MICROSCOPIC ROAD SAFETY COMPARISON BETWEEN CANADIAN AND SWEDISH ROUNDABOUT DRIVER BEHAVIOUR

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Abstract

Despite similar population densities, levels of urbanization, climates, and levels of economic development, road accidents across the province of Québec (and the rest of Canada) are twice as high as in Sweden, as measured by accident frequency and severity. Some of this disparity may be explained by differences in road design, but some of this disparity is hypothesized to also be attributed to latent behavioural factors present in the general population.

The objective of this research is to investigate latent differences in road user behaviour and experience that may explain differences in accident history beyond any road safety effects derived from road design and traffic composition. To that aim, a number of roundabouts in Québec and Sweden are selected on the basis of similarity in design, for cross-sectional comparison. The modern roundabout is chosen as a case study as its implementation in North America is identical to that of Europe (where the design originated), and because roundabout operation relies heavily on road user behaviour (right-of-way is performed exclusively through rules of priority). This approach to intersection control is in stark contrast with typical stop-sign and traffic light control used throughout North America. Analysis of behaviour and resulting safety is performed proactively using automated computer-vision-based trajectory extraction of road users from video data, coupled with surrogate safety methods. Surrogate safety measures of interest for this study include speed and time-to-collision, modeled using motion-pattern motion-prediction.

Accident records available at the sample of roundabouts studied are found to be consistent with national averages of each country respectively (twice as high and severe in Québec as in Sweden). After controlling for various geometric design features, land use, construction year, traffic exposure, and traffic patterns, an overall tendency of lower speeds and fewer serious conflicts (as measured by time-to-collision) are found at the Swedish roundabouts.

These results are found to be consistent with local and national accident records, and would suggest that some important latent regional factors—possibly related to educational or enforcement—

are at play at the microscopic level. Further investigation of these regional factors is warranted in future road safety studies.

Résumé

Malgré des densités de population, des niveaux d'urbanisation, un climat et des niveaux de développement économique semblables, les accidents de la route à l'échelle du Québec (et du reste du Canada) sont deux fois plus élevés qu'en Suède, en se basant sur les mesures de fréquence et de sévérité des accidents. Une partie de cette disparité peut s'expliquer par des différences dans la géométrie des routes, mais une partie de cette disparité pourrait être attribuée à des facteurs comportementaux latents présents dans la population générale.

L'objectif de cette recherche est d'étudier les différences latentes dans le comportement des usagers de la route qui peuvent expliquer les différences témoignées dans l'historique des accidents au-delà des effets de la sécurité routière dérivés de la conception des routes et de la composition du trafic. Un certain nombre de carrefours giratoires au Québec et en Suède sont sélectionnés compte tenu d'une similitude de conception, afin d'effectuer une comparaison transversale. Le carrefour giratoire moderne est choisi en tant qu'étude de cas car sa mise en œuvre en Amérique du Nord est identique à celle de l'Europe (origine du design) et parce que le carrefour giratoire repose fortement sur le comportement des usagers de la route (par les règles de priorité implicites). Cette approche du contrôle des intersections est en fort contraste avec le panneau d'arrêt et le contrôle des feux fortement utilisés en Amérique du Nord. Une analyse de l'extraction automatisée des trajectoires des utilisateurs de la route est effectuée à partir de données vidéo à l'aide de la vision par ordinateur, et couplée à des méthodes d'analyse substitutif de sécurité pour analyser le comportement et la sécurité résultante de manière proactive. Les mesures substitutives de sécurité intéressantes pour cette étude incluent la vitesse et le temps-à-la-collision, conceptualisés à l'aide de modèles de prédiction à base des patrons de mouvement.

L'historique des accidents enregistrés à l'échantillon de carrefours giratoires étudiés sont conformes aux moyennes nationales de chaque pays respectivement (deux fois plus élevé et plus sévère au Québec qu'en Suède). Après avoir contrôlé pour diverses caractéristiques de conception géométrique, l'utilisation du sol, l'année de construction, l'exposition à la circulation, et les motifs de circulation, une tendance générale à des vitesses inférieures et moins de conflits sérieux (mesurés par le temps-à-la-collision) sont trouvés aux carrefours giratoires suédois.

Ces résultats sont cohérents avec l'historique des accidents locaux et nationaux et suggèrent que certains facteurs latents régionaux importants—éventuellement liés à des facteurs éducatifs ou de mise en application—opèrent au niveau microscopique.

1 Introduction

While the broad concepts behind road design and signalisation are universally recognized for the sake of road user mobility between regions of the world—e.g. to accommodate visitors—specifics of intersection design philosophy and signalisation differ significantly between North America and Europe. This is not surprising given that the United States and Canada are not signatories of either the 1949 Geneva Protocol on Road Signs and Signals or the 1968 Vienna Convention on Road Signs and Signals which codify road signalisation throughout nearly all of Europe and much of Asia. Instead, intersection design in the United States and Canada, and much of the Pacific, is based on the 1935 Manual on Uniform Traffic Control Devices.

Design differences are especially striking regarding traffic control at intersections without traffic lights. While European design tends to favour a limited use of stop signs in favour of yield signs, or no signalisation or other forms of explicit control at all, North American design favours two- and four-way stop signs almost exclusively. In fact, in general, yield signs in North America are used exclusively for slip lanes or merges, and never to control square intersections directly. Given the yielding nature of the roundabout design, it is unsurprising to learn that roundabout adoption has been very slow in North America. While roundabouts are a relatively new phenomenon in North America, they have existed in the United Kingdom since 1966 where the modern design of the roundabout was first conceived (at the Transport Research Laboratory).

However, roundabouts are beginning to flourish across North America, against the prevailing stop-sign-predominant intersection design philosophy. Thus, studying this discrepancy in road design philosophy and resulting road safety record is especially relevant today given that many North American road users may not be familiar with fully unsignalised (no traffic lights or stops signs) intersection design that the roundabouts introduce and this has been cited as short and medium-term issue to overcome with further implementation of roundabouts in North America [e.g. 24]. To this end, there exists a need to study any differences in driving culture between the two continents, whether that difference is induced, or latent. In this work, an international, microscopic comparison of road user behaviour between a sample of road users selected from North America (specifically Québec) and from Europe (specifically Sweden) is performed using surrogate safety methods. Studying driver behaviour at roundabouts between these two regions is particularly relevant given that both regions share several climatic, environmental, demographic, and level of development similarities, and that, unlike many other types of road designs, roundabouts in North America have been directly transplanted from the first European designs [19] and in practice are functionally similar.

The choice of using surrogate safety methods for this analysis was made to solve several issues related with historical accident data collection and comparison between jurisdictions, and, furthermore, offers much greater insight into road user behaviour and collision mechanisms [31].

While many international studies of road safety and design have been conducted, to date, only a limited number of international behavioural comparison studies have been attempted, and none have been conducted at the level of detail, and scale as in this study. This paper briefly reviews the literature and methodology to be used before presenting an exploratory analysis and regression analysis of speed, time-to-collision, and yielding post-encroachment time across 19 Québec and Swedish merging zones carefully selected to be similar in geometric design and environment.

2 Literature Review

2.1 Regional Effects

As highly-developed countries, Canada, and Sweden especially, are among some of the safest countries in the world for motorists, cyclists, and pedestrians. Despite this, annual traffic fatality rates in Canada are nearly twice as high than in Sweden, as measured per 100,000 inhabitants

[22, 21]), per 10,000 registered motor vehicles [21], and per billion veh-km travelled [21], and this despite a relatively comparable car occupancy and mode share [21]. Figures of reported accidents per 100,000 inhabitants share a similar trend [20]. These numbers are summarised in Table 1. While all of these rates have been observed to be decreasing consistently over the last 40 years, the proportion between the two countries has been fairly constant [20]. Furthermore, fatality and accident rates in Québec are consistent with, and thus representative of the Canadian national average [3].

Table 1: Comparison of Historical Accident Statistics

Statistic	Canada	Sweden	Ratio	Year	Source
Fatalities per 100,000 inhabitants	6.8	3.0	2.26	2010	[22]
Fatalities per 100,000 inhabitants	5.5	2.7	2.03	2013	[21]
Fatalities per 10,000 registered motor vehicles	0.85	0.45	1.88	2013	[21]
Fatalities per billion veh-km travelled	5.6	3.4	1.65	2013	[21]
Accidents per 100,000 inhabitants	501	210	2.39	2013	[20]

The disparity in road safety between Sweden and Québec is unexplained given that both share similar population sizes and density, levels of urbanisation (81% in Québec versus 86% in Sweden), climate, and economic development factors. The disparity might instead be explained by one of two sets of microscopic factors: road design, and road user behaviour and road culture. To this end, a comparative study of road user behaviour between the two regions is warranted by first isolating geometric factors as these are the most straightforward to control. One important difference is that cycling prevalence is significantly higher in Sweden than in Canada or Québec. On the other hand, grade-separated cycle crossings tend to be favoured in Sweden for most busy roundabouts[25].

2.2 Roundabouts

Roundabouts might arguably be one of the best candidates of road design for direct comparison of road user behaviour and driving culture between North America and Europe. Although a relatively new phenomenon in North America (the first roundabout in Quebec dates back to 1998), roundabouts are one of the few types of road designs with near identical geometric and aesthetic design in both regions. This is in large part due to the heavily European-influenced design of the roundabout in North American, e.g. roundabout design guides [as in 19] including Québec's very own guide [17].

Key differences between the roundabout designs are mostly-pedestrian and cyclist related, as Swedish sidewalks tend to incorporate cycle paths, even at intersections and roundabouts, but that these often bypass the roundabout entirely via grade-separation [25]. In general, cyclist aversion to roundabout lanes might be attributed to higher accident rates and compounded by a lack of the safety-in-numbers effect [5].

2.3 Road User Behaviour Comparison Studies

A couple of recent and relevant works stand out, including a comparison of road safety records between Sweden and Finland [23] and a study of general cyclist perceptions between Brisbane and Copenhagen based on stated preference surveys [4]. However, while these and a small number of other studies exist comparing measurable difference in driving behaviour and driving culture between regions, few if any exist that do so using microscopically-collected road-user data and tightly controlling for geometric and land use factors, i.e. a level of analysis comparable to the study of gap acceptance of a saturated multi-lane roundabout in Lund performed by Irvenå and Randahl using some manually-annotated video data to calibrate microsimulation software [12].

This lack of research is in part due to the challenge of coordinating such a study, and also in part due to the lack of a robust framework and technology for collecting and processing large amounts of driver behaviour. The bulk of international road safety comparison research seems to be concentrated on historical accident data [18]. The level of detail of the analysis presented here is made possible with improvements of large-scale automated surrogate safety analysis tools and frameworks [28].

3 Methodology

3.1 Site Selection

Existing roundabout data for Québec was taken from a related road safety project at roundabouts [30]. This pool of data includes traffic video data for roughly 20% of Québec's 110 roundabouts (at the time of study) with uniform representation of various land use, geometric design, and regional characteristics. From this data, six roundabouts were retained for this study.

In Sweden, four roundabouts were selected to complement the existing Québec data. These roundabouts were selected on the basis of similar geometric design and land use. This typical design is characterized by a single lane (on the approach, exit, and ring, each), an approach speed limit of 50 km/h, an outside radius of 15-25 meters, very-low to medium urban density, suburban or light commercial land use, moderate visibility over the centre island, and pedestrian crosswalks. Québec roundabout vertical signalization design is functionally identical to Swedish design, though differs slightly in terms of aesthetics (using an MUTCD-influenced style). The Swedish roundabouts chosen were all located in the Skåne province, near the city of Lund.

Despite a longer history of roundabout construction in Europe and Sweden, the Swedish roundabouts selected for this study are relatively new compared to other areas of Europe and are incidentally comparable in age to Québec roundabouts: these samples are both, on average at least ten years old, to control for short term effects derived from recent construction.

It should be noted that while the approach speed limits were all set to 50 km/h, the city center of Lund (a distance greater than 500m from any included roundabout) has a speed limit set to 30 km/h and features significant traffic calming measures. On the other hand, a 2008 study of blanket speed limit reductions across Sweden found that these had little effect in reducing speed

[11]. Similar blanket speed limit reductions can be found at the municipal level of some, but not all, of the included Québec roundabouts, though given the built environment, all of them feature 30 km/h reduced speed limits in relative close proximity.

One important distinction between the Québec and Swedish roundabouts regard pedestrian and, especially, cyclist flows. In Québec roundabouts, cyclist flows at roundabouts are virtually non-existent and pedestrian flows are very low; in comparison cyclist and pedestrian flows at many (but not all) Swedish roundabouts are non-trivial. Consequently, only Swedish roundabouts with limited pedestrian or cyclist flows were considered for this study (low pedestrian and cyclist flows are still very common in Swedish roundabouts in low-density areas). As mentioned earlier sidewalk design is the most striking design difference between Swedish and Quebec roundabouts. A majority of sidewalks in the town of Lund integrate a cycle lane both along roads and across intersections, and roundabouts are no exception. On the other hand, it is also common for these sidewalks to bypass the roundabouts entirely via tunnels [25], including at some of the selected sites. Given this, cycling volumes *within* the roundabout are rare at both the Québec and at the Swedish sites sampled for this study.

3.2 Traffic Data Collection

Video data is collected at a number of sites using purpose-built video data collection systems [14, 27]. As mentioned earlier, video data at Québec roundabouts was reused from a related road safety project. Complimentary video data was taken at the selected Swedish sites, deploying a similar video data collection system employing two cameras to cover the entire view of the roundabout. Data collection at the Swedish sites was perofmed under similar weather conditions (mild, partially overcast), periods (weekdays in late spring), and at times when no significant events could disrupt normal driving conditions.

The video data is then processed with state-of-the-art computer vision software purpose-built for surrogate safety analysis applications. The open-source software Traffic Intelligence extracts all road user trajectories from image space using feature-based-tracking [26], providing Cartesian coordinates of all moving objects within a scene thirty times a second. This high-resolution data of all road users within a traffic scene is needed for the road user behaviour analysis to follow. Given the large volume of data to be processed, additional software is used to partially calibrate and automate the analysis and to annotate the traffic scene with contextual metadata [28].

Example trajectory data extracted from two cameras at one site is shown in Figure 1. In this case two cameras are placed in the north-west corner to provide full and overlapping coverage of the roundabout.

3.3 Merging Zone

The merging zone is defined as in [30]. It encapsulates any region of the roundabout where an approach and an exit lane physically overlap with the ring, as well as any sufficient portions before and after this region to capture road users entering and exiting this region (circa 10 meters of approach and exit). Given that all roundabouts have multiple approaches and exits and that in the vast majority of cases these alternate in order around the ring, multiple merging zones exist within the roundabout.

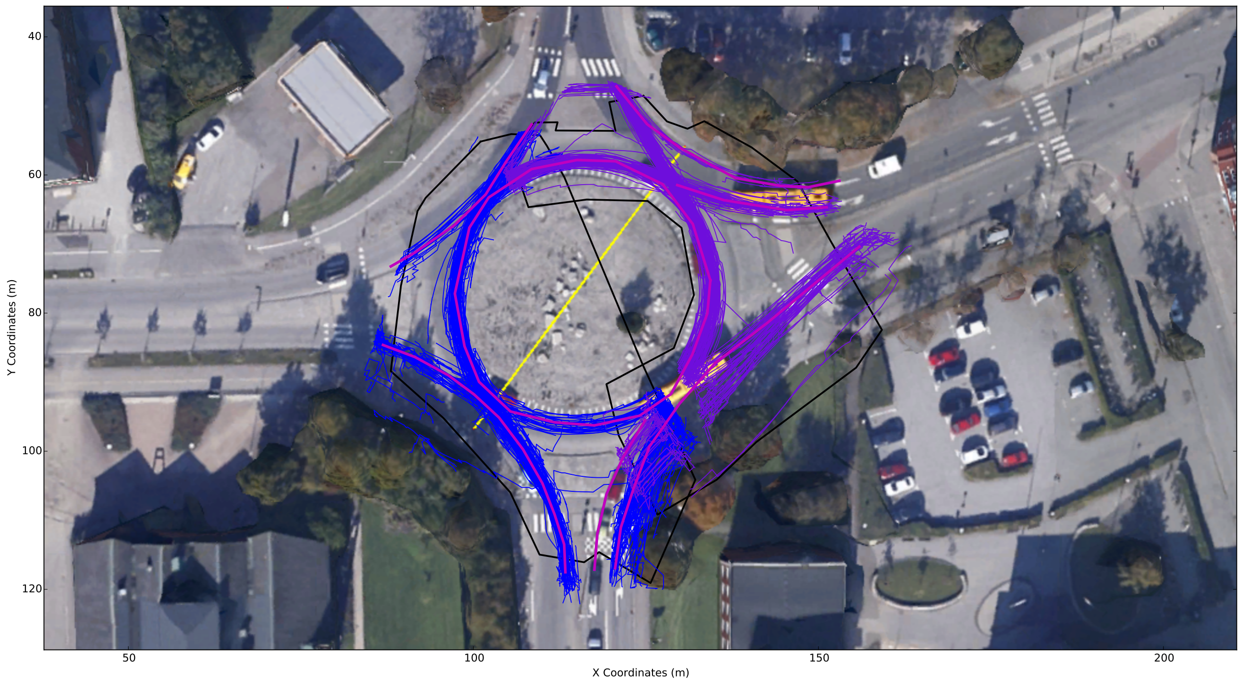

Figure 1: Trajectory data, image-space masks, and corresponding meta data coverage at a Swedish roundabout using two cameras.

The rationale for using merging zones as the unit of study, instead of roundabouts as a whole, is that, while many factors such as land use are shared between merging zones of the same roundabout, many more are not. This includes flows and flow ratios especially, but may also include a host of geometric factors such as lane configuration, signage, presence of a crosswalk, approach angle, etc. which can vary from one merging zone to the next even within the same roundabout [30]. Studying merging zones individually also better encapsulates the microscopic nature of the data being collected and analysed: roundabouts are often large enough for road user interactions on different sides of the roundabout to occur more or less independently [this is especially true if center island obstructs view 15].

While the sites are selected in such a manner so as to control for as many factors as possible, inevitably, some variation between sites still exists, especially regarding traffic volumes and patterns (no two intersections are perfectly identical); these differences are identified such that they may be controlled during analysis. Table 2 lists a summary of the merging zones selected at each roundabout studied and along with the most important geometric and land use variations, as well as a summary of historical accident data at each roundabout. Quality of the available historical accident data is relatively poor, with sampling periods ranging from 2 to 15 years (with an average of 7) and data missing entirely at one roundabout. Furthermore, this historical accident data is collected for the entire roundabout instead of the merging zone exclusively since accident geolocation was not precise enough to associate with individual roundabout merging zones (this is especially true for the Québec data). These problems justify using surrogate safety measures for this study, and more generally. However, the pattern in this data is consistent with the regional trends in accidents cited earlier: accidents seem to be twice as likely to occur in Québec than in Sweden, suggesting that from a safety point of view, the selected roundabouts are comparable with respective national trends.

Traffic data is prepared from the video data. In addition to flow rate, the flow ratio tends to govern how many interactions occur across any single merging zone, and of what nature these interactions tend to be. This is self-evident: when more road users are present simultaneously within the merging zone and when the presence involves more mixing from independent sources of arrivals (the effect of the flow ratio), more interactions must necessarily take place. This is especially important for low-demand sites where simultaneous arrivals may be rare events. The flow ratio is defined as

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

where Q_{app} is the total flow rate at the approach and Q_{conf} is the total conflicting flow (in the roundabout lanes at the beginning of the merging zone). It follows that a negative flow ratio would indicate that the conflicting flow is greater than the approach flow, and vice versa for a positive flow ratio. Mixed land use involved mostly residential and commercial land use, and occasionally institutional land use. All sites had a posted approach speed limit of 50 km/h. Some of the Québec roundabouts had a 35 km/h speed advisory posted as well. Swedish roundabouts do not have posted speed advisories [13].

3.4 Behavioural Measures

The parameters of interest for this particular study are the most notable surrogate safety measures: speed (and speed profiles), time-to-collision (TTC) [9], and post-encroachment time (yPET). Note that yPET is an ordinary PET measure [1] but is designated yPET as 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. 7, 6] 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 generalised predictor of collision probability as it models ”near-miss” situations between any types of road users traveling 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 modeling [2], 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, though, unlike TTC, without making any assumptions of motion, relying exclusively on observed behaviour It is thus less flexible in modeling 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 associated with gap time

Table 2: Merging Zone Inventory

Site (Sweden)	Land Use	Urban Density	Outside Radius (m)	Hourly Flow (veh/h/ln)	Flow Ratio	Construction year	Accidents per year
Fasanvägen/ Trollebergsvägen-1	Mixed	Medium	25.0	408.4	-0.432	1965	4.1
Fasanvägen/ Trollebergsvägen-2	Mixed	Medium	25.0	394.7	0.283	1965	4.1
R103/Företagsvägen-1	Mixed	Very low	22.0	281.8	0.293	2003	1.0
R103/Företagsvägen-2	Mixed	Very low	22.0	289.0	0.517	2003	1.0
R103/Företagsvägen-3	Mixed	Very low	22.0	226.8	0.252	2003	1.0
R103/Företagsvägen-4	Mixed	Very low	22.0	218.4	0.934	2003	1.0
Ruben Rausings gata/ Borgs väg-1	Mixed	Low	22.0	123.9	0.646	2010	1.5
Ruben Rausings gata/ Borgs väg-2	Mixed	Low	22.0	121.4	0.568	2010	1.5
Svenshögs/Norra Gränsvägen-1	Residential	Low	16.5	191.0	-0.417	1995	1.4
Svenshögs/Norra Gränsvägen-2	Residential	Low	16.5	142.9	0.054	1995	1.4
MEAN			**21.5**	**239.9**	**0.270**	**1995**	**1.8**
Site (Québec)	**Land Use**	**Urban Density**	**Outside Radius (m)**	**Hourly Flow (veh/h/ln)**	**Flow Ratio**	**Construction year**	**Accidents per year**
des Soeurs/du Golf	Residential	Medium	25.0	315.1	-0.327	2004	7.0
des Soeurs/Rene-Levesque	Residential	Low	22.5	178.8	0.421	2003	1.4
Fréchette/Anne-Le-Seigneur	Mixed	Low	24.5	51.5	0.600	2003	7.0
des Sources/Riverdale	Residential	Low	18.5	236.9	-0.361	2003	0.7
Mouettes/Alouettes-1	Residential	Low	15.5	64.6	-0.518	2004*	-
Mouettes/Alouettes-2	Residential	Low	15.5	93.4	0.607	2004*	-
St-Emilie/St-Denis	Residential	Low	18.5	46.6	0.112	2005	1.0
Talbot/Jacques-Cartier-1	Mixed	Medium	18.0	150.8	0.608	2004	7.7
Talbot/Jacques-Cartier-2	Mixed	Medium	18.0	238.6	0.534	2004	7.7
MEAN			**19.5**	**152.3**	**0.186**	**2004**	**4.19**

* No construction date available. Date is estimated from historical aerial footage and carries an uncertainty of ± 2 years.

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 modeled, 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.

3.4.1 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" [2]. 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 modeling movement in complex environments [29] 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 are modeled and measured continuously, unlike measures of yPET which result in a single measure between any two road users. Furthermore, multiple collision courses might be modeled 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 modeling, 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 [29].

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. 16]. 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 [27].

While surrogate safety measures such as speed are easily summarised at the site level using descriptive statistics (given the consistency of normal-like distribution of speed observations at any given site), TTC is less well summarised as it tends to have a distribution shape that varies from one site to the next. There are generally two approaches used in the literature to making TTC comparisons between sites:

- serious event comparison (SEC), which sets an assumed target threshold or set of rules of “seriousness”, e.g. $\zeta < 1.5$ seconds corresponding to the commonly cited driver reaction times of 1.5 seconds [10, 8], and counts the number of events (pairs of road users), where the representative safety indicator, e.g. $TTC_{15^{th}}$, meets this criterion. This approach thus evaluates the rate of serious events per unit of traffic exposure, or converts them into predicted collisions using conversion factors [10]. This approach is simple to implement and is the most analogous to current approaches to road safety study, but has the two main disadvantages being that it is a very coarse measure, and it makes the most assumptions about the significance of the safety indicator, e.g. in this case, a strict relationship between $TTC_{15^{th}}$ and a reaction time of 1.5 seconds is assumed. If collision-course probabilities are modeled, as in the case of discretised motion patterns, serious events can be further weighed by their modeled probability: weighted SEC [27].
- safety continuum comparison (SCC), which attempts instead to evaluate the effects of each safety indicator individually without explicitly attributing collision probability or ”seriousness” to safety indicators besides the value of the safety indicator itself. Stated differently, the objective of this approach is to decrease TTC overall, without directly investigating equivalent collisions or events. This approach is disaggregated by nature: all safety indicators impact safety in proportion to their value. This results in a data set that is hierarchical: each site having multiple road user interactions, each having different $TTC_{15^{th}}$.

4 Results

Speed, time-to-collision, and yielding post-encroachment time are measured from the trajectory data collected at all 19 roundabout merging zones and presented in this section.

4.1 Exploratory Analysis

Overall, speed is found to be normally distributed at each site for each movement profile. Comparing hourly flows versus speed, it is clear that increased traffic has a significant effect on speed, as illustrated in Figure 2. However, it can also be seen that the Swedish sites have significantly reduced speed, even after controlling for effects of congestion (traffic flow rate). Figure 2 also demonstrates that the selected sites have, from one hour to the next, roughly comparable traffic demand patterns, although variation is present from hour to hour at the same site (as is expected).

Given that the recorded speeds seem to vary based on movement types, speed measures are plotted continuously for each of the following four movement profiles [as proposed and first demonstrated in 30]:

1. vehicles travelling through the merging zone on the roundabout ring exclusively,
2. vehicles leaving the roundabout via an exit lane,
3. vehicles entering the roundabout via an approach lane, and
4. vehicles entering and exiting the roundabout via an approach lane and the next exit lane.

For example, a road user wishing to turn right at a roundabout only needs to travel across a single merging zone i.e. following a single movement type (4) through this merging zone. However, a road user wishing to make a through movement at the same roundabout must cross two successive merging zones following one movement type (3) through the first merging zone followed by a second movement type (2) through the second merging zone. In the same way, a left turn at a roundabout corresponds to movement (3) followed by one movement (1), and finally one movement (2). Finally, a U-turn or a turn at a roundabout with more than four approaches will follow movement (3) followed by multiple movements (1), and finally one movement (2).

The observed speed of road users travelling along these profiles is illustrated in Figures 3 and 4. A similar overall reduction in speed is noted at the Swedish sites, although this discrepancy is found to be most pronounced for movement type (4). Furthermore, the average approach speed just ahead of each approach yield line also appears to be lower at the Swedish sites.

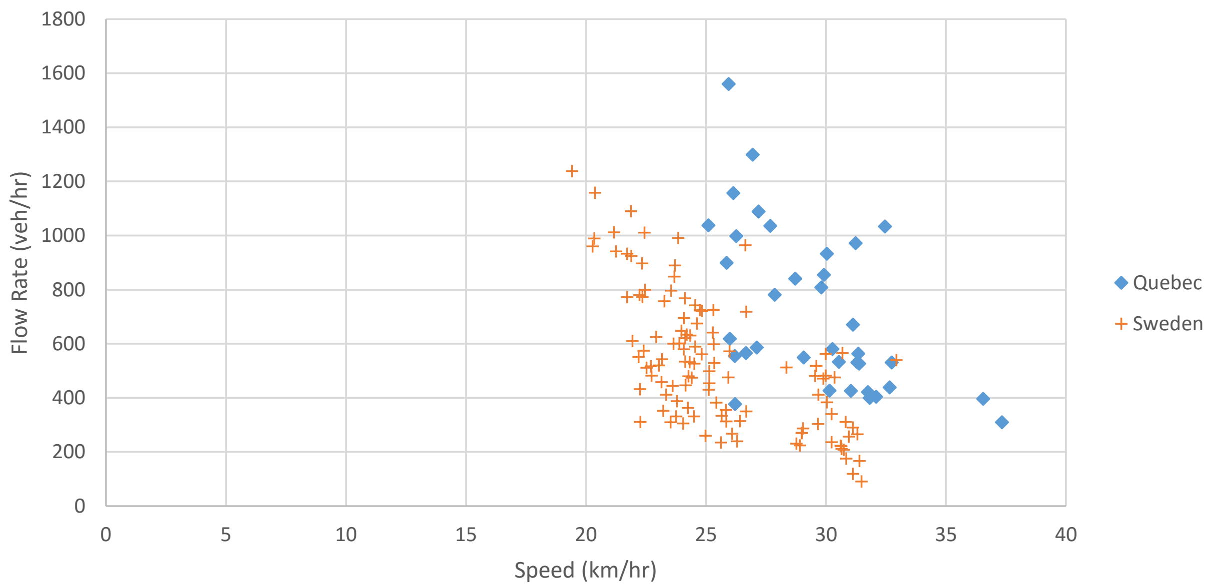

Figure 2: Hourly average speed across roundabout merge zone for all movement types.

4.2 Regression Results

4.2.1 Speed

A stepwise linear regression is performed on mean road user merging zone speed measured (in km/h) at each merging zone individually, testing all explainable differences between sites, shown in Table 2, with the exception of accident statistics, given that this dataset isn't as reliable. The coefficients of regression, adjusted R^2, Wald test score, and number of observations are provided in Table 3.

Note that roundabout outside radius, flow ratio, land use, urban density, and construction year were not significant in predicting mean speed. Instead, a relatively good model (with an adjusted $R^2 = 0.658$) with only two factors remains:

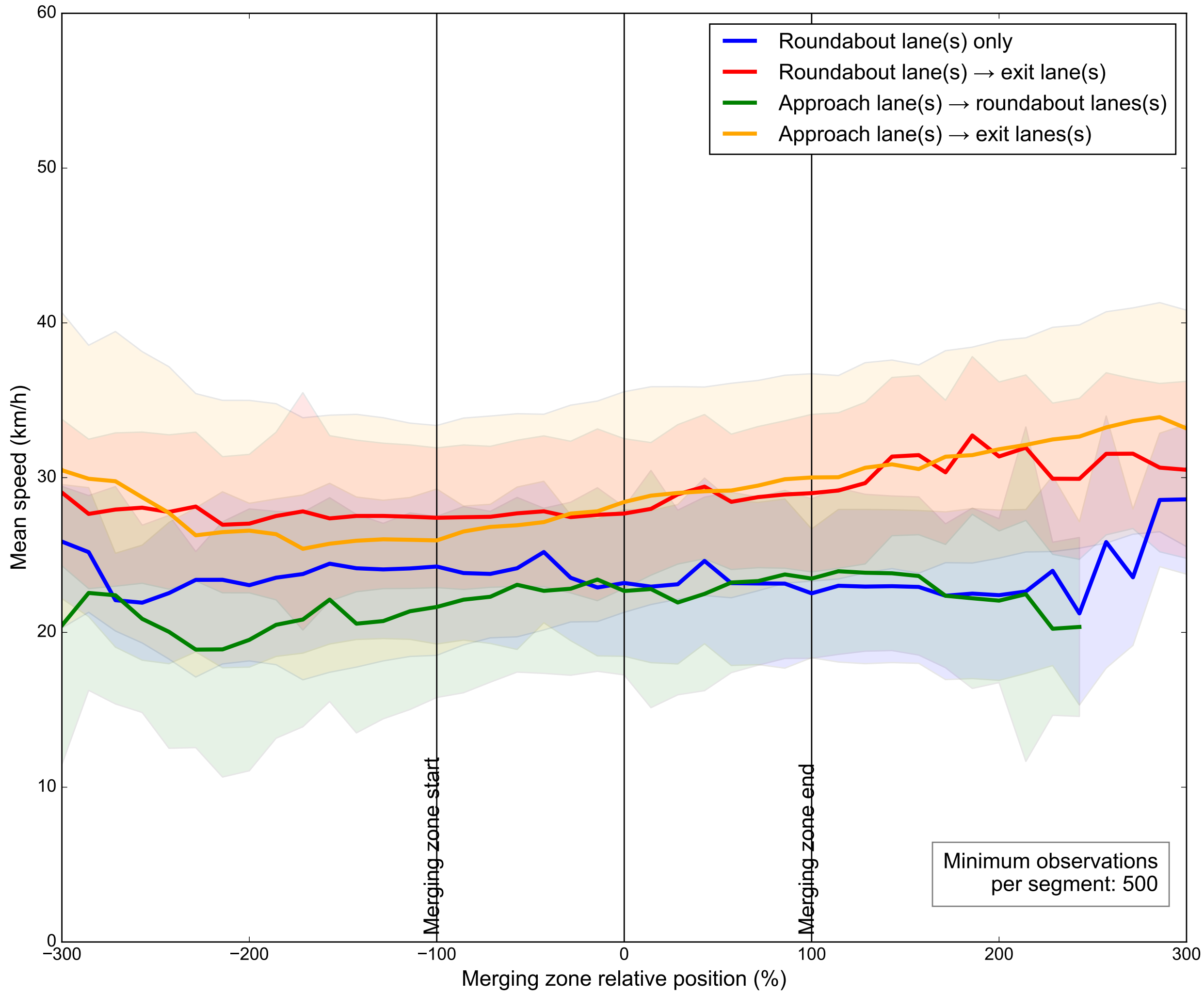

Figure 3: Mean speed for each movement profile across Québec merge zones along with $\pm\,1\,\sigma$ speed for each.

- A significant reduction in mean speed of 4.5 km/h is observed at the Swedish sites.
- Increases in hourly traffic volume are correlated with reductions in mean speed as well. This is not surprising, given standard traffic flow theory (e.g. Greenshield's Model).

The conclusions of the regression analysis support what was suggested in the exploratory analysis, concluding that regional effects such as education, enforcement (recall that all sites in this study have identical posted speed limits), or culture might be in play instead.

4.2.2 Yielding Post-Encroachment Time

A stepwise linear regression is performed on median $yPET_{\zeta<5}$ at each site, to test all explainable differences between sites, as shown in Table 2. $yPET_{\zeta<5}$ observations are separated into lead $yPET_{\zeta<5}$—when the roundabout road user enters the merging zone first—and lag $yPET_{\zeta<5}$—

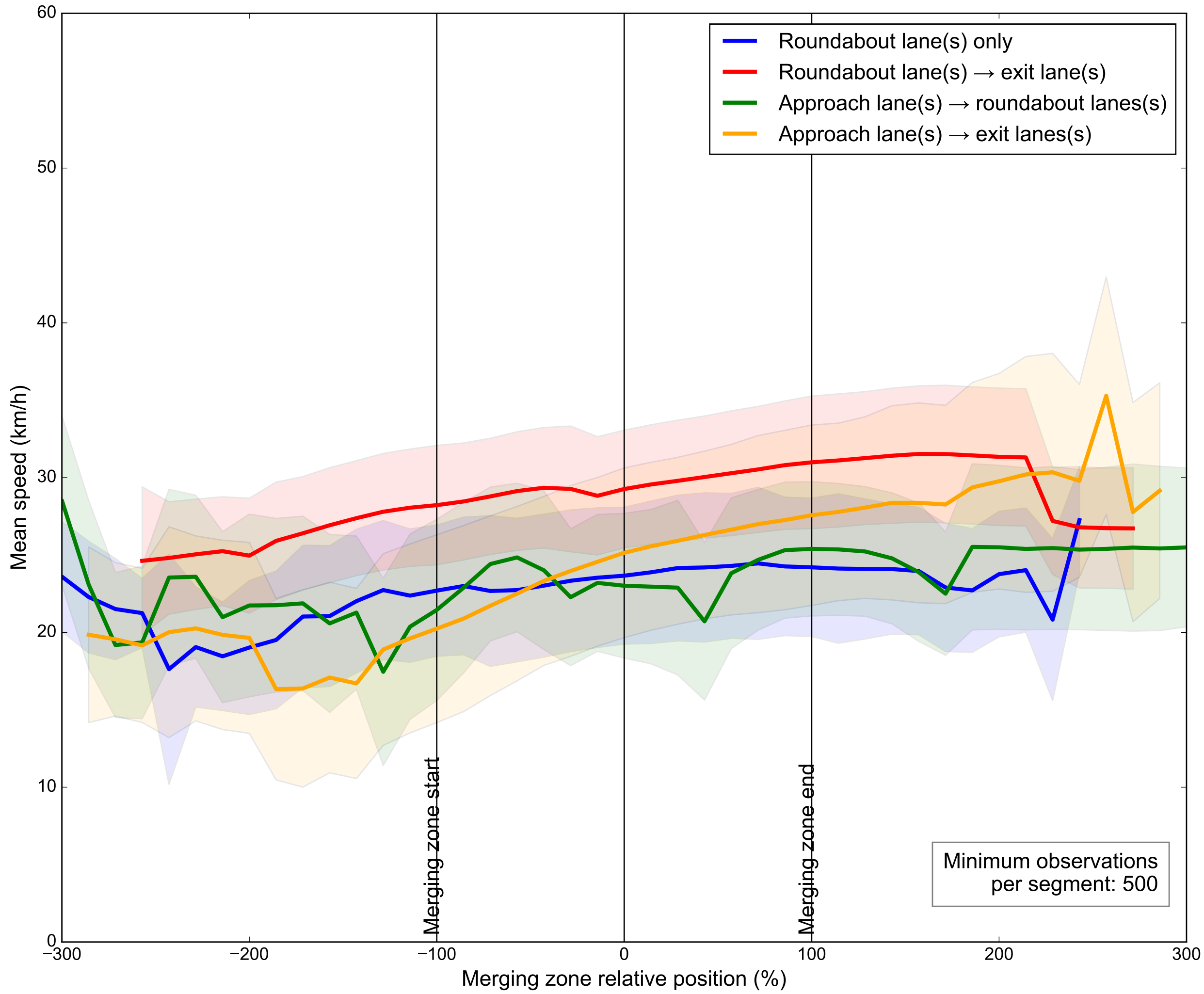

Figure 4: Mean speed for each movement profile across Swedish merge zones along with $\pm\, 1\ \sigma$ speed for each.

when the approach road user enters the merging zone first. The coefficients of regression, adjusted R^2, Wald test score, and number of observations are provided in Table 3.

No suitable regression model is found for lead $yPET_{\zeta<5}$. Meanwhile, while Outside Radius and Flow are found to be associated with lag $yPET_{\zeta<5}$, having a moderately powerful relationship, region is not found to be significantly correlated with median lag $yPET_{\zeta<5}$ either.

4.2.3 Time-to-Collision

A stepwise linear regression of motion pattern-based serious $TTC_{15^{th}cmp}$ events (measured in events per hour) is performed, using the previously mentioned weighted SEC methodology with a literature-standard threshold of $\zeta < 1.5$ seconds. No statistically significant model is found to explain $TTC_{15^{th}cmp_{\zeta<1.5}}$ events, however.

Table 3: Linear Regression Models for Mean Speed and Median Lag Yielding Post-Encroachment Time

	Mean Speed		Median Lag yPET	
	Coefficient	$P > \|t\|$	**Coefficient**	$P > \|t\|$
constant	35.898	0.000	1.303	0.018
Swedish Site	-4.460	0.007	-	-
Outside Radius (m)	-	-	.0798	0.010
Flow (per hour per lane)	-0.0240	0.003	-.00336	0.001
Adjusted R^2	0.6582		0.4475	
Wald prob. $> F$	0.0001		0.0034	
Observations	19		19	

Next, a SCC regression is attempted. As SCC TTC data is hierarchical—tens of thousands of TTC observations at each site—a random effects regression model is used, using the log of the dependent variable $TTC_{15^{th}cmp}$:

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

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.

Results of the regression are shown in Table 4. The regression yields a moderately predictive model with a between $R^2 = 0.425$ (which accounts for differences between merging zones). The difference in safety between sites seems to be in large part accounted for by the Swedish Site variable, as it is associated with an increase in expected $TTC_{15^{th}cmp}$ of 0.293 seconds, thus suggesting that sites located in Sweden benefit from a non-trivial reduction in collision probability. Construction year (or elapsed time since roundabout construction) is not found to be correlated significantly suggesting that, at this time scale at least, acclimatisation to roundabouts is not a significant effect.

A very minor within-effect is also noted, with fifteen-second traffic exposure being associated with an increase in $TTC_{15^{th}cmp}$ at a rate of 0.017 seconds per road user present within 15 seconds. This appears to be somewhat counterintuitive, but it might suggest that increasing driving complexity really does have a positive effect on increasing driver alertness. Furthermore, as evidenced with the angle of incidence parameter, interactions with a small angle of incidence, i.e. rear end conflicts, seem to be associated with lower $TTC_{15^{th}cmp}$ values than with a larger angle of incidence, i.e. side swipe conflicts.

Table 4: SCC Random Effects Regression Models for $TTC_{15^{th}cmp}$

	Coefficient	$P > \|t\|$
constant	0.583	0.000
Swedish Site	0.293	0.029
Fifteen Second Exposure	0.01690	0.000
Interaction Angle	0.003279	0.000
Within R^2	0.0540	
Between R^2	0.4244	
Overall R^2	0.0204	
Wald prob. $> F$	0.0000	
Observations	23565	
Groups	19	

5 Conclusion

In this paper, a highly detailed international comparison of roundabout merging zone behaviour is performed aiming to explain regional discrepancies in road safety using collision course modeling and surrogate safety measures. Conclusions derived from the surrogate safety measures of: speed, yielding post-encroachment time, and time-to-collision are found to be consistent among each other as well as with observed discrepancies in national historical records of road safety after controlling for a number of road geometry, land use, traffic composition, weather and climate conditions, temporal effects, and traffic exposure factors. This leaves a latent, unobserved component of road user behaviour that might be affected by local road use norms. This discrepancy might be explained by systematic lack of exposure to roundabouts (or yield signs) within an entire region. It remains to be seen, whether the rest of this behaviour is shaped by collective trends in education, enforcement, or design policy, i.e. “culture”, but it seems clear that road user behaviour is shaped by more than site-specific effects.

Additional research is warranted for investigating how systematic overuse or underuse of certain design elements, such as stop signs and yield signs, shapes driver behaviour towards other elements of the system. Future reasearch is also warranted examining other, complementary types of microscopic driver behaviour data between these countries, such as distracted driving habits and traffic violations.

Limited historical accident data was also available at individual sites and would seem to suggest that these effects present at the selected sites are generally consistent with national historical records of road safety as well as the conclusions drawn from the studied surrogate safety measures. However, given the issues with this localised accident data set, this last observation remains, for the time being, inconclusive, prompting further investigation. In general, a more thorough statistical analysis using larger sets of localised accident data will be beneficial in further solidifying conclusions drawn from surrogate safety measures.

One other limitation of this study is that, while the sample of Québec roundabouts can be considered to be regionally representative of most of the province of Québec, the roundabouts sampled in Sweden were all located in or nearby the city of Lund. Comparison between North American sites and a greater variety of European sites will be needed in a future study to determine if the regional effects demonstrated in this paper apply evenly across entire continents, or if these regional effects vary at a smaller scale (e.g. from city to city), even after controlling for environment and geometry[e.g. as in the speed study 11].

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