# A Surrogate Safety Analysis at Protected Freeway Ramps Using Cross-Sectional and Before-After Video Data

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## ABSTRACT

This study presents a surrogate approach for safety analysis of freeway facilities using automated trajectory collection and behavioural analysis from surrogate measures of safety (in particular time to collision). This methodology is proposed as a potential alternative or complement to the classical approach based on historical accident data, particularly suited for evaluating the microscopic safety effects of road treatments for which there is a lack of traffic and accident data. A short theoretical discussion of traffic conflicts is followed by a proposed methodology illustrated using as a small sample of freeway ramps as an application environment. From this sample, video data is obtained as part of a safety study to investigate the effectiveness of the "one-way lane-change closure" treatment near urban freeway ramps in Montreal, Canada. To illustrate the applicability of our methodology, two comparative examples are presented: (1) a cross-sectional study and (2) a before-after study involving two sites, one of which had video data available before and after the implementation of the treatment. Various methods of aggregating the data, spatially and temporally, are explored in the applications.



## KEYWORDS:

Driver behaviour, highway design, surrogate safety, traffic conflicts, traffic safety, video analysis

## INTRODUCTION

An important area of research in road safety is the identification of the safety effectiveness of countermeasures to problematic transportation facility designs. Improving road safety through effective countermeasures is always a top priority for researchers, practitioners and the public in general.

However, determining the safety effectiveness of a treatment can be a difficult task; in particular when very little historical before-after accident data and empirical evidences are available from past studies. In some cases, data exists, but it is incomplete. Moreover, pilot projects pose the problem of exposing the public to unknown potential accident risks. The question remains, how does one reliably evaluate new transportation safety strategies without risky pilot projects and long, and extensive data collection projects as in the classical before-after approach?

In this respect, researchers and practitioners are seeking valid and quick proactive safety evaluation methods to evaluate safety treatments without exposing traffic to potential increases in accident risk. Such methods, also collectively known as surrogate safety analysis, can be traced back at least to the late 1960's (1) where conflict measures were devised to solve the problem of long return periods for collision observations (2). The primary surrogate safety approach consists of conflict analysis (3) (4). The effectiveness of the conflict analysis approach has been much disputed and the primary arguments against the approach typically include the subjectivity of conflict observation, the difficulty in defining surrogate measures of safety, and an ambiguous relationship between conflicts and collision frequency and conflicts and collision severity (5). Additionally, the cost and reliability of manual data collection is another impediment to the widespread use of the approach.

This research aims to tackle some of these technical challenges by making use of emerging information technology systems to facilitate objective and consistent traffic behaviour data collection. Specifically, the objective of this research is two-fold: 1) to develop a methodology to determine the safety status of freeway ramps using conflict analysis and 2) to demonstrate its applicability using, as an application environment, a small sample of highway ramps with and without a "one-way lane-change closure". The results of the case study are divided into two outcomes: a cross-sectional and a before-after analysis. Moreover, for this purpose, vehicle size, position, speed, and acceleration data is extrapolated from video footage for multiple vehicles simultaneously. This data is then mined to develop surrogate measures of safety for a given location.

The paper is organized as follows: the next section will cover previous research, followed by an overview of the methodology, a description of a case study to apply the methodology and some initial observations and experimental results.

## LITERATURE REVIEW

Surrogate safety analysis is not a new subject of research. Many papers in road safety have argued for and against the use of conflict analysis as a reliable safety measure, both on the standpoint of collision severity and collision frequency. The reader is invited to consult (3), (5) and (6) for detailed summary of the conclusions of numerous conflict studies. A recurrent argument against conflict studies in transportation safety involves the difficulty in obtaining quantitatively defined and objectively measured data and that the application of the methodology is often too broadly defined.

Lately, however, obtaining objective data for surrogate safety analysis is becoming more feasible with advances in video tracking algorithms, increased access to more affordable processing power, increased data management, and emerging transportation information technology systems. The use of video analysis for transportation studies is rising dramatically. Many traffic behaviour studies have been conducted around data collected from cameras, e.g. Sarvi et al. (7); video data has been used for simulation calibration and traffic flow theory (e.g. the NGSIM program (8)); and some companies now offer automated traffic counting solutions using video detection. Automated video analysis for conflict analysis has been developed and used extensively by Sayed, Saunier and Ismail primarily for road safety analysis at intersections, including vehicle conflicts (9) and pedestrian-vehicle conflicts (10) (11) amongst others.

As a key element in the development of accurate traffic measurements, there is a growing interest in computer vision for automated traffic video analysis, which allows for the acquisition of multiple traffic data along road sections. Versavel lists volume, speed, density, headway, and location as the primary traffic data; and counts, speed (acceleration), vehicle length, class, type and position as the individual vehicle data (12). The reader is invited to consult (13), (14) and (15) for more detailed information on the specifics of feature-based vehicle tracking.

Supported by previous studies (9) (10) (11), the main benefit of automated video analysis for safety analysis is that it offers a flexible, convenient, low-cost method of collecting real, detailed driver behaviour data in the hopes that trajectory-based behaviour data holds some predictive power in estimating road collisions. This data has the advantage of being microscopic in scope without the need to install intrusive monitoring equipment.

However, video analytics is not without limitations including: the complexity of computer vision algorithms, the sensitivity to field of view and visibility, and individual vehicle tracking problems in high-density flows. Measurement accuracy is highly dependent on the quality of the camera installation as well as flow conditions; to this end, particular mobile hardware for video data collection operations is still under development, in particular for data collection at freeways. Weather conditions (i.e. visibility), obstacles (i.e. road signs, posts and overpasses), camera field of view and angle, curved roadway sections, and occlusions from dense traffic and large vehicles (i.e. trucks) are all potential sources of tracking errors. Higher accuracies can be achieved by limiting these line-of-sight issues. Of course, many of these limitations are not specific to any particular trajectory-tracking technology, nor to human observers. Given ideal conditions, the practical rated accuracy of traffic detection by means of automated video analysis is in the 95-99 % range for counting detection, in contrast to human error which yields 90-95% accuracy (12). Performance measures for tracking algorithms, however, are less clearly defined and make results from different systems difficult to compare. Automated analysis also has the significant advantage of having no loss of attention or error in judgement, and the ability to consistently measure position, velocity, and acceleration. Finally, videos can always be manually reviewed at any step of the procedure.

Despite the important developments in the field of surrogate safety analysis in the last years, some gaps in the literature still persist. These gaps include the need for a broader application in multiple types of environments and scopes (and how different environments and scopes affect the significance), and the need to quantify the link between conflict measures and their absolute collision prediction power. As such, this paper will be exploring

## METHODOLOGY

The steps are outlined as follows:

1) Collection of a sufficiently large video data set efficiently for each site.
2) Spatial calibration of the camera image space to the roadway ground plane using aerial imagery.
3) Trajectory data extraction:
    - **Feature** tracking (moving pixels).
    - **Object** recognition and empirical error filtering (**features** are grouped together into **objects** for each physical vehicle they represent based on proximity and motion similarity (13)).
4) Definition of a relevant **conflict measure** related to freeway driving behaviour.
5) Interaction classification, path prediction, potential collision detection, and conflict measurement analysis.

6) Conflict measures summary, comparative analysis, and interpretation according to choice of chosen conflict measure.

For steps 3 to 6, some additional details are provided as follows:

## Extraction of trajectory data

This study makes use of the video analysis tool developed at the University of British-Columbia to track vehicles from video data (13) (16). Individual pixels are tracked and followed over the course of many frames and recorded as feature trajectories.

The positional analysis of vehicles requires accurate projection of the pixel coordinates in image space to real-world coordinates that lie on a reference surface with known model (pavement surface). When video data is collected by a third party, access to the camera is not possible and therefore all camera parameters must to be inferred from video observations and an orthographic (aerial) image of the intersection. This is done using a robust calibration method relying on various features such as the shape, position, and length of remarkable objects in both image and world spaces (10). Additional issues are caused by slight camera orientation drift over time, which was dealt with automatically by tracking the stationary portion of the field of view. Time is measured in frames: a datapoint (position per object per frame) is collected for each new video frame and there are 29.96 frames per second. A displacement of 1 metre from one datapoint to the next (1 m/f) represents an object traveling at a speed of 29.96 m/s or 107.86 km/h. This high polling rate produces very large datasets of small increments.

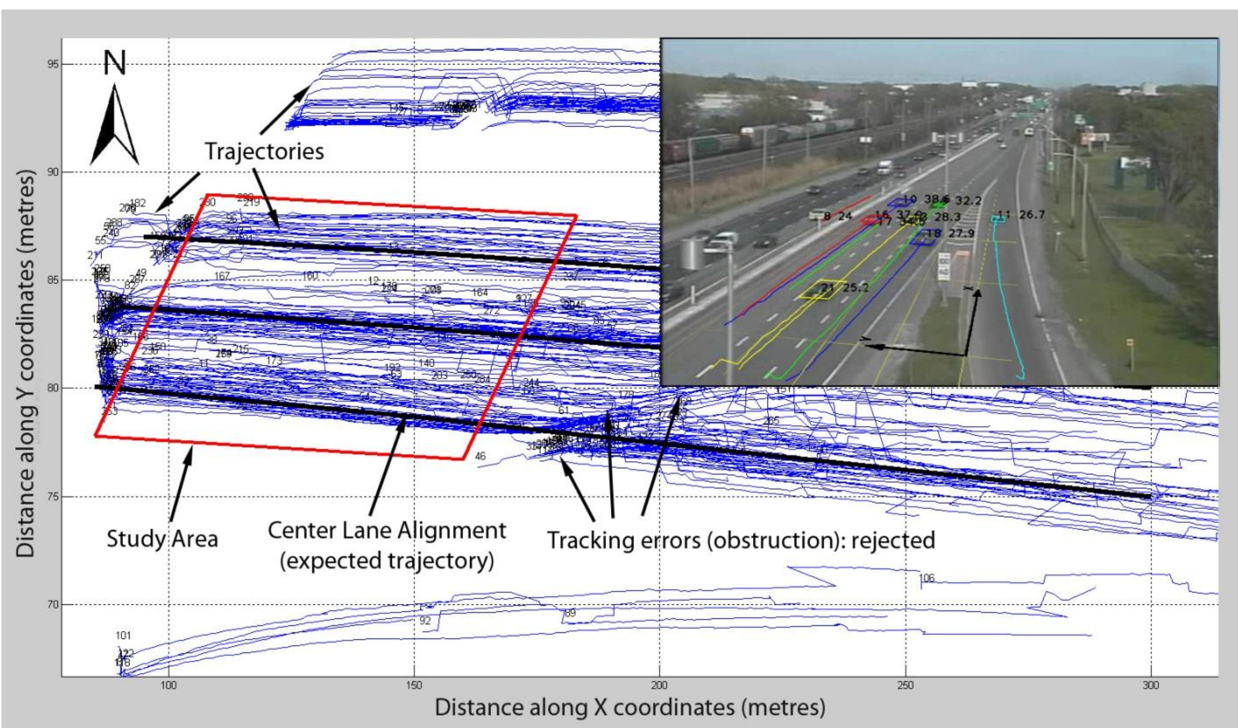


**Figure 1: Sample X,Y data for spatial analysis of entrance 56 (Bouchard), Autoroute 20 eastbound, Dorval, Montreal. Datapoints are filtered to include only the study area (50 m long by 10 m wide).**

A second phase of data filtering was developed specifically for this study to optimize the tracking reliability under the constraints of highway flow and for the type of camera angles used to record the video footage. This phase includes edge and warm-up truncation, expected trajectories coordinate transformation, noise reduction and tracking error filtering (such as duplicate objects, multiple vehicles per object, split objects, etc.) for manual review. These filtering routines were empirically validated.

Figure 1 shows sample trajectories being extrapolated from the camera's view. Vehicles were assigned a lane and a set of transformed coordinates for rear-end calculations based on an expected trajectory representing the average path of trajectory clusters.

## Definition of a relevant conflict measure related to freeway driving behaviour

Conflict Measures have been broadly defined by many publications, but in general they tend to be derived from three variables: the positions x and y of two or more vehicles as a function of time t. In a 2003 report (17), Gettman and Head compiled a list of the major and reoccurring surrogate measures of safety used in literature. The report identified seven major measures: gap time (GT), encroachment time (ET), deceleration rate (DR), proportion of stopping distance (PSD), post-encroachment time (PET), initially attempted post-encroachment time (IAPT), and time to collision (TTC). The FHWA report defines these measures primarily as indicators of probability of collision. It should be noted however that the exact relationship between conflicts and collisions has yet to be clearly defined.

For the purpose of freeway conflict analysis where we assume no head-on or perpendicular-lateral conflict situations and a certain amount of constraint-of-direction, we focus primarily on two types of major interactions: rear-end (type A), and lateral-diagonal (type C). Each of these can be observed as either converging or diverging (see Figure 2 and 3 for the classification). Out of all the measures mentioned previously, TTC is found to be the most reliably measured, tends to be already collinear with other measures (e.g. GT, DR, PSD), and is the most frequently observed in a highway environment (e.g. the other major conflict type (PET) was measured less than 0.1% of the time) and so is chosen as the primary measure of comparison (9). Additionally, it is already a popular choice in the literature. In situations where TTC does not exist (as the vehicles are not predicted to collide), but paths converge, a PET measurement is recorded instead. Additionally, the position (x, y) of each predicted collision point CP is recorded.

The TTC measurement can be defined as the time until two objects, whose paths defined by unchanging speed and direction at that point in time intersect, meet and collide (18). A straight line TTC path prediction and collision method was deemed sufficient for the requirements of this paper as all studied examples are in straight highway sections. The algorithm used to make TTC measurements is based off of the work by Laureshyn et al.(6). See Figure 2 for an illustration of the path prediction and measuring algorithm used. We leave the discussion of other methods such as "expected trajectory" (9) and path-probability prediction for future work.

In order to make the TTC measure absolutely useful in the context of road safety, it is important to understand its relationship with collision probability, if it reliably exists. Unfortunately, a formal relationship between the two still requires much research. Conceptually, as mentioned before, we agree that TTC is a measure of the remaining time, at any time *t*, before two vehicles are expected to collide without driver reaction. Thus the observed outcome of such an event, on average, is proposed as a method of empirically measuring the probability of collision at time *t*, given a TTC and other factors such as driver reaction time, visibility, vehicle performance and impairment, and a sufficiently large number of observations and scope of research:

$$Probability\ of\ collision_{t} = PC_t = f(TTC, factors) \qquad (1)$$

By definition of time-to-collision, the probability of a collision for TTC = 0 is 1:

$$PC_t\ \ 0, factors\ \ = 1 \qquad (2)$$

Furthermore, we can assume that the general relationship between probability of collision and TTC is exponentially decaying, given otherwise identical factors: as TTC increases, drivers have increasingly more time to react and alter their predicted path, voiding the collision prediction in the process. To illustrate the methodology, we chose an arbitrary, non-calibrated exponentially decaying empirical model:

$$PC_t\ TTC, \alpha\ = \frac{1}{e^{\alpha \times TTC}} \tag{3}$$

where $PC_t\ TTC, \alpha$ is the probability of collision over time step $t$ according to TTC and an empirically-calibrated adjustment factor $\alpha$. Future work will aim to calibrate this model accordingly, explore other exponentially decaying models, and, using factors including road conditions and average driver reaction times, etc., define a general model.

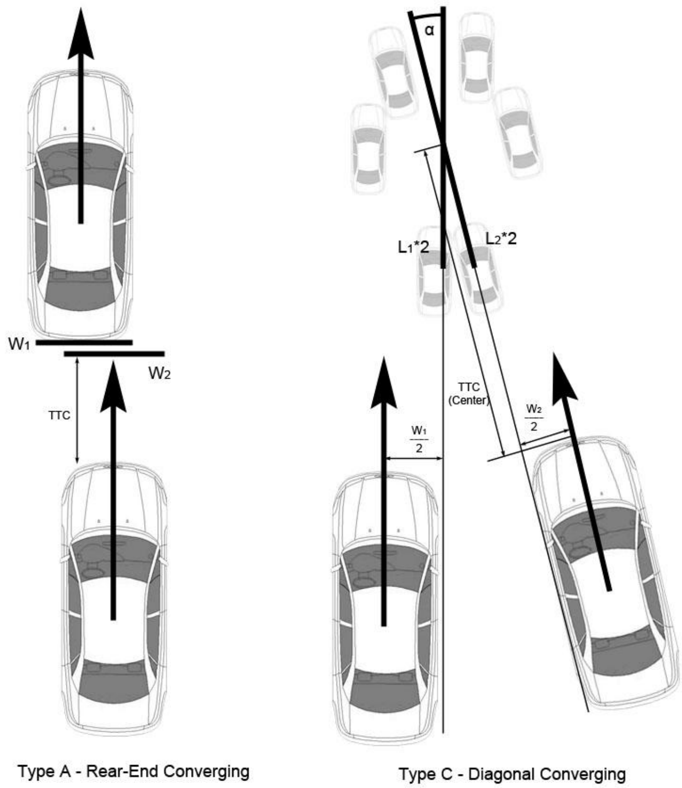


**Figure 2: Predicted conflict types. TTC is calculated from speed, position, width W, length L, and angle of conflict α for converging interactions.**

## Interaction classification, path prediction, potential collision detection, and conflict measurement analysis

Using the definition of the chosen conflict measure in the previous step, we process all trajectories according to a chain of interaction, type, and measurement checks and calculations. This step is outlined in Figure 3. Raw measures of interaction events, types, TTC, predicted points of conflict CP(x,y), PET and converging/diverging interaction ratios are output.

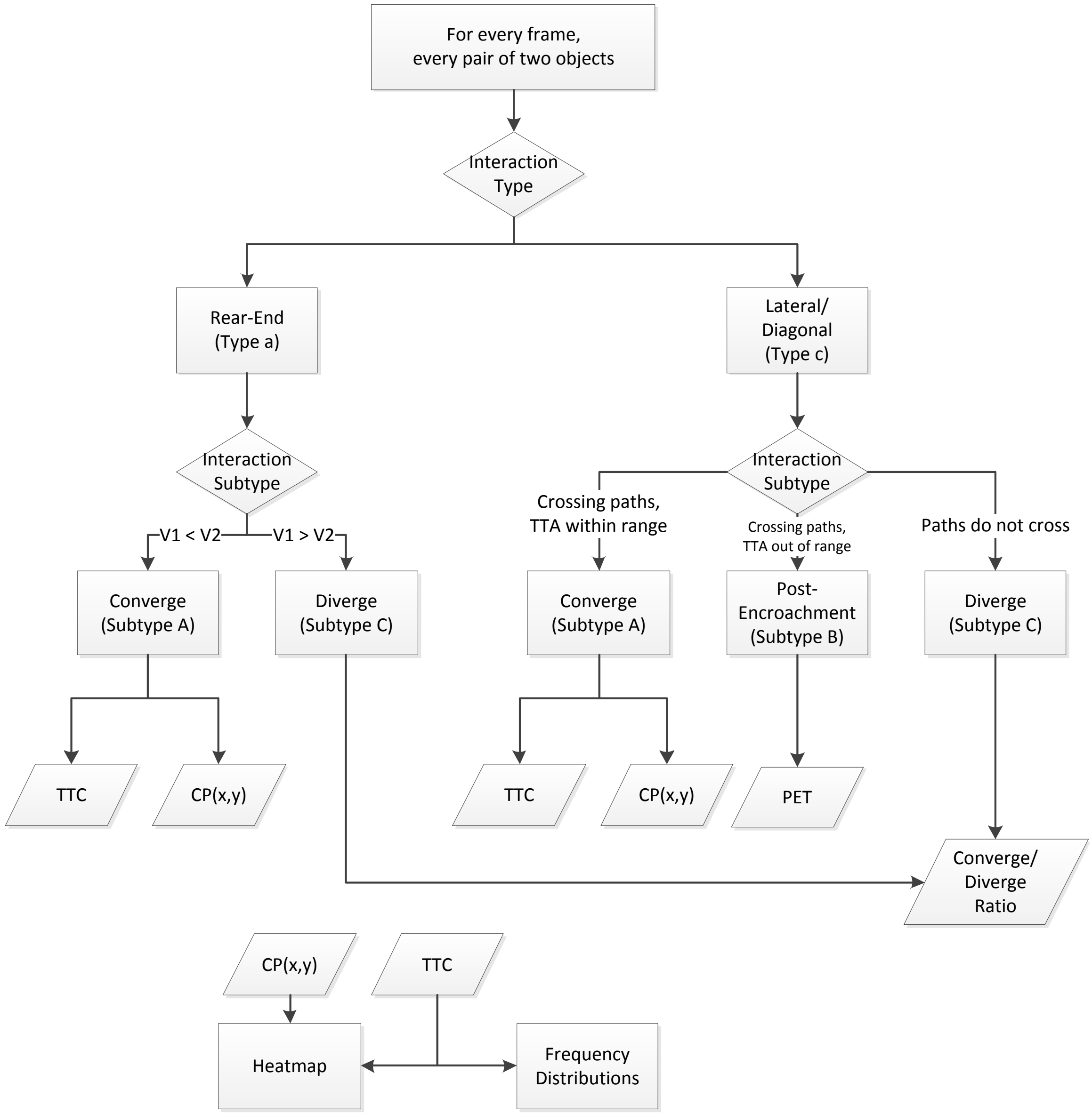


**Figure 3: Interaction classification and data extraction flowchart. Time-to-Arrival (TTA), Conflict Point (CP), Leading Car Speed (V1), Following Car Speed (V2).**

## Measure summaries

We present two particular ways of comparing conflict measures between analysis cases. The first method is a coordinate-density conflict-point "heatmap" created by building a two-dimensional weighted histogram of all CPs using Equation 3 as weight.

The second method is a distribution of all instantaneous TTC observations or a distribution of the minimum TTC observed for every unique pair of objects or individual object; in practice, at least for freeway applications, the TTC distribution associated with unique pairs is found to be almost identical to the distribution associated with unique individuals, save for a slight shift associated with isolating minimum measures (likely also due to outliers). Either way, comparative analysis should be consistent.

For the time being, TTC distributions can be compared graphically or by comparing the sum of their associated probabilities using Equation 3 divided by the total amount of objects and driving length.

$$\frac{Accidents}{veh \times km} = \frac{PC_t\ TTC, \alpha = f(factors)}{objects \times analysis\ length} \tag{4}$$

Other relevant behaviour data is also extracted, including: speed distributions; a lane change matrix; the percentage of converging interactions to total interactions, where > 50% would suggest that a section of highway has a tendency to push vehicles together, whereas < 50% would suggest a highway has tendency of pulling the vehicles apart; the rear-end to diagonal interaction ratio, and PET distributions.

## A CASE STUDY: FREEWAY RAMPS

The proposed methodology is illustrated with a study of a set of freeway ramps with and without a "lane-change closure" marking (termed LCGV1) located between the middle and outside lanes in exit and entrance ramps of freeways—see Figure 4. Analysis is attempted using a cross-sectional and a before-after comparison methodology.

a)


**Figure 4: Example LCGV1. a) Exit ramp section diagram demonstrating an LCGV1 and an illegal lane change. Lanes are numbered sequentially starting with the outer-most lane, excluding merging lanes. b) LCGV1 along Autoroute 720 eastbound, entrance 3 (right), Montreal. Source: MTQ.**

This marking treatment is particularly popular in urban multilane freeways in Quebec, Canada. The treatment typically bans lane changing from the middle or inside lanes to the outside lane along the weaving zone, but allows lane changes from the outside lane to the inside lane. This marking was initially implemented on ramps that do not meet all required design standards. For instance, ramps treated with this type of marking were those with poor approaching visibility, short weaving zones, or close proximity to other ramps (see also (19)). However, this marking has proliferated to standard sites as well. Despite its popularity, this safety treatment has been a source of concern because the potential impact on highway safety, including vehicle conflicts and collisions, has not been fully understood and the benefits are still debated.

### Site selection

The ramps involved in this case study are those for which video data was available as part of a previous historical before-after LCGV1 treatment study. Video data was collected for two test sites on the Island of Montreal. The sample analysis was performed just upstream of one treated entrance and two non-treated entrances. For one of the non-treated sites, additional video was obtained one year later with treatment applied.

Low-light and peak periods were avoided as they were problematic for data collection. 20E-Dorval had a slightly reduced study area as occlusion from a lamp-post caused some tracking problems near the concrete pier head.

The traffic conflicts analyzed for the case study correspond primarily to the traffic movements on all lanes upstream of the pier-head to properly capture behaviour related to movement in anticipation of the entrance of other vehicles. It is also theorized that the beginning of the lane-change ban is a critical point of conflict for drivers as is the pier-head. The Highway Capacity Manual defines 450 meters upstream of an exit or 450 meters downstream of an entrance as the design influence zone (19).

**Table 1: Characteristics of the three data sets evaluated. The loop detector flow is estimated from expansion factors and loop detector data.**

| Site | 720E-Green | 20E-Dorval | |
|---|---|---|---|
| type | Freeway Entrance | Freeway Entrance | |
| Lanes | 4 | 3 | |
| Treatment | Yes | No | Yes |
| Meas. Avg. speed | 60 km/h | 95 km/h | 105 km/h |
| Meas. Avg. flow | 2193 veh/h | 2866 veh/h | 2598 veh/h |
| Est. Loop Det. flow | 3187 veh/h | 2636 veh/h | 2636 veh/h |
| Sample frame |  |  | |
| Orientation | Looking downstream | Looking downstream | |
| Nearest upstream ramp | 465m | 502m | |
| Nearest downstream ramp | 473m | 506m | |
| Study area | 75m | 50m | |
| Distance from pier-head | 0m | 75m | |
| Datapoints/h | 364,600 | 320,000 | 298,770 |
| CPs/h | 96,000 | 45,000 | 32,000 |
| Unique int./h | 4,000 | 19,000 | 19,000 |
| Hours analyzed | 6 hours, off peak | 5 hours, off peak | 10 hours, off peak |
| Date | May 12, 2010 | May 12, 2010 | May 11, 2011 |

## EXPERIMENTAL RESULTS

To show the applicability of this methodology, two applications are introduced below. In the first example, a cross-sectional study between the treated 720E-Green site and the untreated 20E-Dorval site is explored. In the second example, a before-after analysis between the untreated and treated 20E-Dorval site is explored.

**Example 1: Cross-sectional analysis**

720E-Green (Treated) is compared with 20E-Dorval (Untreated). The percentage of converging interactions was found to be 50.0% for the 720E-Green site and 49.5% for the 20E-Dorval site, indicating that the 720E-Green site has a balanced ratio of converging to diverging ratios while the 20E-Dorval site tends to push vehicles apart.

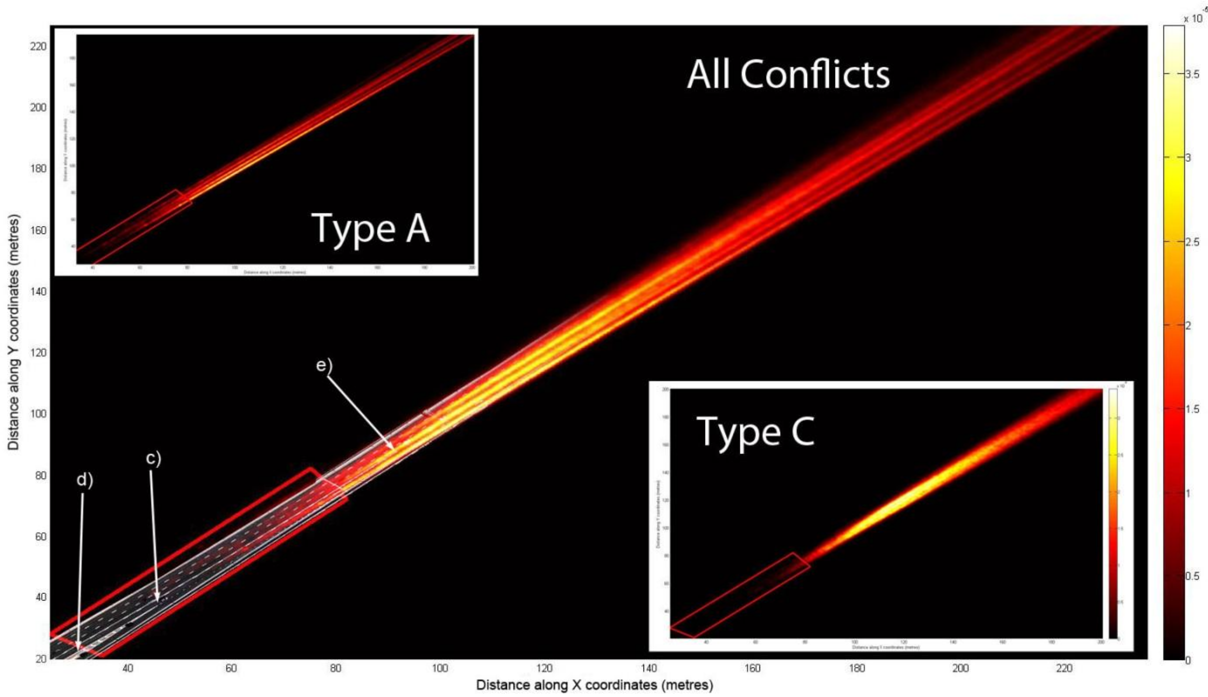


**Figure 5: "Heatmap" for the 720E-Green site; distances in metres, not to scale.**

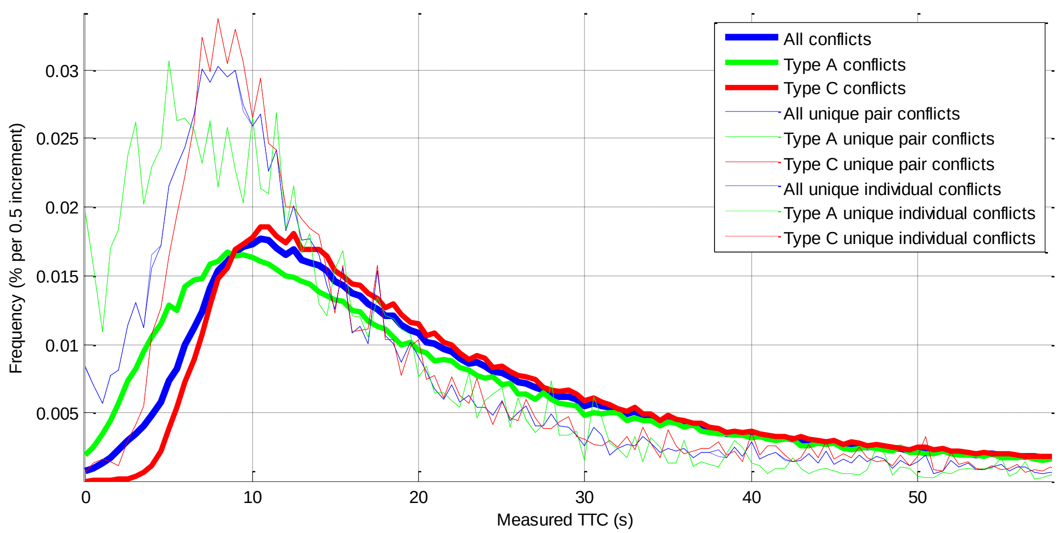


**Figure 6: TTC distribution for the 720E-Green site. The distributions for unique pairs and unique individuals overlap.**

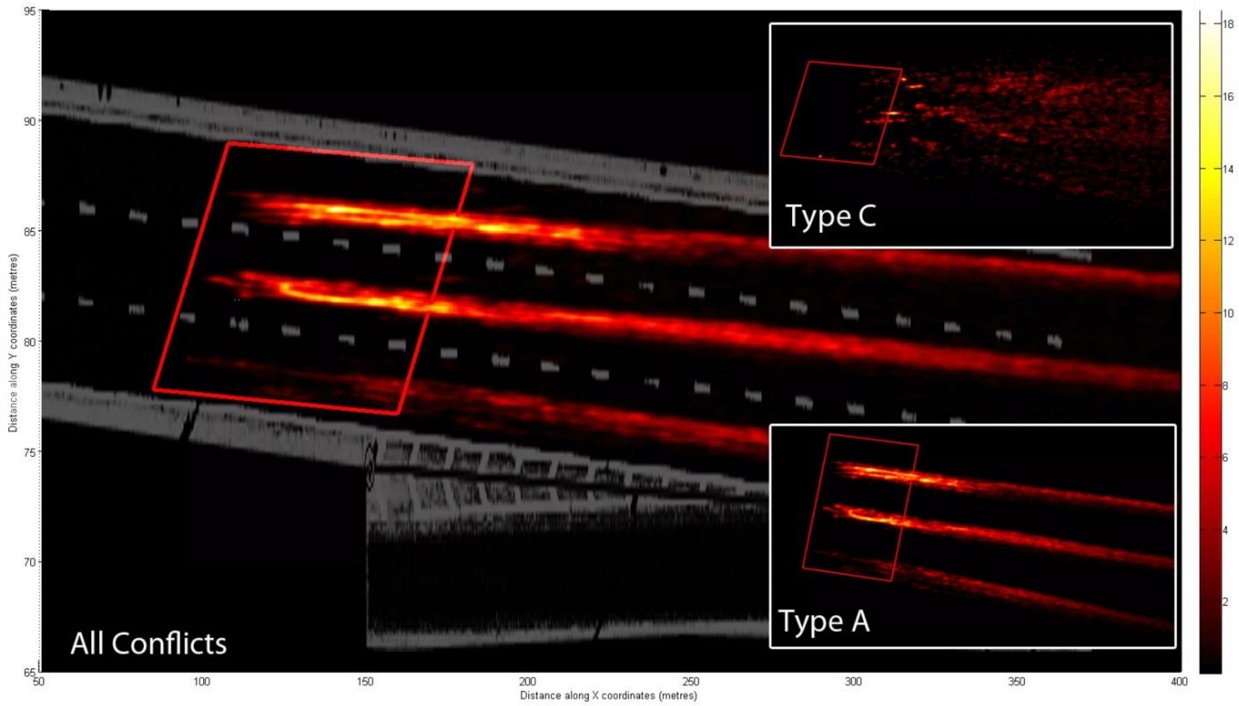


**Figure 7: "Heatmap" for the 20E-Dorval site before treatment; distances in metres, not to scale.**

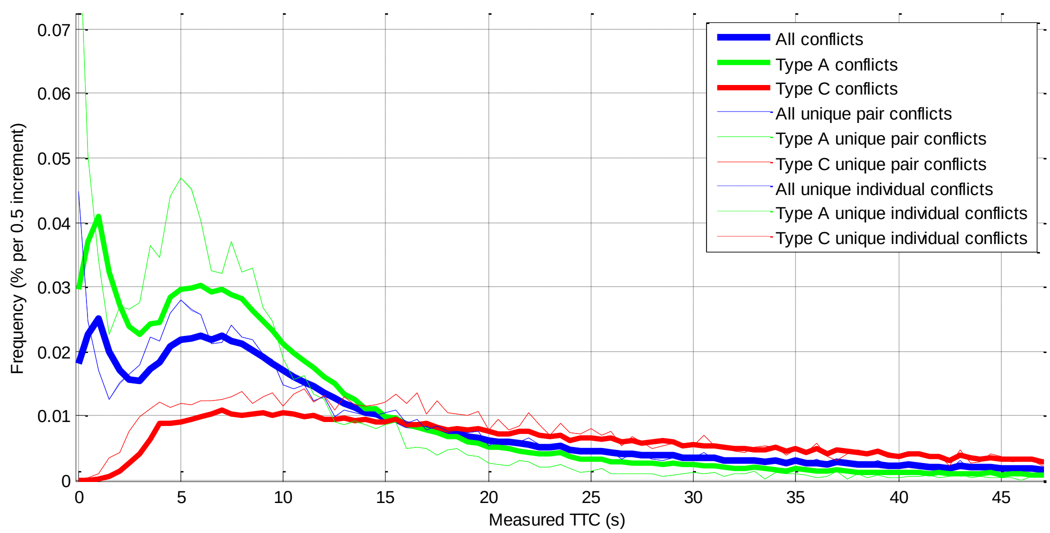


**Figure 8: TTC distribution for the 20E-Dorval site before treatment. The distributions for unique pairs and unique individuals overlap.**

Also, the dominant conflict type found for the 20E-Dorval site are type A (rear-end) conflicts with more than twice the number of recorded type A conflict interactions as type C (diagonal converging) interactions. The dominant conflict types found for the 720E-Green site are type C (diagonal) conflicts with almost twice the number of recorded type C conflict interactions as type A conflict interactions. This might simply be explained by a greater rate of observed lane changes for the 720E-Green site, and more lanes to change too, but might also simply describe a behavioural tendency of more following vehicles in the 20E-Dorval and more overtaking vehicles in the 720E-Green site.

The heatmaps' density as shown in Figure 5 and Figure 7 should be read as a concentration of potential collision points as weighted by hypothetical Equation 3. Nevertheless, we can observe significant differences between the 720E-Green (treated) and 20E-Dorval (untreated) site. There are a great number of points with low TTC on the outside (first) lane of the 720E-Green site, particularly for type A conflicts (rear end) just past the entrance's merging section. 20E-Dorval's low-TTC points tend to cluster on the second and third lanes. Hotspots tend to cluster just beyond the analysis area, as the predicted zones of collision are those generated by the movements of the vehicles inside the study area only. Considering the significant differences in measured speed between both sites, it appears that the clustering position of the CPs along the alignment direction of the freeway is related to vehicle speed. This is also evident when comparing the TTC distribution shapes. At this point, the idea that the treatment might have a certain "traffic calming" effect at this site cannot be ruled out.

The TTC measures appear to be distributed somewhat according to a gamma distribution (Figure 6 and Figure 8). The TTCs seem to be concentrated around different points for each site. 720E-Green has a peak concentration at 10 seconds while the peak concentration of TTCs for 20E-Dorval is just above 5 seconds, with an odd first peak at TTCs of around 1 second for type A (following) conflicts only. The distribution shapes are markedly different between sites.

Different aggregation is attempted for each conflict type as demonstrated in each distribution chart: aggregation by unique pair of conflicts (minimum observed TTC for each pair of vehicles) and aggregation by unique individuals (minimum observed TTC per vehicle, irrespective of relationship with other vehicles). Unique individual distributions overlap nearly exactly, indicating that, within a study area of 50-75 metres, nearly all, if not all, vehicles only engage in at most one minimum conflict with a single other vehicle.

The aggregated distributions of minimum TTC are in contrast with the distribution of all conflicts which have nearly 100 times more observations. The result is that the aggregated distributions are noisier versions of the full distributions with peak concentrations marginally shifted towards smaller TTCs. The error involved in relying on the noisier distributions (as well as possible outliers) makes minimum aggregated distributions undesirable for practical use.

Furthermore it should be noted that the overall shape of distributions did not vary appreciably from hour to hour, even under moderate (no more than +/-20%) changes in flow characteristics.

## Example 2: Before-after analysis for 20E-Doval

Results of after-treatment videos are compared with results from the same site (20E-Dorval) before-treatment. The heatmap in Figure 9 shows a greater concentration of conflicts in the second lane, particularly for type C, lateral conflicts. Interestingly, the concentration of conflicts in the first and third lane appears to be reversed with respect to before-treatment: the third lane has a smaller conflict concentration than the first (although the changes between before and after heatmaps are not presented absolutely).

The TTC distributions show more changes in shape. Particularly, the second peak of type A (following) conflicts disappears and the first peak is now a little more pronounced. Type C (diagonal converging) conflicts have small changes (see calculated difference below).

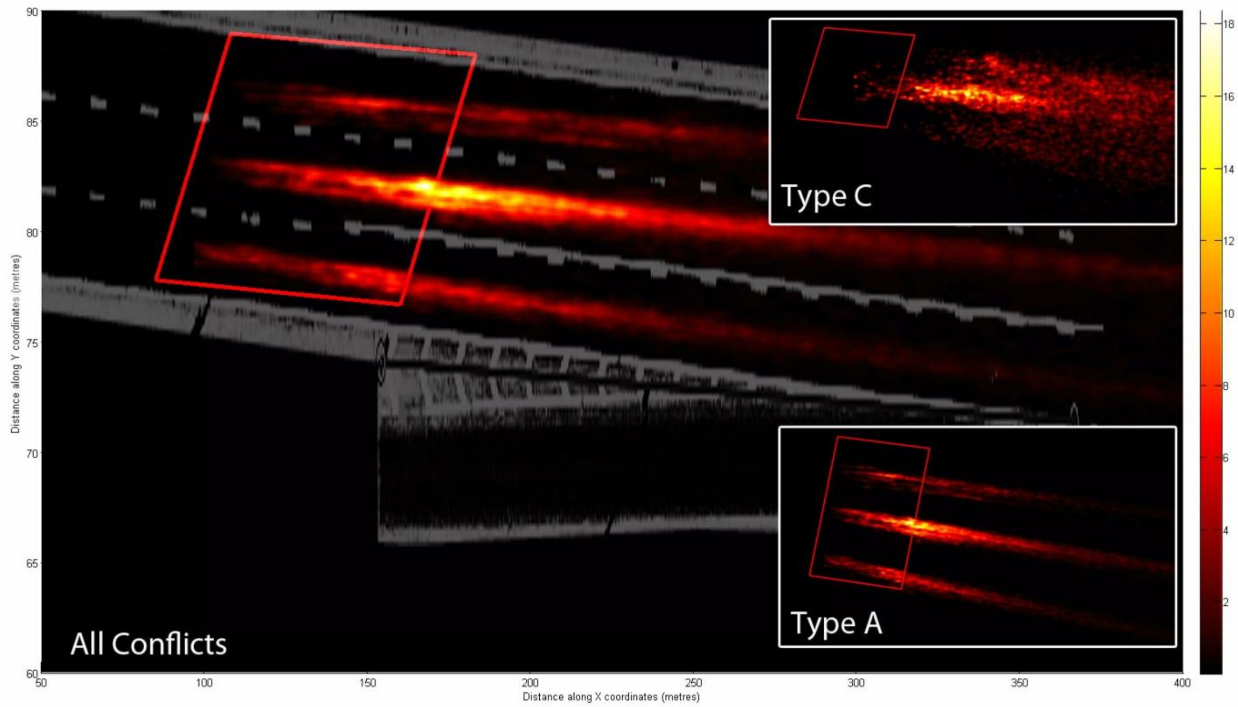


**Figure 9: "Heatmap" for the 20E-Dorval site after treatment; distances in metres, not to scale.**

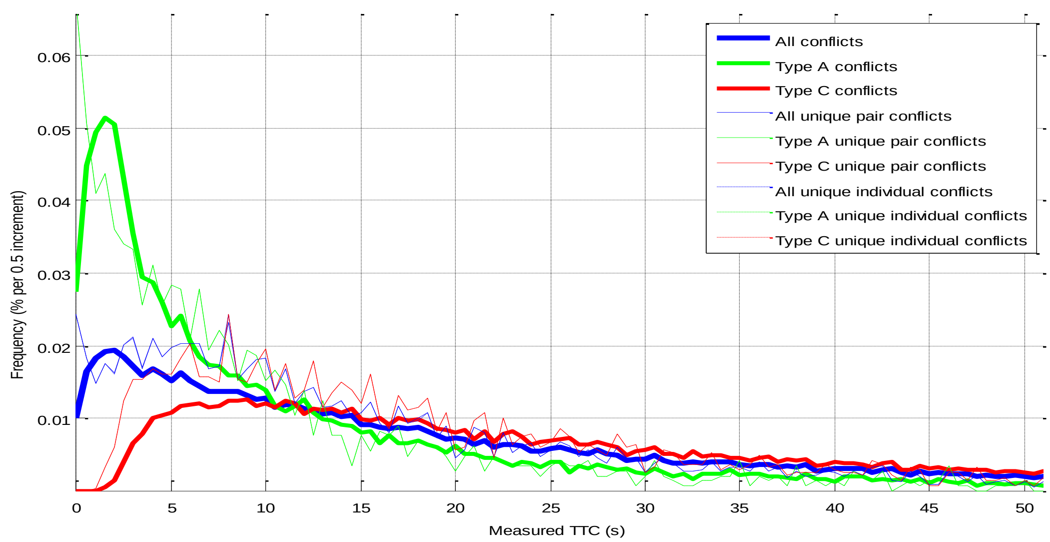


**Figure 10: TTC distribution for the 20E-Dorval site after treatment. The distributions for unique pairs and unique individuals overlap.**

### Numerical Comparisons

Table 2 presents the predicted accident rate using the hypothetical (non-calibrated) accident rate as calculated using Equation 4, the model proposed in Equation 3, and according to different parameters of α**.** Again, this is for exploratory purposes only. A full study should define a consistent α between control sites with known accident rates. Proper selection of control sites is therefor critical. Comparable estimates of similar α are more or less consistent, particularly between the before-after comparison. It's also interesting to note that conflicts of different types have drastically different explanatory power for similar calibration values. Conflicts of various types should therefore use different calibration models.

It is hoped that future work with very large sample sizes and a full calibration effort will reveal conflict patterns which could lead towards general models of prediction without the need for case-control.

**Table 2: Basic sensitivity analysis of hypothetically calculated accident rates (accidents/million-vehicle-km) according to parameter alpha and Equations 3 and 4.**

| α | 720E-Green | | | 20E-Dorval (Untreated) | | | 20E-Dorval (Treated) | | |
|---|---|---|---|---|---|---|---|---|---|
| | All | A | C | All | A | C | All | A | C |
| 0.1 | 4352 | 5188 | 3933 | 7713 | 8025 | 6331 | 8609 | 9463 | 6918 |
| 1 | 117.5 | 338.3 | 6.924 | 971.5 | 1171 | 84.82 | 1279 | 1870 | 110.0 |
| 10 | 10.35 | 30.50 | 0.249 | 79.06 | 96.93 | 0.001 | 75.11 | 113.0 | 2.063 |
| 100 | 0.911 | 2.727 | 0.006 | 6.816 | 8.357 | 0.000 | 7.214 | 10.86 | 2.090 |
| 1000 | 0.119 | 0.355 | 0.000 | 0.9229 | 1.131 | 0.000 | 1.126 | 1.695 | 0.000 |

The lane changes per veh-km were also recorded and are presented in Table 3. 720E-Green shows the greatest rate or lane changing, likely due to a lower speed and shorter distances between merging sections and confirms a subjectively observed greater rate of freeway entering and exiting activity in the area. In either treated case, the rate of lane changing from the second to the first lane (which the treatment is designed to ban) was found to be higher than for an untreated example, although it should be noted that in the 20E-Dorval (Treated) case, the study area was just upstream of the beginning of the treatment: an increase in merging should be expected for drivers in anticipation of roadway markings.

**Table 3: Summary of lane changes in lane changes per vehicle-kilometer (lc/veh-km) **Lane changes from the second to the first lane are those which the treatment is designed to forbid.**

| Site | 720E-Green (Treated) | 20E-Dorval (Untreated) | 20E-Dorval (Treated) |
|---|---|---|---|
| 1 → 2 | 1.42 | 1.58 | 1.23 |
| 2 → 3 | 2.70 | 1.15 | 0.55 |
| 3 → 4 | 1.70 | - | - |
| 4 → 3 | 1.25 | - | - |
| 3 → 2 | 1.41 | 0.33 | 0.55 |
| 2 → 1** | 1.83 | 0.62 | 1.11 |

## CONCLUSION

This study presents and demonstrates the applicability of the surrogate safety analysis method based on TTC extraction and calculation for before-after and cross-sectional comparative study types.

Although the analysis is not conclusive, simply for lack of a larger sample size and the fact that a properly calibrated conflict to collision probability mapping relationship was not used, our observations of the impact of the treatment can be summarized as follows: we observed that overall the effectiveness of the treatment depends on the type of conflicts compared, the flow conditions and the network characteristics. The safety benefits between sites disagree totally although it might be argued that the cross-sectional study skews results by introducing differences in geometry.

One consistent observation between study types is the clear shift in CP concentrations to the outside lanes, suggesting perhaps that the treatment puts additional stress or distractions on drivers. The lane-change summary also suggests two things. The increase in lane changes at the 20E-Dorval site which had a study area just upstream of the treatment might indicate a migration of lane changes further upstream at a critical point at the beginning of the treatment, effectively increasing the amount of conflicting interactions per unit area (as evidenced by the type C heatmap). The relative lane changes at the green 720E-Green site which has a study area over the treatment suggests that the treatment is not the most important factor in affecting driver's decisions regarding lane changes.

For these reasons, the case study will be further explored with accident calibration data and a greater data sample in future research. To this end, more data will be collected: more video at higher resolutions, with less compression artefacts and at multiple locations allowing for a greater coverage of merging sections and interaction zones

Another goal will be to understand the conflict to collision mapping probability, both on a macroscopic and microscopic scale and according to different environmental and behavioural factors. The usefulness in using TTC as an intermediary measure of risk lies in the correct understanding of its relationship with collision probability under varying circumstances. It is a convenient safety measure for its ease of its collection, particularly in situations where accident data is unavailable for safety reasons, as well as a safety risk hotspot identification tool on a more microscopic level, but only as long as patterns can be found and accurate modeling is possible.

Some room for improvement exists for more refined road user tracking and path prediction, particularly the use of improved filtering to take advantage of high polling rates to increase accuracy of speed and position measurements.

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