Detailed Driver Behaviour Analysis and Trajectory Interpretation at Roundabouts using Computer Vision Data

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Word count

Text	3841
Tables (1 X 250)	250
Figures (12 X 250)	3000
Total	*7091*

Date of submission: **August 01, 2012**

ABSTRACT

With recent and important upgrades to North American intersection design guides, roundabouts are gaining popularity as a method of reducing road conflicts, streamlining flow, and curbing excessive speeding of busy intersections. The current design approach, however, makes use of spot-mean speed measures and design criteria which do not take into account yielding behaviour and acceleration/deceleration which may be affected by regional driving culture and local roundabout design.

This research paper introduces the methodology being developed for the detailed analysis of driving behaviour, trajectory interpretation, and conflict measures in modern North American roundabouts from video data extracted by means of computer vision. The analysis explores the methods used to prepare microscopic speed maps, compiled speed profiles, lane-change counts, and gap time measures. It also introduces and discusses the interpretation of trajectories at the scale of roundabout merge sections instead of looking at safety from the point of view of a roundabout as a unified system.

The research finds significant variation in distributions of speed across five case study roundabouts in the province of Québec, Canada, which may be explained by regional differences in design and road use. It also reports aggressive gap times and uneven traffic flow as a contributing factor to speed.

INTRODUCTION

Roundabouts, a staple in European urban road design, are gaining traction in North America as a proposed means to improve road safety and capacity, and to reduce emissions of at-grade intersections. This shift towards roundabouts has followed early research initiatives in the 1960's to modernize the roundabout concept and, much more recently, the introduction of several North American roundabout design guides, including the FHWA Technical Summary (1), TRB's sponsored NHCRP Report 572 (2), and NHCRP Report 672 (3) and local guidelines such as Québec's guide (4).

Roundabouts have been proposed as an alternative method of managing conflict points inside intersections. Generally speaking, the design principle of a roundabout is to provide an at-grade crossing with fewer points of conflict. For details, refer to NHCRP Report 672.

It is important to distinguish between roundabouts and rotaries (also called traffic circles). The former are generally more compact, are unsignalised, and require entering vehicles to yield (right-angle approach), while the latter are usually much larger, can include signalization at each approach, or otherwise do not necessarily require entering vehicles to yield (tangential approach). However, roundabouts tend to occupy a larger land area than the smaller intersections they typically replace (although a greater percentage of it can be used as green space). As a result, and despite alleged benefits to flow and safety, a general trend has emerged of refurbishing rotaries into roundabouts, replacing large, complex intersections of more than four approaches, or constructing new roundabouts predominantly at city limits or in new land developments (2).

Although European roundabouts have been extensively studied and despite many short-term macroscopic North American studies, there is a lack of research concerned with localised and long-term driving behaviour. There is however acknowledgment of problems with low familiarity among drivers (5). This paper aims to examine driver behaviour and indicators of road safety of roundabouts, to structure the automated conflict analysis methodology (particularly at a microscopic level, i.e. individual lane changes) and to conduct basic driver behaviour analysis related to conflicts for a sample of roundabouts across Québec, Canada. Basic driver behaviour analysis generally covers lane changes and speed profiles, and rate of compliance with prescribed driving regulations and practical design problems of driving regulations (such as driver familiarity, culture). The conflict analysis methodology relies on the interpretation of vehicle trajectories and the statistical analysis of the resulting indicators to identify problematic interaction hotspots or important potential points of collision.

This paper briefly overviews roundabout literature focused on safety and driver behaviour, then elaborates the scope of analysis, video data collection, trajectory interpretation, and behavioural measures and methods, and provides driver behaviour analysis of five case study roundabouts in Québec.

BACKGROUND

Roundabout Safety

Despite a theoretical reduction in number of conflict points, there is still some debate over the practical reduction in accidents, particularly regarding individual design elements, design execution, and regional driving behaviour. The NHCRP Report 672 summarizes crash reduction studies in the United States and internationally, though admittedly these reductions in accidents were mostly favourable for single-lane, rural, low-AADT sites. A recent study by Gross *et. al.* showed reductions in accident rates (historical analysis), using an empirical Bayes (EB) study of converted roundabouts (6). European studies of roundabout conversions are already well established with Elvik summarizing 113 such studies and finding that results were mixed, though slightly favourable for small roundabouts. Other studies targeting particular groups of road users have found increases in accidents, however, including a study of cyclists (7) and cycle facilities (8) by Daniels *et al.*

Recently, Chen *et al.* found that average approach speed to be the most significant predictor of accidents and used Bayesian Poisson-gamma and zero-inflated Poisson models to predict accidents (9).

This study used mean approach spot speed as outlined in NHCRP RPT 572, which is acceptable for macroscopic studies, but may be inadequate for thorough analysis of geometric elements as speed is suspected to change significantly across different roundabout elements.

Al-Ghandour studied roundabout slip lanes using SSAM (a tool for the analysis of conflicts generated in microsimulation) along with Poisson regression to conclude that slip lanes reduce conflict occurrence (10), though it is not yet quite clear how isolating conflicts can lead to improvements in design safety, as some might argue that decreasing exposure and therefore learning opportunities encourages drivers to take more driving risks. It should be noted that the NHCRP design guide classifies roundabout slip lanes as non-standard since they can induce conflicts with cyclists and pedestrians. In any case, lane layout and design varies heavily from jurisdiction to jurisdiction.

Roundabout conflicts and driver behaviour

Hydén and Várhelyi studied 21 roundabouts and found that speeds (as recorded at "junctions and on stretches" in addition to speed profiles using the car-chase method (11)) always reduced 4 months after implementation of the roundabout, although some gains in speed reduction were lost after 4 years (12). Roundabout speeds tended to stabilize around 30 km/h; one approach with a before operating speed of 20 km/h saw its operating speed increase after the implementation of the roundabout, suggesting that roundabouts might have a fixed effect on speed. The study suggested that these changes in speed had a negative impact on travel time and emissions for major streets, while seeing gains on smaller streets.

Sakshaug *et al.* used video-assisted manual conflict analysis to justify the design of separated cyclist facilities inside roundabouts with mixed results. It was generally found that most significant conflicts arose at approach crossings which are independent from cycle track integration design (13).

Guido *et al.* studied conflict measures (such as the time to collision (TTC)) at roundabouts, though the work remains highly theoretical and does not assess risks in terms of observed accidents nor comparatively between sites (14). The methodology considered thresholds on conflict measures instead, such as the 1.5 s threshold on TTC proposed in (15).

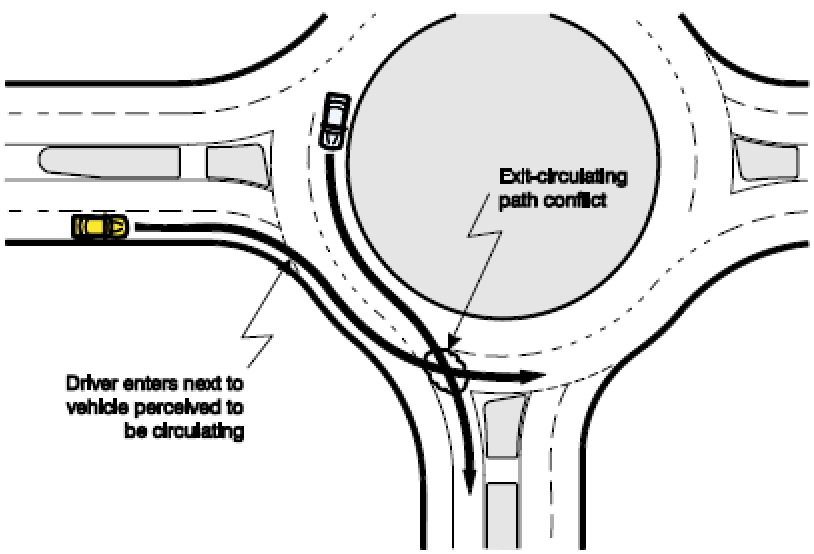


Figure 1 – Comparison of conflict points inside of a traditional intersection and a roundabout. Image source: NHCRP Report 672.

Besides single-lane merging conflicts at approaches, a unique problem of multi-lane roundabouts are conflicts arising from short merging zones: drivers with a tendency to take the shortest path available will use the inside lane for through and left-turn movements, only to return to the outside-most lane immediately upon exiting, intersecting others attempting to enter on the outside lane (depicted in Figure 1), and this problem is exacerbated by merging lengths of a typical small-sized roundabout that are too short to signal intentions and by the proportion of exiting drivers that do not signal properly. Most design guides acknowledge this issue but dismiss the problem with the assumption that speeds are slower therefore potential collisions would be less severe (3). Other conflicts identified are present in parallel movements and include failure to maintain lane position, which can induce problematic lane exchange.

Non-safety-oriented research

Mussone *et al.* recently demonstrated video-based trajectory analysis for a single roundabout using the VeTRA engine and reported the vehicle speed profiles (16). Results were focused on the methodology, and not the interpretation of the results.

Several other papers have looked at roundabout elements such as non-standardized roundabout models (17) and roundabout weaving areas (18) and are noteworthy for deconstructing sub-elements of roundabout design, though these were limited to vehicle flow rates only.

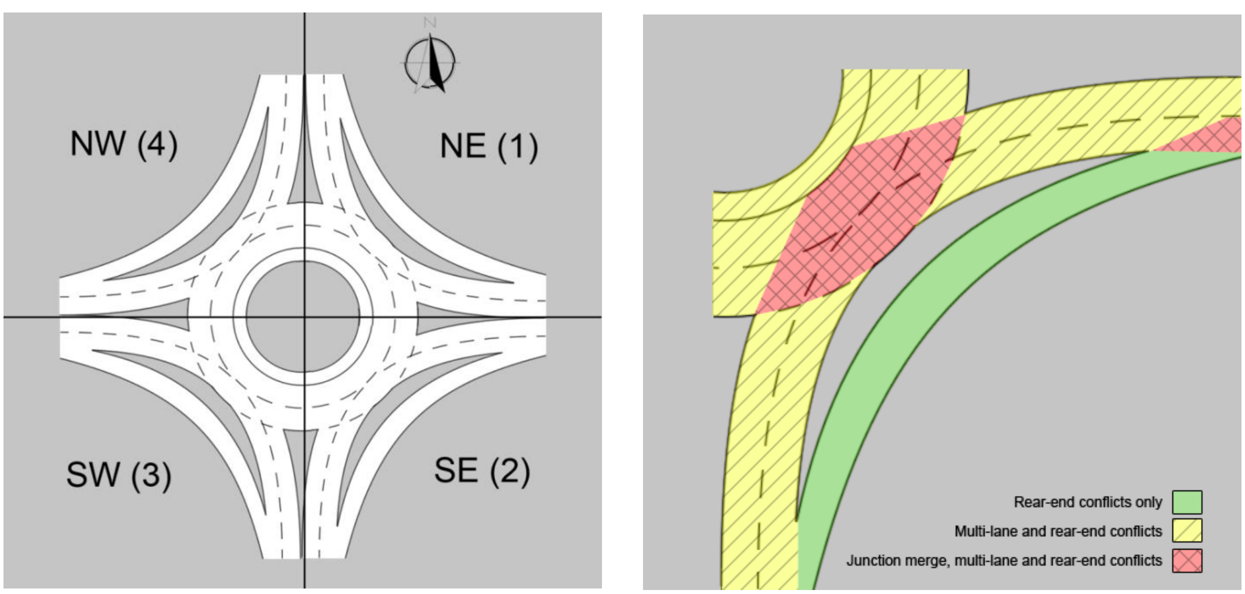
METHODOLOGY

A subsection-based analysis of roundabouts, which isolates study areas into component lane junctions (approach-exit "quadrants" which delimit a common merge section), is proposed for the following three reasons:

I. Conflicts are microscopic events which occur at the scale of individual merge sections and lane changes, of which many exist for every roundabout. It is logistically impractical to film most roundabouts in their entirety for analysis.

II. By design of a roundabout, conflicts arising in one quadrant are necessarily independent from conflicts arising in other quadrants, though theoretically, individual vehicles present in one quadrant may interact with vehicles in the following quadrant along the quadrant boundary.

III. Whole roundabouts available for this study are rarely symmetrical and almost never comparable as a whole, in the case of both internal characteristics (number of lanes, approach angle, diameter, etc.) and external characteristics (distance from approach intersection, land use, etc.)



a) b)

Figure 2 – Roundabout quadrant diagrams depicting the breakdown of sub regions: a) a typical four-approach roundabout cut into four quadrants; b) conflict zones for one typical quadrant.

Figure 2a presents a typical multi-lane roundabout with optional slip lanes cut into 4 quadrants. Quadrant size and number can vary by number of approaches and exits, and can also vary according to road configuration.

Figure 2b illustrates identified conflict zones for each quadrant. Roundabouts are assumed to have no head-on or right-angle conflicts—at 90 degrees or more—except when a driver incorrectly manoeuvres inside the roundabout (these events were observed frequently during data collection). Multi-lane corridors generate natural lane-change conflicts while junction merges generate additional, forced lane-change conflicts. Rear-end conflicts exist at all times and in all corridors.

Video data collection

As a first step, a set of roundabouts is selected for video data collection. Filming is conducted using a purpose-built mobile video camera system (19) during weekdays, under normal traffic flow conditions between 6 a.m. and 8 p.m., although not all hours are retained for analysis because of low incidents or flow rates. These sites and recording times are primarily chosen for containing a similar number of vehicular interactions (two or more vehicles operating in neighbouring vehicle-space) at a time. Choice of layout and geometry vary significantly, however, in order to explore how these variations might affect behaviour.

For each quadrant, a camera is set up on a nearby light pole, usually situated on an approach or exit opposite the main junction area, as depicted in Figure 3. Care must be taken to avoid occlusion which could lead to tracking problems and distortion problems from wide angles of view, though this distortion can be corrected to a certain degree. For conflicts, it is more desirable to focus on approaches rather than exits, as most conflicts are generated from converging flows except where exiting requires a lane change (20).

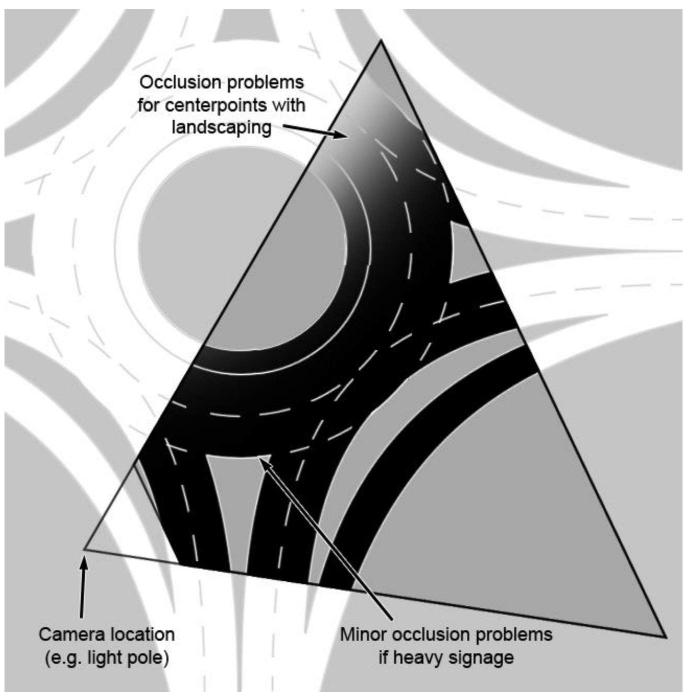


Figure 3 – Camera installation with field of view. Areas of concern of typical occlusion are highlighted.

Trajectory data generation

In order to record vehicle trajectories, previously developed video-based automated tracking technology is used as presented in (21), (20), to extract the position of vehicles in Cartesian space over time on a discrete scale of 15 observations per second. Figure 4 illustrates sample trajectory positions for one roundabout under study.

Trajectories are bounded to a defined analysis area in order to focus analysis on a particular region of interest. This practice also removes warm-up error typically seen at the edges of the video. Trajectories are then programmatically associated with a lane alignment for each lane as defined in Figure 5 using a hybrid sub-path/envelope methodology (see (22) for a detailed review of trajectory path assignment and analysis). Velocity and, to a lesser extent acceleration, are then calculated and smoothed, using a moving average window over 5 frames or 0.33 seconds.

It is interesting to point out that the mean trajectory of each lane does not perfectly overlap inside the junction area in this single-lane example, suggesting that drivers will have a tendency to drive on the inside of any curved portion of the roundabout. This phenomenon is already well known in traditional curve design practice.

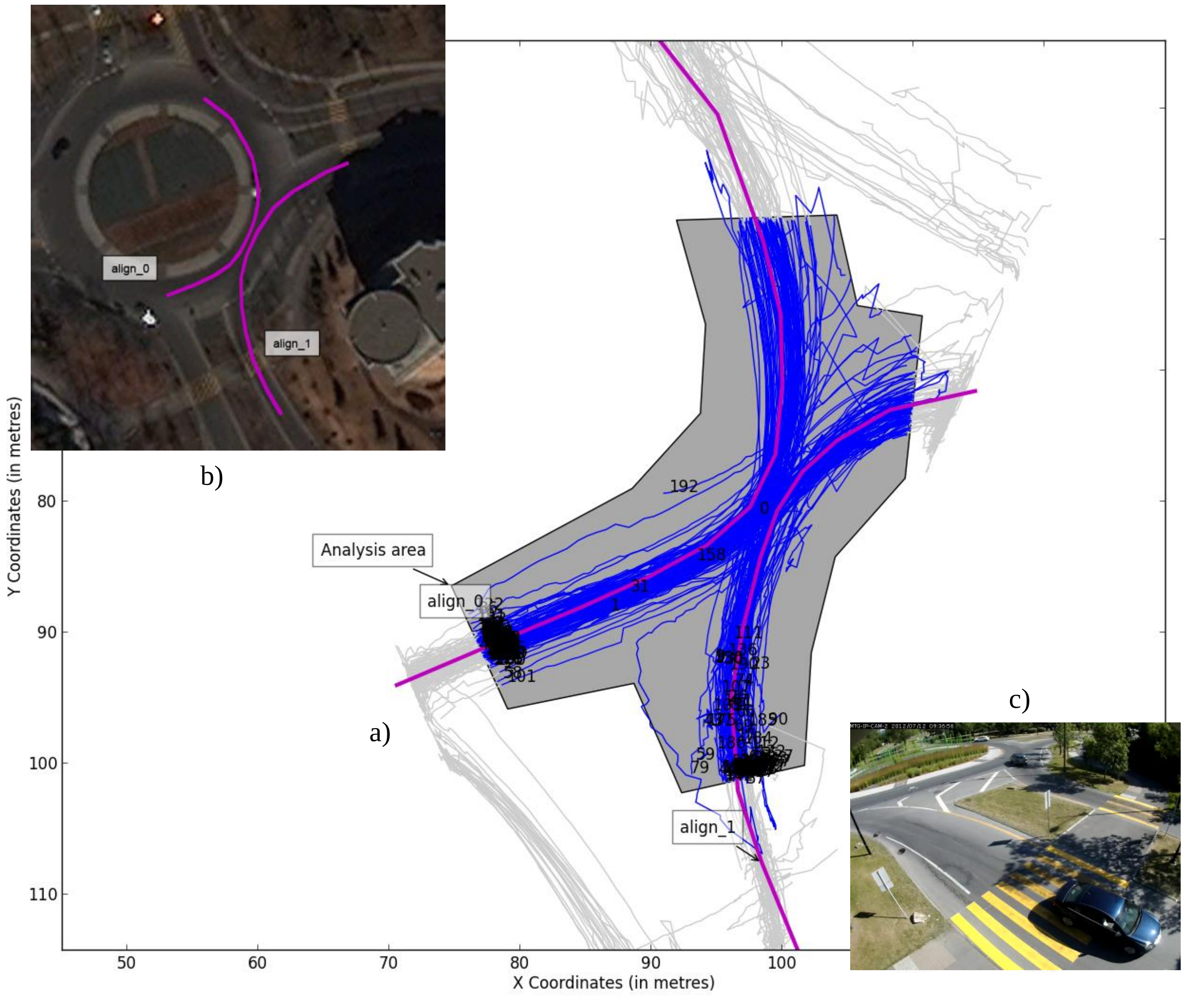


Figure 4 – a) Sample trajectories with b) satellite imagery and 3) sample video view (the approximate location of the camera is at coordinates (85,125)). The analysis area delimiting trajectories and reducing warm-up tracking errors, as well as the lane alignment paths are shown. align_0 corresponds to the single roundabout lane. align_1 corresponds to the approach, shoulder and exiting lane. Some tracking errors still persist inside the analysis area.

Figure 5 illustrates the typical arrangement of lane alignments—to which each trajectory is mapped. Merging and diverging actions can be detected with a high degree of accuracy, particularly between distinct and physically separated corridors. With multi-lane corridors however, distinguishing between lane changes and merges can be a little ambiguous. For this reason, lane alignment overlap is usually removed if lanes and trajectories both overlap. In this case, the convention is to leave roundabout lane alignments continuous (as they have priority of way) and to cut approach and exit alignments and measure temporary lane changes into the roundabout and then back out. For example, a vehicle traveling along the entire align_1_1 in Figure 5 will register as having merged into align_0_0, then into align_0_1, then back into align_0_0, and finally back into the exit portion of align_1_1. This trajectory crosses paths three times to form three conflict points and is generally discouraged as it poses the problems presented in Figure 1.

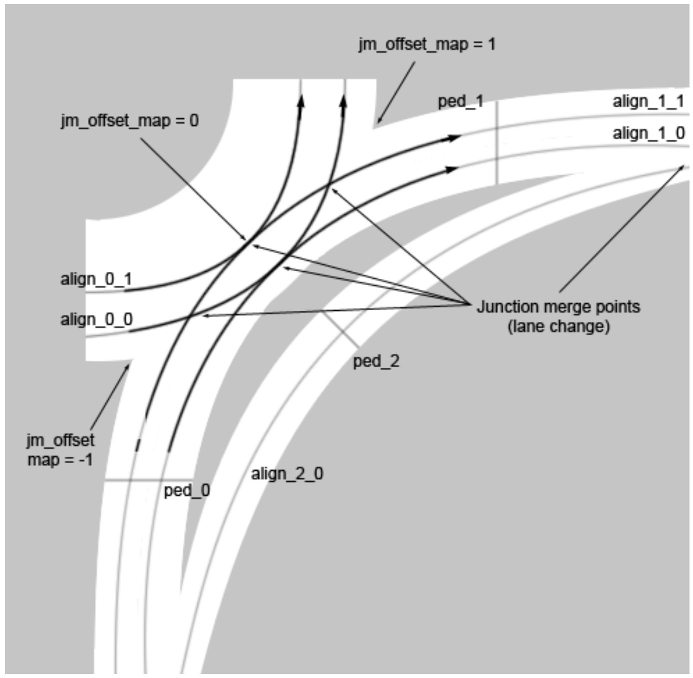


Figure 5 – Typical arrangement of trajectory alignments for a multi-lane quadrant.

Driver Behaviour Measures

The following measures are inferred from compiled and interpreted trajectory data:

- *Speed map/profile*: provides the evolution of the velocity (speed and orientation) of each vehicle along the entire analysis length.
- *Yielding*: identifies inadequate yielding behaviour at approaches.
- *Lane changes*: identifies locations in Cartesian space with substantial lane-change density, lane-change direction, and lane use.
- *Incorrect manoeuvres*: identifies manoeuvres which follow proscribed driving behaviour such as entering the roundabout in the wrong direction, u-turns at the approach median, crossing lanes to exit the roundabout, etc.
- *Conflict measures*: includes typical safety measures such as gap time, but can also include more advanced measures such as time-to-collision (TTC). These measures represent indicators of interaction “severity,” or proximity to a potential collision.

Figure 6 illustrates a sample mean speed map with overlaid vector field, both built from compiling velocity data into 2-dimensional histograms. The mean speed map clearly shows variation in speed according to location as well as direction, though does not provide information about speed distribution and local variation.

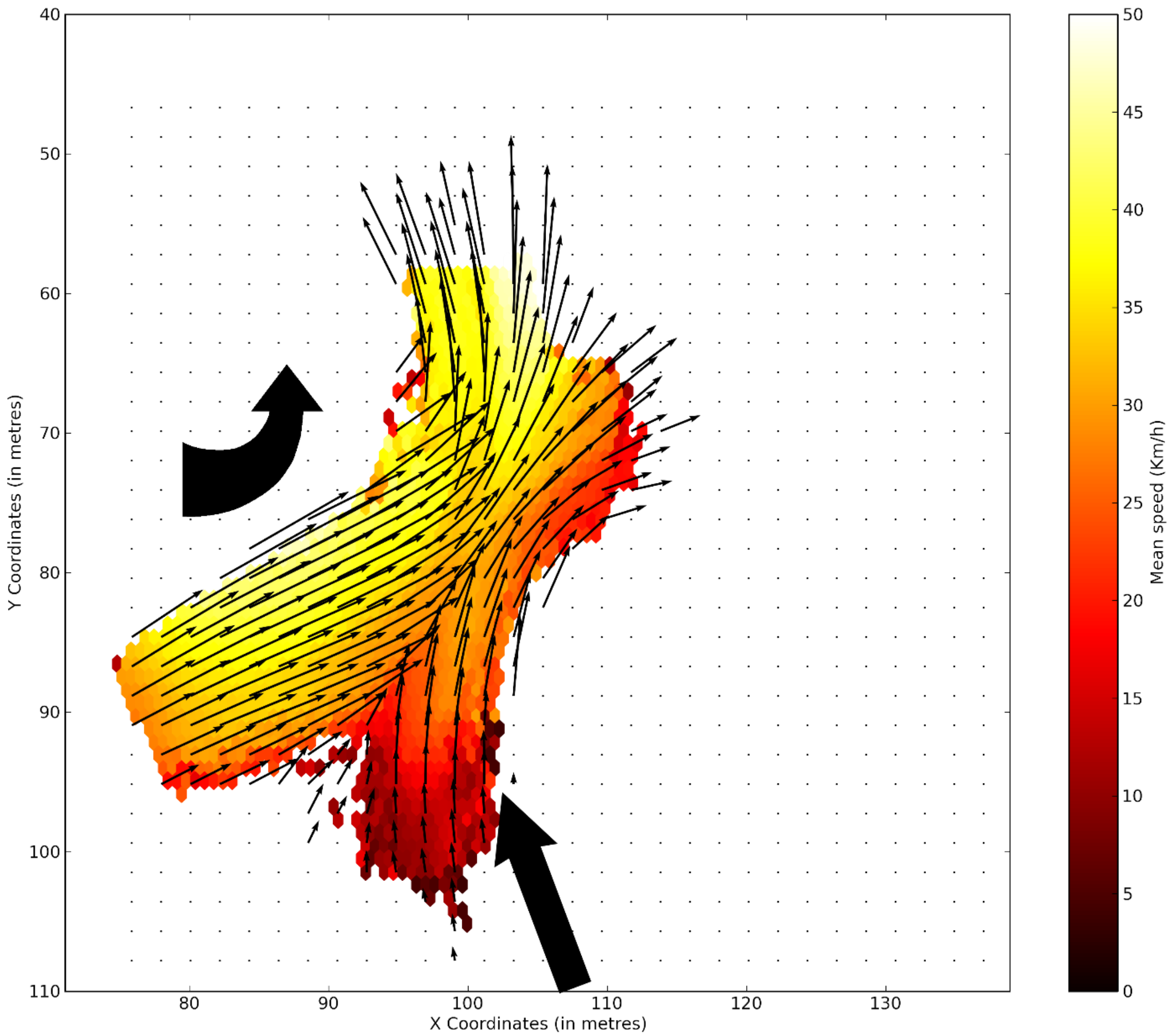


Figure 6 – Sample mean speed map (2-dimensional histogram of mean speed observations in an 80-bin by 80-in grid) with overlaid velocity vector field (large black arrows indicate movements in the center and on the approach). Speeds inside the roundabout are noticeably faster than at the approach or exit.

Figure 7 addresses the previous deficiency by plotting the exact mean speed along with +/- 1 standard deviations (speeds are observed to be normally distributed, see results) for each position along each alignment. The alignment is measured in metres starting from an arbitrary origin, but the top axis indicates the start and end position (-1 to 1) of the road junction and merge zone as illustrated in Figure 2b, for the purposes of comparing geometry of different scales. The observation rate rises and falls as lane changes occur and flow ratios change. The sum of all observations will also have a tendency to fall as faster speeds tend to result in fewer overall observations.

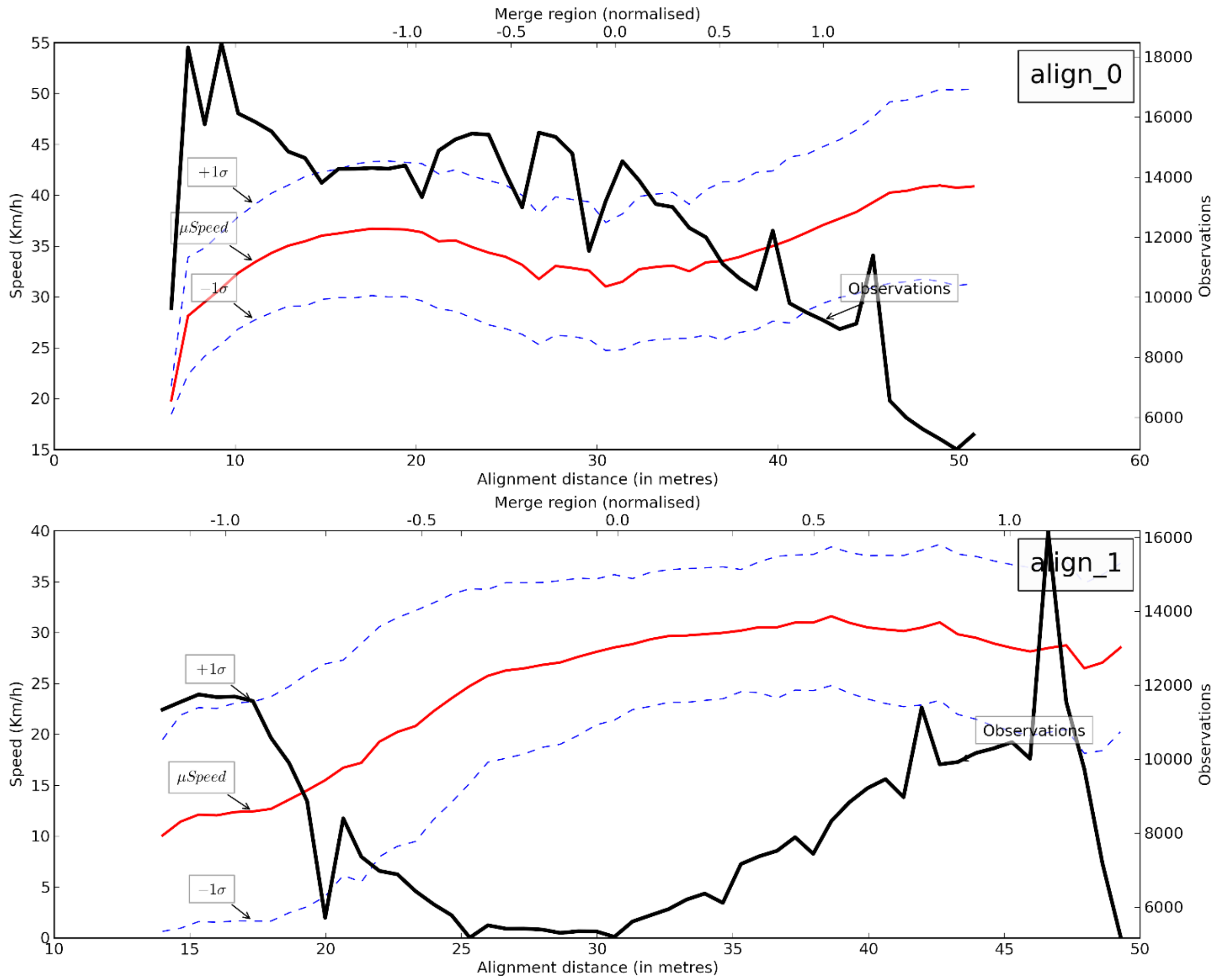
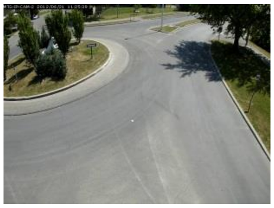


Figure 7 – Sample speed profile (mean with +/- 1 normal standard deviation) and observations.

EXPERIMENTAL RESULTS

Table 1 lists the five case study sites. All five sites have major variations in layout. DesSoeurs-duGolf is unique in that it is a mixed multi-lane and single-lane roundabout—with inside turning lanes but no internal medians—and hatched curb extensions. It is also host to the crossroad of two major roads and has a high flow rate on all sides, which makes it one of the few observed roundabouts without heavily polarized flows (uneven traffic flow, throughout the day and within a site). DesSoeurs-ReneLévesque is unique in that it only has 3 approaches in total (T-intersection), although the analysis area was still contained within a quadrant of 90 degrees in size. DesSources-Riverdale is characterised by a residential/suburban environment and low flows. It also features a major road which connects at right angles. Frechette-AnneLeSeigneur is a typical roundabout with no specific characteristics. Nobel-Curie is Québec’s oldest roundabout and is multi-lane throughout. The design speed for all of these roundabouts is 35 km/h while the local speed limit ranges from 40 to 50 km/h.

Table 1 – List of sites.

Site	*Number of Vehicles Tracked*	*Analysis Time (Minutes)*	*Vehicles/ Hour*	*Layout*	*Sample View*
DesSoeurs-duGolf	14665	750	1173	4 approaches Symmetrical Major through/major Multi/single lane	
DesSoeurs-ReneLevesque	4789	569	505	3 approaches Non symmetrical Major through/minor Single lane	
DesSources-Riverdale	420	225	112	4 approaches Non symmetrical Major turn/minor Single lane	
Frechette-AnneLeSeigneur	4296	490	526	4 approaches Symmetrical Major through/minor Single-lane	
Nobel-Curie	3388	480	423	4 approaches Symmetrical Major through/minor Multi-lane	

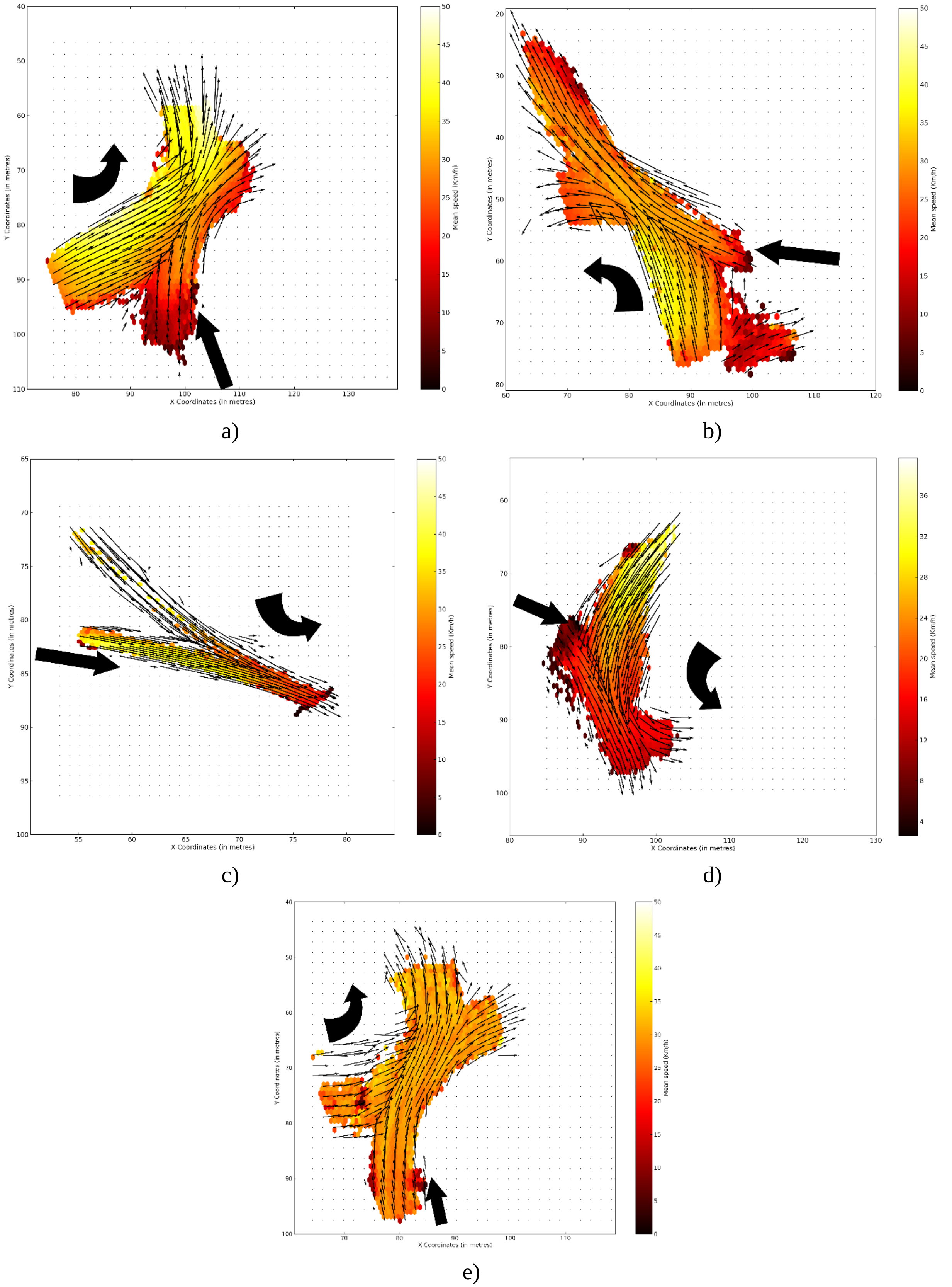


Figure 8 – Speed profiles and velocity vector fields for: a) desSoeurs-duGolf; b) desSoeurs-ReneLevesque; c) desSources-Riverdale; d) Frechette-AnneLeSeigneur; e) Nobel-Curie. Colour ramps are scaled from 0-50 km/h in all maps.

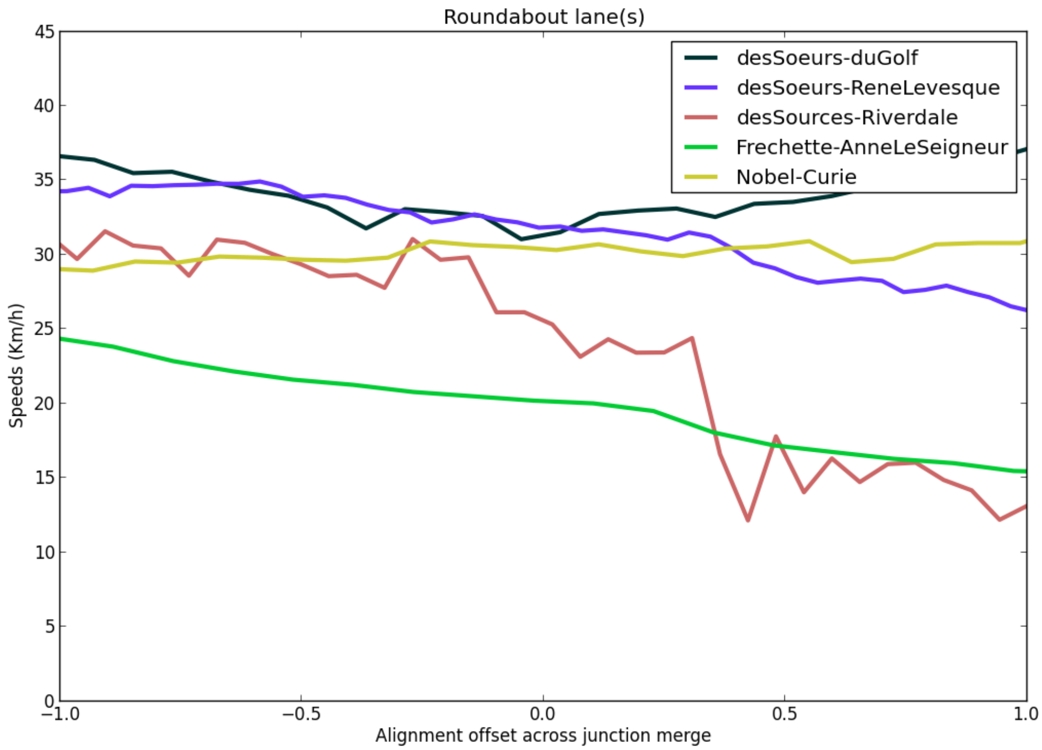


Figure 9 – Mean speed profile for all roundabout lanes (align_0).

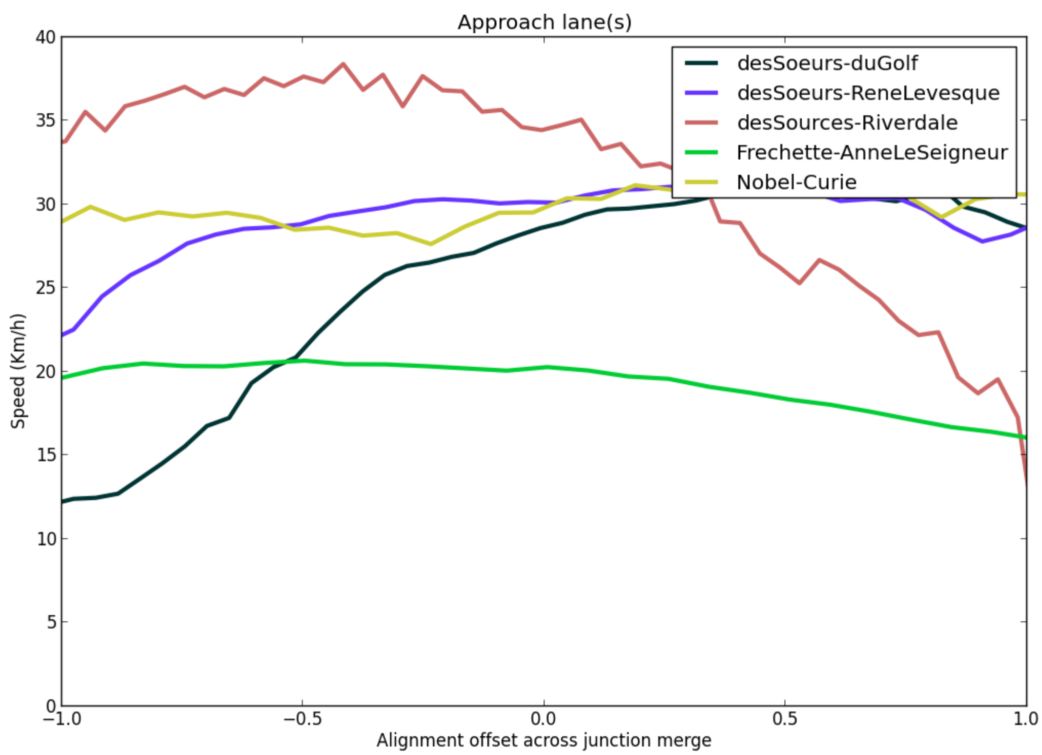


Figure 10 – Mean speed profile for all approach and side lanes (align_1).

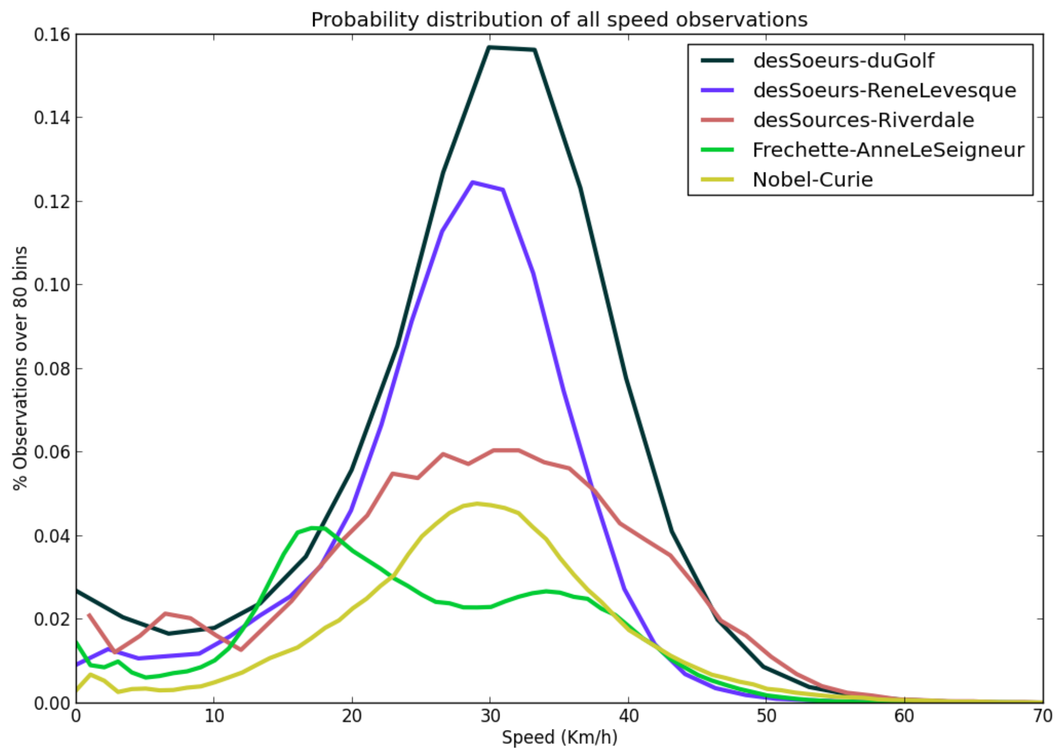


Figure 11 – Distribution of measured speeds for all observations of all roundabouts.

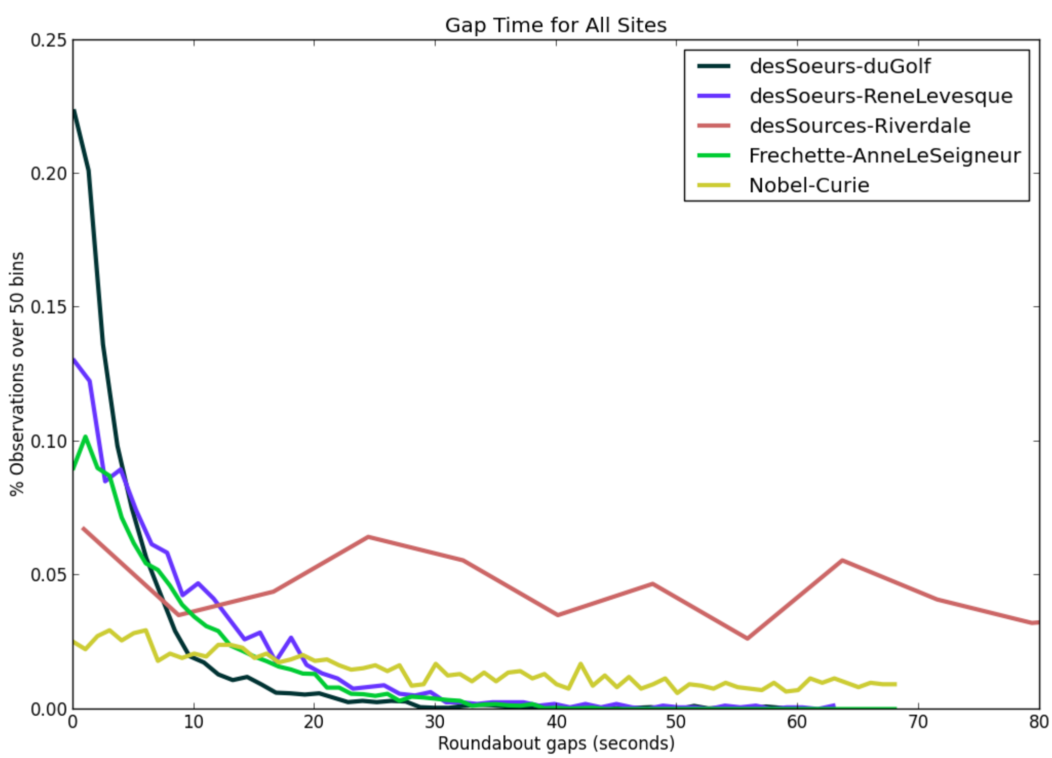


Figure 12 – Distribution of gap time in seconds between approaching (entering) vehicles and the next vehicle inside the roundabout for all roundabouts.

Figure 8 lists the generated speed maps/velocity vectors for each site. Lighter/yellow areas indicate high average speeds while darker/redder areas indicate lower average speeds (all colour ramps are scaled from [0-50] km/h). With the exception of Nobel-Curie, all roundabout lanes average 35-40 km/h just before hitting the merging zone. This area is primarily sampled by vehicles *already in the roundabout*. The merge area has varied average speed, from 20 km/h up to 40 km/h in the case of desSoeurs-duGolf. As one would expect, approaches are characterized by low speeds, from vehicles yielding, with the exception of desSources-Riverdale, which has a very high approach speed. This is most likely explained by the very low flow and nearly tangential approach angle. Surprisingly, Nobel-Curie stands out as having a uniform speed, likely because flows are extremely polarized (this roundabout feeds only a handful of corporate and industrial parking areas). Even within roundabout lanes, speeds are the highest on the innermost portions, suggesting drivers in a hurry do more than speed: they also take the shortest route through the roundabout.

Figure 9 and Figure 10 explore the speed profiles according to relation with geometry, by lining up merge zones and separating roundabout lanes, and approach/exit lanes and the turning shoulder. Frechette-AnneLeSeigneur reports a surprisingly low average and consistent speed, although this effect is possibly explained by heavy traffic, small diameter, and a larger sample of trucks (not shown).

There is no clear trend, though speeds also tend to increase at the start of the junction zone (at -1 offset) and stabilize half-way through the junction zone (at 0 offset), particularly desSoeurs-duGolf, which experiences very high demand translating to high roundabout entering wait times.

Speed distributions are repeated in Figure 11, presenting the distribution of all observed speeds for each site. All sites show a clear normal distribution centered on 30 km/h with the exception of Frechette-AnneLeSeigneur, as discussed previously.

Lane changes, stopping behaviour, and gap time measures were recorded in addition to speed profiles. Gap time measures are illustrated as a probability distribution in Figure 12. With the exception of desSources-Riverdale which had too low a flow rate to produce meaningful interaction measures, the majority of gaps seemed to be concentrated within 0-10 seconds. It is still a little early to interpret gap times in relationship to yielding behaviour without a thorough discussion of yielding factors and limits, however it looks as though there is a logical relationship between very small gaps and high speed.

CONCLUSION

This paper lays out the framework for a trajectory interpretation and microscopic analysis of driving behaviour in roundabouts and more generally for key road infrastructure elements including: alignment assignment, geometry remapping (for the purpose of site comparison), and behavioural measures. However, a significantly larger sample of sites will be needed to investigate regional and geometry-specific variation of driver behaviour in depth. A comprehensive list of accidents at each site is being constructed in parallel to investigate the predictive power of behavioural measures as well as surrogate safety measures.

The experimental results on the five Québec sample sites provide practical experience interpreting speed profiles and illustrate the important variation in behavioural measures across even a limited number of sites. Trends are found to exist, though they appear not nearly as uniform as may be needed when working with prescribed spot-mean speed measurements. Most importantly, the results seem to confirm the literature regarding macroscopic speed, but identifies large and inconsistent local speed variation. Polarization of traffic flow also proved to be a significant aspect in determining the shape of the speed profile.

It should be noted that some limitations exist, particularly regarding the accuracy of the results. Computer vision is a field in heavy development with much room for improvement. While the tracking results used for this research are deemed adequate for exploratory analysis, higher-level interpretation of trajectories—both feature recognition and movement interpretation—or better data collection equipment (particularly a view from a higher angle) is still needed for improved accuracy. A notable and urgent area under development concerns volumetric correction of parallax errors, and vehicle class and size estimation.

Still, errors tend to be reproduced from site to site, minimizing error during comparative analysis and particularly when using similar camera orientations, though this approach is less useful when examining specific vehicle trajectory cases. Computer vision is also not suited for interpreting non-visual cues of behaviour including honking and screeching caused by tire slip, two types of events observed frequently—though informally—during data collection. Sound-based conflict recording technology has been used before and may prove useful in conjunction with the current deployment of computer vision.

ACKNOWLEDGMENTS

This research project is funded by the Québec Fund for Research on Nature and Technology (FQRNT), the Québec Ministry of Transportation (MTQ), and the Québec Fund for Health Research (FRSQ) as part of their research program on road safety. The authors wish to acknowledge the help of participating municipalities and the MTQ for this research.

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