions in accident rates and accident severity across a large data set, though it also suggests that roundabouts have the least effect on mitigating property-damage-only (PDO) collisions (7). This study also looked at contributing factors and recommends tapered central islands above installations with islands which are not elevated or that have elevations with cylindrical shape (obstruction of visibility). Finally, it notes that cyclist collisions increased over the same period.

Similar results have been shown in Sweden (2, 8) and in 28 other studies (10). Overall, there is clear evidence of roundabouts reducing accident severity.

Roundabout Safety Studies in North America

Experience and research in North America are still lacking, though some efforts have nevertheless been made. One study found a decrease in collision severity, particularly for fatal collisions, using an empirical Bayes model on 24 stop-controlled intersection conversions into roundabouts (11, 12). A more recent, but similar, study found essentially the same result across 28 sites in the same region (13). Meanwhile, closer to Québec, Burns found that large passenger vehicles, multiple vehicles, and night time were associated with increased accident severity (14).

Behavioural and Surrogate Safety Studies

Surrogate safety analysis is a pro-active road safety diagnosis methodology which aims to improve road safety analysis methods by complementing historical accident data (or supplanting it altogether when it is not available) with cheap and short observations of ordinary traffic behaviour (15). Speed is a classic surrogate safety measure, though this designation is rather new: many studies in the literature infer from or target speed directly for purposes of road safety. Its effects on collision severity are well known, though its effects on collision probability are less sure (16).

Roundabout speed is consistently measured around 30 km/h in the literature (17). In fact, it has been observed that, while high-speed areas typically have their speed decrease to 30 km/h after implementation of a roundabout, areas with lower speeds (e.g. 20 km/h) can have their speed increased to 30 km/h as well (2). This effect has been also observed at the microscopic level in Québec (18).

There are many other surrogate safety measures, but time-to-collision (TTC) is the surrogate measure of safety of choice for its relative maturity, simplicity, and transferability properties. TTC measures the time remaining, at any instant in time, before two road users on a potential collision course collide: higher values are better for safety. It does not have the same level of validation in the literature as speed, but while speed is a good predictor of collision severity, TTC promises to be a good predictor of collision probability, a property which is arguably lacking with speed (16). Therefore, modelling both speed and time-to-collision should give a good overall representation of collision risk associated with road user behaviour.

Several collision-course modelling techniques are used in the literature, chief amongst them in terms of ubiquity is constant velocity (9). However, the constant velocity motion-prediction model is deemed inadequate for TTC measurement in roundabouts, as road users in roundabouts rarely follow straight trajectories, both inside the roundabout and on a significant portion of the approach. Fortunately, some more sophisticated naturalistic motion-prediction models have been developed to overcome this shortcoming: motion patterns are used for their ability to learn normal movement within a traffic scene. A discretized motion-pattern matrix method has been developed specifically for roundabouts (19).

METHODOLOGY

Scope

Early in the research project, a decision was made to decompose roundabouts into symmetrical and repeating sections for use as units of analysis. There are several reasons for this:

- Roundabout **branches vary in number** (between two and six, with a median of four branches) and branches can vary greatly in geometry even among branches of the same roundabout, which makes detailed description of the entire roundabout as a whole very complex. Instead, a smaller number of measures are chosen to describe a larger number of repeating design elements found at each branch, for example: number of approach lanes.

- There are **practical limitations** to performing video-data collection which covers the entire roundabout *and* a sufficient distance upstream of the approaches.
- Roundabouts are large enough that they can and often do contain **multiple independent road user interactions simultaneously**. For example, a motorist approaching a four-legged roundabout from one section (e.g. north-west) can do so independently of any movement occurring on the opposite section (e.g south-east). This is not strictly true for all interactions, however; particular care should be taken at the transitionary zone between sections.

These sections are termed *quadrants* as they cut the most common roundabout configuration, a four-way roundabout, into four sections using two axes of symmetry. Though other configurations do exist and roundabouts are rarely perfectly symmetrical in reality, the general principle still applies: a quadrant is defined as the section of a roundabout delimited by an approach and the next immediate exit, bounding a central weaving zone (depicted in Figure 1, first presented and discussed in (18)) where the approach and exit lanes overlap with the lanes of the central ring. In this zone, road users experience weaving conflicts in addition to all others.

These weaving conflicts are virtually unique to roundabouts and are the key aspect of the yielding mechanisms that govern right-of-way behaviour at the roundabout as a whole. These weaving zones are also of particular interest because they contain the most complex driving situations: single-lane corridors generate rear-end conflicts, multi-lane corridors generate rear-end and lane-change conflicts, while weaving zones generate rear-end, lane-change, and weaving/merging conflicts. This is still a smaller theoretical conflict diversity than at signalized intersections, a point commonly brought up in the literature as justification for roundabout safety (1, 20), yet it does not account for conflict frequency.

Pedestrian-motorist conflicts normally do not overlap with the weaving zone as the crosswalks are normally set back from the roundabout by a couple of car-lengths. Interactions between users, motorists, and pedestrians alike, located on an approach and an adjacent exit, and vice versa, can be considered independent from one another as they are normally always separated by a median.

While factors are mostly recorded per quadrant, some factors, particularly factors related to the built environment, affect the roundabout as a whole so are thus measured site-wide.

Factors

Each quadrant has 60 recorded factors. These factors include geometric design, signalization, and built environment factors. The most interesting and least covariant of these factors are retained for this study and are presented in the following sections.

Geometric Design Factors

Table 1 lists the most important and least collinear geometric factors under study. This includes lane number and arrangement at the start and end of the roundabout, lane number and arrangement

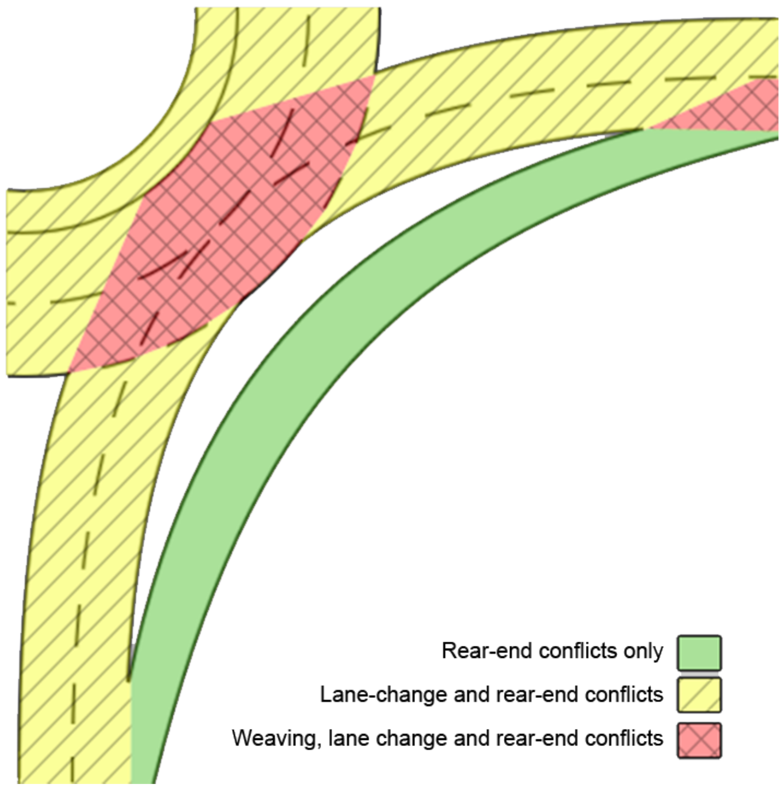

FIGURE 1 A quadrant with highlighted conflict zone complexity.

at the approach and exit, inside and outside radii, size of the quadrant measured as an angle (typically affected by the number of branches), and upstream intersection distance. Note that the posted speed limit is the legal speed limit, not the recommended roundabout speed. The measurement criteria can be seen in Figure 2.

Built Environment Factors
Table 2 lists the built environment factors under study. These are descriptive observations of network topology and land use—zoning and road classification. Private roads and commercial land use are rather under-represented, as these produce very low traffic volumes. Mixed land-use is used in situations where multiple types of land-use occur near a roundabout. This is typically the case where commercial rows intersect a residential neighbourhood. The effect may not be comparable to the sum of its parts, however, so is treated separately.

Traffic Data
Traffic-flow data is obtained from the automated analysis video data: vehicle trajectories extracted from video data using computer vision techniques built for traffic analysis applications. In this case, the computer vision tool used is the Traffic-Intelligence project, an open-source traffic-analysis software (21). See section 5.1 for more details on the source and size of the data.

TABLE 1 Important Geometric Design Factors and Descriptive Statistics from the Dataset

Variable	Description	Type	Min	Mean	Max	Units
n_start_lanes	Number of lanes in roundabout	Integer	1	1.29	2	-
n_app_lanes	Number of approach lanes	Integer	0	1.31	2	-
n_exit_lanes	Number of exit lanes	Integer	1	1.21	2	-
n_slip_lane	Number of slip lanes	Integer	0	.024	1	-
a_quad_size	Angular size of quadrant	Continuous	45	91.07	145	Degrees
r_out_start	Outside roundabout radius	Continuous	13.5	24.90	54	metres
r_in_start	Inside roundabout radius	Continuous	6.5	13.36	41	metres
w_apron	Width of truck apron	Continuous	0	2.98	7.75	metres
d_app_inter	Upstream dist. to nearest intersection	Continuous	36	381.35	2924	metres
app_speed_limit	Upstream posted speed limit	Continuous	30	59.02	90	km/h

TABLE 2 Built Environment Factors: Network Class & Land Use

Variable	Description	Count
	Network Topology	
_constant	Private Road	0
nc1	Collector	6
nc2	Arterial	20
nc3	Regional Highway	10
nc4	Access Ramp	5
	Land Use	
_constant	None	8
lu1	Residential	16
lu2	Commercial	1
lu3	Industrial	7
lu4	Mixed	5
lu5	School	0
lu6	Institutional	4

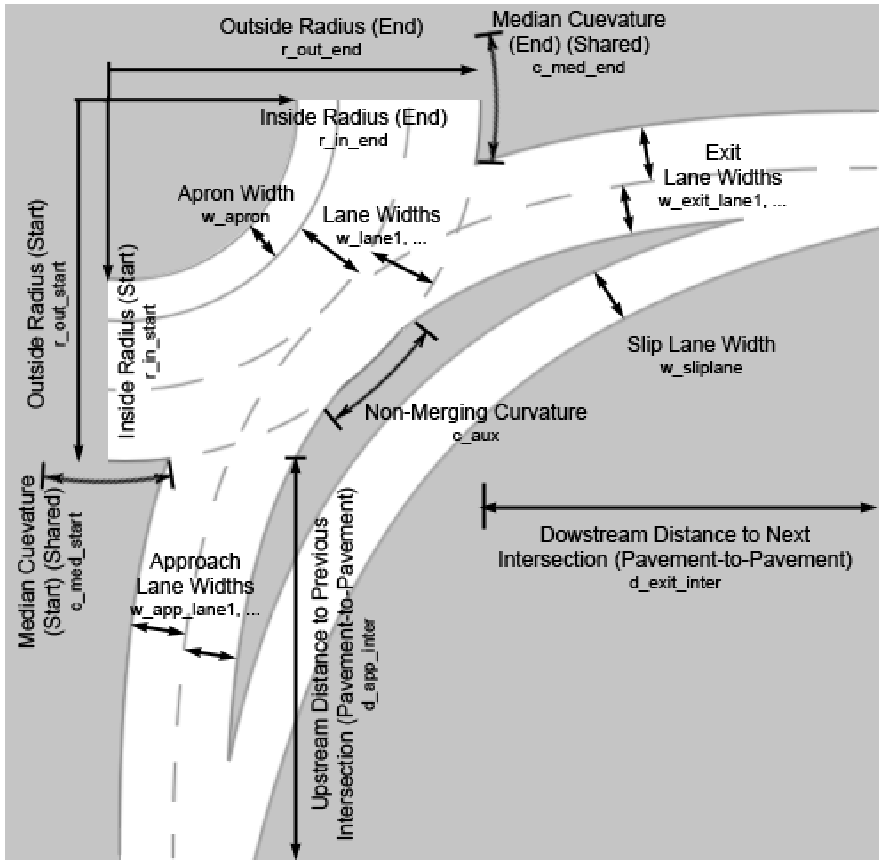

FIGURE 2 17 different geometric design factors can describe the physical design of any roundabout quadrant.

Trajectory data is obtained from the tracking of moving features within camera space. These feature tracks are a series of continuously measured positions mapped to real coordinates using a scene projection transformation by way of a homography matrix. These features are continuous, forming a path (trajectory) moving through space and time representing a road user's movement through the scene. Features are grouped together into objects using specifically calibrated algorithms for the task of identifying individual road users in the a scene (though context-insensitive classification is still a work in progress). Some secondary filtering techniques were developed to automate validation and error correction (19, 21).

Traffic flow and flow ratios can be obtained by performing counts on these objects according to the context of the specific metric. In this case we collect per-lane per-hour counts over the time of the study. Flow ratio is calculated as follows:

$$Q_r = \frac{Q_{approach} - Q_{roundabout}}{Q_{approach} + Q_{roundabout}} \tag{1}$$

where $Q_{roundabout}$ is the count of vehicles entering the weaving zone from within the roundabout and $Q_{approach}$ is the count of vehicles entering the weaving zone from the approach. A ratio Q_r close to -1 indicates a large traffic flow arriving from a within the roundabout (users who have priority) with little mixing. A ratio Q_r close to +1 indicates a large traffic flow arriving from the approach (users who do not have priority) with little mixing. A ratio Q_r close to 0 indicates equal traffic flow mixing between the approach and within the roundabout with good mixing. This is more common with low flows, as priority rules tip the balance of flow in favour of drivers already in the roundabout approaching saturation. A polarized flow ratio tends towards -1 or +1.

Speed
Speed is similarly obtained from trajectory data. It is derived from position observations between successive frames. It should be noted that a moving average filter with a half window of 5 frames is applied to this data to reduce tracking noise, but this still corresponds to speed measurements performed several times per second per object.

Time-to-collision
A discretized motion pattern matrix method developed specifically for roundabouts (19) is used for this study. We also elect to model all traffic events, using a conservative minimum probability of collision detection of 0.001, and using the indicator aggregation by the 15th percentile unique per user pair as described in (22).

Site Selection
Site selection was performed according to a number of criteria including practical constraints and statistical representation. Data collection feasibility was scored on a five-point scale measuring data collection cost and quality and sorted to generate a feasibility rank. Among a population of nearly one hundred candidate roundabouts in the province of Québec, starting from the most feasible, thirty sites were chosen to provide a good representation of design and land-use characteristics, knowing that a fraction of these sites would have to be rejected due to logistical issues (e.g. adverse weather, road closures, or equipment failure hampering data collection efforts). In particular:

- An adequate geographical coverage of the province of Québec and land-use types was desired. Sites were selected throughout all but one of the the major populated regions of Québec, as well as some of the more rural areas to provide regional representation. As listed in Table 2, representation of the built environment factors is adequate, although with a few exceptions. Notably, roundabouts on private roads are difficult to access for data collection and, in any case, provide little safety information as traffic flows are too small. Also, while roundabouts can often be found in school or commercial zones, these roundabouts did not serve through-traffic, serving instead as limited access points for parking lots or campus roads. These sites were rejected.

- Roundabouts located on the territory of the provincial transportation agency are all built to very similar specifications and are significantly more consistent in design than municipal roundabouts. However, provincial roundabouts tend to serve more network classes than municipal roundabouts, which serve collector roads for the most part. Forty percent of the sites were located on provincial territory, while the remainder were strewn across seven different municipalities.

TABLE 3 Data details

Roundabouts	20
Analysis Areas	37
Hours of Video Data	473.9 hours
Total Traffic Volume Observed	79,432 veh
Veh-km Traveled	9505.97 veh-km

Modelling

Speed can be nicely averaged as it is generally normally distributed. However, TTC is not always so nicely distributed. Therefore different aggregation methods should be used. So instead of using aggregation, this data will be analysed in a disaggregated manner. The data is thus effectively unbalanced panel data, where sites are the panels containing individual observations of behaviour (speed, TTC indicators, gap acceptance). Random effects modelling is chosen for the analysis using the formula

$$ln(Y_{ij}) = \mu + \sum_{k=1}^{n} \beta_k X_{kij} + u_{ij} + \epsilon_{ij} \quad (2)$$

where Y_{ij} is the safety indicator of the jth road user at the ith site, β_k is the coefficient of factor X_{kij} from $k = 1..n$ factors and μ is the average safety indicator (base case). u_{ij} and ϵ_{ij} are the between-entity error and within-entity error respectively. Regressing for the natural logarithm instead of the dependant variable directly mitigates issues with non-normal distributions, which is particularly the case with TTC. A useful model for evaluating the effects of sites has a large between-R^2 and minimises within-R^2 effects.

EXPERIMENTAL RESULTS

Data Size

Video data was collected at 37 different merging sections of varying geometrical configuration across 20 different roundabouts with varying land-use across the province of Québec. Video was shot using a purpose-built mobile video-data collection system designed for temporary, high-angle video data collection, with tamper-proof, weather-proof, self-contained cameras mounted on a 3.5 to 10.5-metre pole (21).

At these 37 merging zones (the study sites), video data was recorded for varying lane configuration, geometry, land use, and traffic volumes. The merging zone of the roundabout is defined as the portion of the ring intersected by an approach and the next exit, and the area proper is the area where the approach and exit lanes overlap with the ring. There is generally one merging zone between every pair of adjacent branches, unless one of these branches does not have an approach (these are rare and not included in the study). Video data at each site was taken during one mild summer workday from 6 AM to 7 PM or 10 PM and captures both peak traffic hours though most of the roundabouts experienced saturation (18). See Table 3 for details.

Dependent Variables

The dependent variables being modelled are absolute speed and time-to-collision (TTC). A quick correlation test between TTC values and absolute speed values at the time of TTC capture for each observation returns a Pearson correlation of -0.2150, signifying that the two are mostly independent. This is further illustrated in a scatter of each individual observation in Figure 3. After instantaneous indicator aggregation by 15th percentile, there are a total of 61,089 TTC observations and 58,379 associated speed observations (the difference being rejected on the grounds of quality).

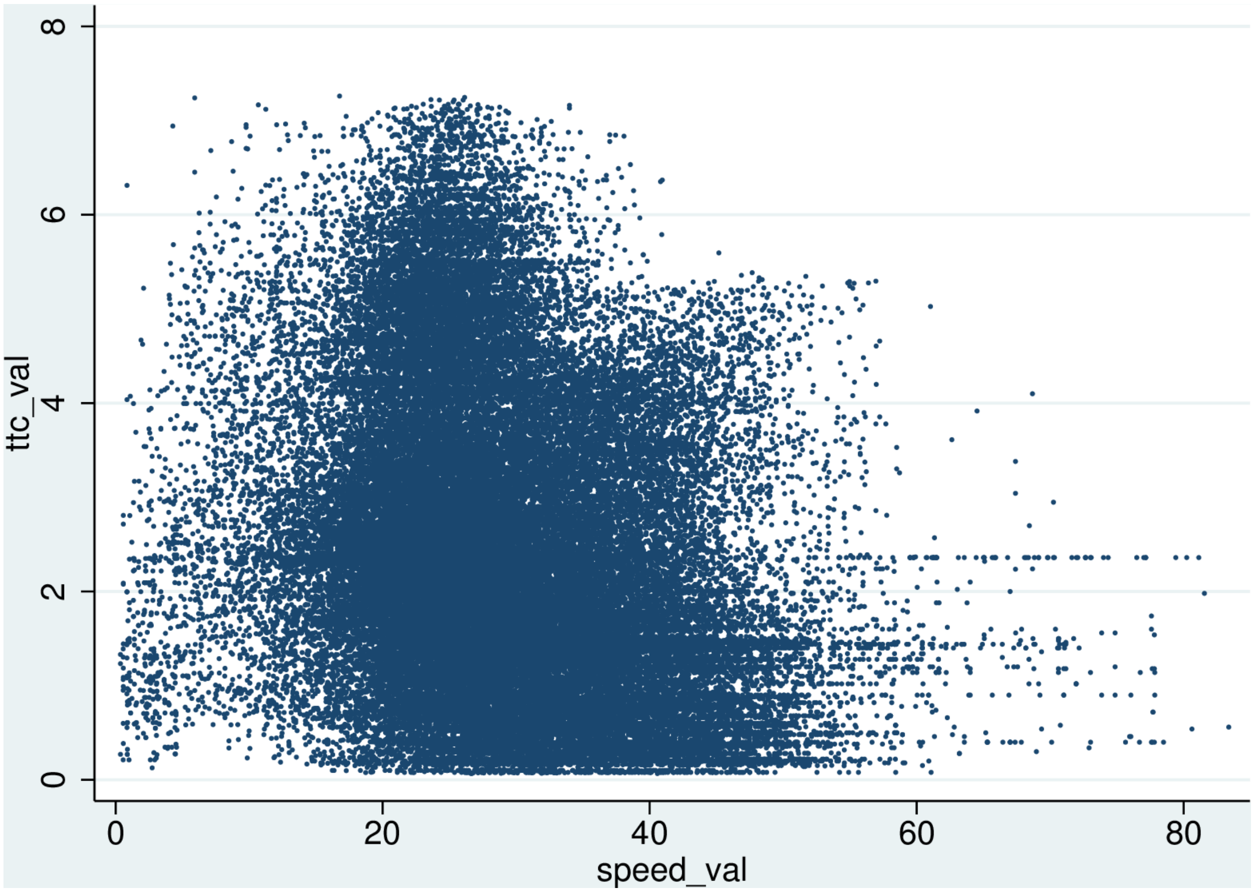

FIGURE 3 Scatter of individual speed versus TTC observations.

Mean Speed Aggregated

A simple linear regression for aggregated mean speed across the 37 sites is explored first. Including dummy variables from land use categories, over 20 variables are available for modelling. With only 37 sites, this leaves very little room for degrees of freedom. While a handful of factors individually contribute significantly to explaining mean speed, only two to three can be used simultaneously before the model significance starts to erode.

Table 4 lists the coefficients and p-values for three factors which stand out: commercial and institutional land-uses as well as number of exit lanes off the roundabout are found to have a traffic calming effect on an average speed of 42 km/h for vehicles travelling through the weaving zone by 5 to 10 km/h. Number of exit lanes having a negative effect on speed is unexpected, may be explained by more regular arrivals of inside of the roundabout providing fewer opportunities for vehicles on the approach to enter the roundabout without stopping. Regardless, in a future study, it should be interesting to compare this effect with yielding behaviour and gap times. Unsurprisingly, speed limits are also correlated with speed, though they are covariant with many built

TABLE 4 Linear regression for aggregated mean speed (p-values and significance in parenthesis)

Factor	**Coefficients**	**Coefficients**	**Coefficients**
Constant	42.14 (0.000 ***)	15.77 (0.003 ***)	26.37 (0.000 ***)
Commercial land-use	-5.31 (0.070 *)		
Institutional land-use	-9.37 (0.054 *)		
Number of exit lanes	-6.91 (0.041 **)		
Approach speed limit		0.33 (0.001 ***)	
Apron width		-1.53 (0.057 *)	
Inflow per hour per lane			0.02 (0.047 **)
R-squared	0.277	0.243	0.099
No. observations	37	37	37

environment factors, so are ignored. The R-squared for this first model is 0.2766, which offers modest explanatory power. To improve results, site clustering and random effects regression is performed next.

Disaggregated Speed Regression

To better manage results due to the number of variables, k-means clustering is employed on all of the variables. Several clusters were performed using between three and six centroids to find a suitable model that i) produces the most meaningful and interpretable clusters, ii) produces a random effects regression model with explanatory power, and iii) where p-values still remain relatively significant. However, because we know the different indicators are statistically independent for the most part, we find that different clusters offer different explanatory power for each dependant variable. Table 5 lists the distribution of observations (at the site level and at the disaggregated level) for the clusters used to model speed and offers a short profile for each.

This regression model offers relatively good explanatory power. The coefficients and statistical test results are provided in Table 6. All but cluster c6_s (2-lane arterials) provides moderate to very strong statistical significance. Cluster c1_s (single-lane residential arterial) is associated with the lowest speeds. From the cluster characteristics, we gather that high and moderate flow ratios have an important effect of increasing speed. Unsurprisingly, the highest speeds attributed to regional highway roundabouts. Large-diameter, 2-lane, roundabout-converted traffic circles had the poorest speed results, probably because the approach angle remained tangential to the circle instead of the usual mostly orthogonal approach of standard roundabouts. Interestingly, roundabouts situated in residential neighbourhoods on collector streets (cluster c4_s) were associated with higher speeds than highway ramps (cluster c3_s), despite the smaller size. This may be attributed to significantly lower flows and thus fewer conflicts.

Disaggregated TTC Regression

Table 7 lists the distribution of observations (at the site level and at the disaggregated level) for the clusters used to model TTC and provides a short profile for each. Weaving zones are slightly less well balanced across groupings, though individual observations are better distributed. Also of note is that clusters c5_s and c5_t are identical.

This regression model offers moderately good explanatory power. The coefficients and sta-

TABLE 5 K-means cluster profile for speed regression

Cluster	Description	Group size	Observations
c1_s	Arterial with wide lanes, far distance to upstream intersections, and very low flow ratios, mixed land-usage	6	5,232
c2_s	Regional, single lane highways in industrial complex with mixed flow ratios	6	13,267
c3_s	A mix of highway ramps and arterials with extremely polarized flow ratios	13	17,130
c4_s	Residential collectors with reasonably well mixed flow ratios and short upstream distance to nearest intersection	6	325
c5_s	Traffic circle converted to roundabout (2 lanes, extremely large diameters, tangential approach angle)	4	10,295
c6_s	2 lane arterials near commercial or institutional land use and very high flow ratios.	6	14,840

TABLE 6 Random effects speed regression

Cluster	Coefficient	p-value
_cons (c1_s)	3.0212	0.000 ***
c2_s	0.3781	0.001 ***
c3_s	0.1612	0.090 *
c4_s	0.2569	0.019 **
c5_s	0.4667	0.000 ***
c6_s	0.1498	0.177
sigma_u	0.1638	
sigma_e	0.3183	
R-squared within	0.0000	
R-squared between	0.4225	
R-squared overall	0.2477	
Prob > Wald chi2(5)	0.0003	
No. observations	58379 (37 groups)	

TABLE 7 K-means cluster profile for TTC regression

Cluster	Description	Group size	Observations
c1_t	Small single and double lane residential collectors	11	4,200
c2_t	Single-lane regional highways and arterials with speed limits of 70-90 km/h and mostly polarised flow ratios	16	26,243
c3_t	2-lane arterials with very high flow ratios	5	13,307
c4_t	Hybrid lane 1->2 2->1 arterials with very low flow ratios	3	4,809
c5_t	Traffic circle converted to roundabout (2 lanes, extremely large diameters, tangential approach angle)	4	10,295
c6_t	Single-lane regional highway with large-angle quadrants (140 degrees) and mixed flow ratios	2	2,235

tistical test results are provided in Table 8. Clusters c5_s and c6_s are not statistically significant. Small, residential, local roundabouts are associated with the second-worst (lowest) TTC performance, after traffic circle conversions which were noted for their issues with higher speed. The best performing group, in terms of safety, appears to be 2-lane arterials with excessively high flow ratios (c3_t). This is probably explained due to the extremely low amount of interactions generated at the weaving zone—instead these results are probably governed by TTC measures generated from lane changing manoeuvres. Clusters c4_t (Hybrid lane arrangement arterials with very low flow ratios) and cluster c2_t (single-lane regional highways and arterials with speed limits and polarised flow ratios) offer the next best TTC performance. The most striking aspect in this model is that higher TTC appears to be associated with flow ratio extremes where as lower TTCs (more dangerous) appear to be associated with highly mixed flow ratios. This might be explained by an increase in generation of complex merging manoeuvres when flows are equivalent within the roundabout and its approach.

TTC Distributions by Cluster

Using the comparison methodology described in (22), Figure 4 provides the cumulative distribution functions of TTC for the clusters c1_t through c6_t. The unambiguous left-shift of TTC observations for cluster c3_t and right-shift for cluster c5_t are consistent with the results of the TTC regression model presented in 5.4: c3_t is associated with the greatest benefits in safety. Clusters c1_t, c2_t, c4_t, and c6_t are inconclusive using this approach.

CONCLUSION

This research looked at two indicators of traffic behaviour—speed and time-to-collision—associated with road safety (collision severity and probability) for 37 weaving zones at 20 roundabouts in the province of Quebec. Random effect regression was used to perform a disaggregated behaviour regression across 37 groups over nearly 80,000 observed vehicles, one of the largest applications of surrogate safety indicators to date.

Among the major findings, a direct regression of factors suggests that the number of exit

TABLE 8 Random effects TTC regression (higher is better)

Cluster	Coefficient	p-value
_cons (c1_t)	3.0212	0.158
c2_t	0.4843	0.001 ***
c3_t	0.6924	0.001 ***
c4_t	0.5123	0.073 *
c5_t	0.1035	0.636
c6_t	-0.3385	0.238
sigma_u	0.3707	
sigma_e	0.6541	
R-squared within	0.0000	
R-squared between	0.4171	
R-squared overall	0.1376	
Prob > Wald chi2(5)	0.0005	
No. observations	61089 (37 groups)	

lanes and width of the apron have a significant negative effect on driving speed within the weaving zone, while more obvious factors, such as roundabout diameter and flow ratio do not have an effect on speed. Flow ratio is found to have an important effect on time-to-collision however, for evenly mixed flow ratios produce the most complex traffic conflicts.

Traffic circle conversions are found to be associated with the highest speeds. Surprisingly, roundabouts in residential areas on collector roads are associated with higher speeds and TTC in the weaving zone. This may be explained by low flows overall and drivers accustomed to not having to yield. Roundabouts connected to regional highways generated relatively higher speeds within the weaving zone despite comparable size, though only moderate TTCs.

While this research provides some important insight into traffic behaviour at North American roundabouts, it is not yet complete. The time-to-collision indicator still needs more validation so these results will need to be revised for better interpretation regarding safety. Results are also somewhat inconclusive regarding multi-lane roundabout configurations. A more detailed analysis targeting lane changing behaviour and conflicts specifically may be warranted for these types of manoeuvres are frequently cited as problematic.

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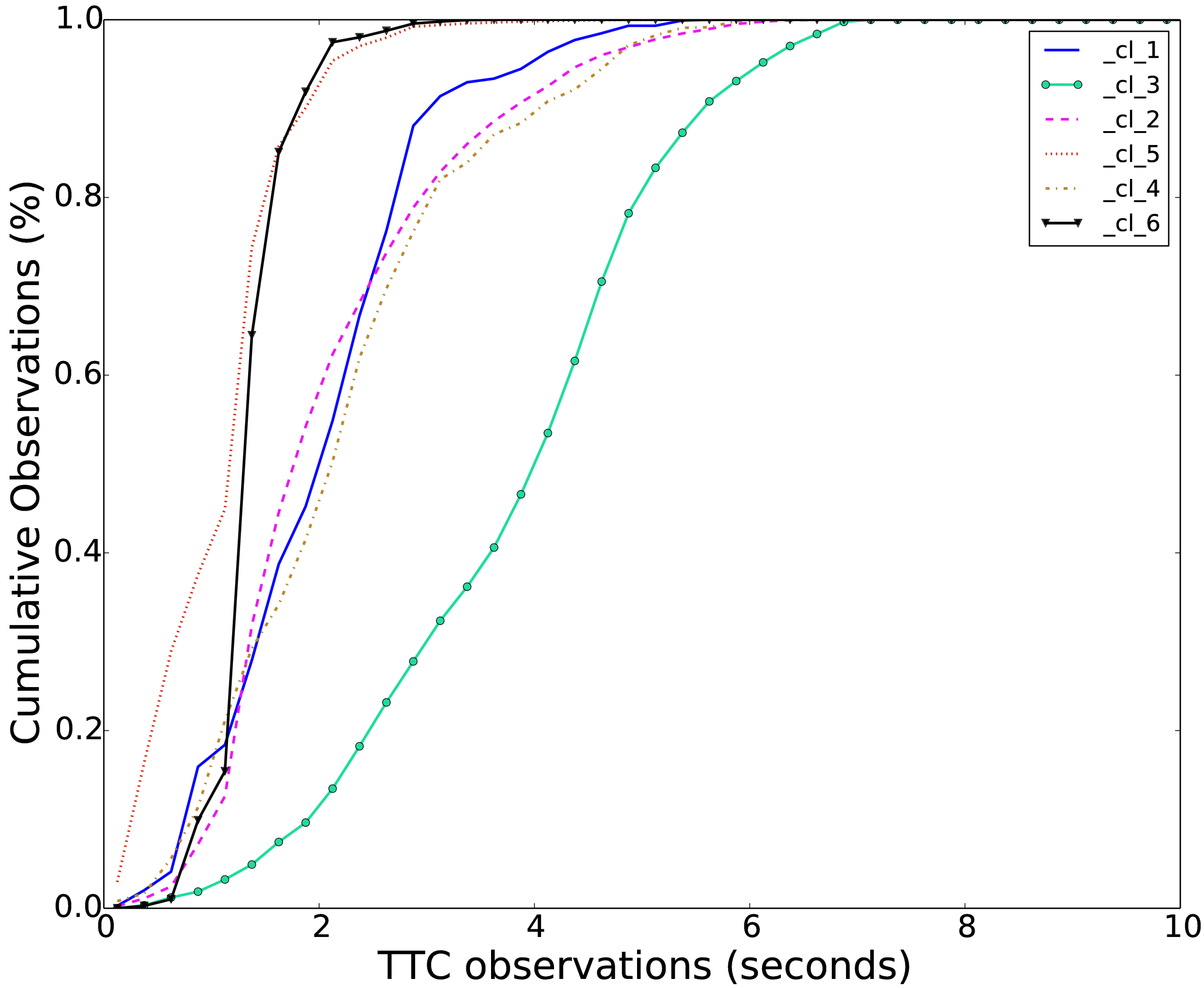

FIGURE 4 Cumulative distribution functions for TTCs aggregated by cluster.

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