Analysis of Driver Behaviour and Collision Risks for Protected Freeway Entrance and Exit Ramps: Trajectories and Surrogate Safety Measures

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ABSTRACT (ENGLISH)

This study presents a surrogate approach for safety analysis of freeway facilities using semi-automated trajectory collection and behavioural analysis from surrogate measures of safety (in particular time to collision). This methodology is proposed as a potential alternative to the classical approach based on historical accident data, particularly suited for evaluating the microscopic safety effects of highway treatments for which there is a lack of traffic and accident data. The proposed methodology is illustrated using as a small sample of freeway ramps from which videos where available as part of a safety study on one-way lane-change closures near urban freeway entrances and exits. Various methods of aggregating the data, spatially and temporally, are explored for road safety analysis.

KEYWORDS

Driver Behaviour, Highway Safety, Lane-change-closure Study, Surrogate Safety Measures, Time-to-collision, Video Analysis

RÉSUMÉ (FRANÇAIS)

Cette étude présente une approche substitutive d'analyse de sécurité sur autoroute reposant sur la collecte semi-automatisée de trajectoires et une analyse des comportements des conducteurs à l'aide de mesures substitutives de sécurité (en particulier, le *temps à la collision*). Cette méthodologie est proposée comme alternative potentielle à l'approche classique basée sur les données historiques d'accidents qui est particulièrement adaptée à l'évaluation microscopique des effets des traitements de sécurité sur autoroute en l'absence de données historiques. La méthodologie proposée est illustrée sur un échantillon de bretelles d'accès pour lesquelles des données vidéos sont disponibles, dans le cadre d'une étude de sécurité sur les lignes de délimitation à gauche de la voie 1 (LCGV1) près des entrées et des sorties d'autoroute urbaine. Diverses méthodes d'agrégation des données, spatialement et temporellement, sont explorées pour l'analyse de la sécurité routière.

MOTS CLÉS

Analyse vidéo, comportement des conducteurs, étude des fermetures de changement de voie, sécurité routière, mesures substitutives de sécurité, temps à la collision

1. INTRODUCTION

An important area of research in road safety is the identification of effective countermeasures of under-designed transportation facilities. Determining the safety effectiveness of a treatment can be very challenging; in particular when very little historical before-after accident data and experience are available from past studies. Furthermore, many transportation authorities do not want to test safety treatments on a large-scale and in a live environment, for fear of unnecessarily putting the general public at risk.

Improving road safety through effective countermeasures is at the center of the transportation safety research. How does one reliably evaluate new transportation safety strategies without waiting for accidents to happen, as in the classical before-after approach? In this respect, researchers and practitioners are seeking valid proactive safety evaluation methods to evaluate safety treatments without exposing traffic to a possible increase 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). 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 (4). 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. This research is expected to provide tools to perform more accurate analytical analysis with the aid of more powerful, more accurately calibrated traffic flow models by integrating real, on-site behavioural data, instead of relying on theoretical behavioural models.

This paper develops a methodology to determine the safety status of freeway exits and on-ramps using video analytics and conflict analysis and indicators. For this purpose, vehicle size, position, speed and acceleration data is generated based on video footage for multiple vehicles simultaneously. This rich data is then mined to develop surrogate measures of safety for a given location. The methodology is developed and illustrated using a case study involving one-way-lane change-closure marking at freeway exists and on-ramps. 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 experimental results.

2. PREVIOUS RESEARCH

Surrogate safety analysis is not a new idea. Many papers 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), (4) and (5) for detailed summary of the results of conflict studies. A reoccurring argument against conflict studies in transportation safety involve the difficulty in obtaining quantitatively defined and objectively measured data and that the application of the methodology is often too broad and therefore yields insignificant results. Chin and Quek (4) further applied conflicts analysis in a freeway merging safety study. This paper will also put to use many of the conflict-prediction models developed by (6).

Obtaining objective data 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. (7); video data has been used for simulation calibration and traffic flow theory (e.g. NGSIM[1]); 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 (8) and pedestrian-vehicle conflicts (9) 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 (10). The reader is invited to consult (10), (11) and (12) for more detailed information on the specifics of vehicle feature tracking.

The main benefits of automated video analysis for safety are two-fold: firstly, it offers a convenient, low-cost method of calibrating driver behaviour parameters for specific roadway types and regions (without the need to install intrusive monitoring equipment), and it provides a flexible tool for complex driving behaviour analysis, particularly useful for microscopic road safety analysis using surrogate safety approaches.

However, video analytics is not without limitations such as 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 the flow conditions. 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) all cause tracking problems. 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, including human observers. Given ideal conditions, the practical rated accuracy of traffic detection by means of

[1] http://ngsim-community.org

automated video analysis is in the 95-99% range for detection (13). 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 velocity and position. Finally, video analysis may be used as an assisting tool, where large amounts of video data are filtered automatically to be reviewed by traffic and safety experts.

3. METHODOLOGY

The main objective is to develop surrogate measures of safety that allow us to define the safety status for a given location using surrogate measures of safety related to the probability of collision. Vehicle size, position, speed and acceleration data is extracted from video footage for multiple vehicles simultaneously, and is then mined for traffic conflict measures and other behavioural data. The measures extracted are then summarized and analyzed to obtain conclusions about the road safety status of a given location, particularly for site comparison. This indicator can be then used for a hotspot identification analysis, control-case studies, or a before-after analysis for assessing the effectiveness of a treatment of interest. The procedure is outlined as follows:

- Define the relevant conflict measurements related to freeway surrogate safety analysis.
- Collect a sufficiently large video data set efficiently for each site.
- Spatial calibration of the measurements done in the camera image space to the roadway ground plane using satellite imagery.
- Extract trajectory data:
    - **Feature** tracking (moving pixels).
    - **Object** recognition and filtering (**features** are grouped together into **objects** for each physical vehicle they represent based on proximity and motion similarity (10)).
- Perform an interaction classification and conflict measurement analysis.
- Summarize measures and define risk indicator.
- Make conclusions.

CONFLICT MEASUREMENTS

These 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 2001 report, the FHWA identified and 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 as indicators of probability of collision.

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 1** for the classification tree and **Figure 3** for a diagram of each of these situations). Converging interactions are evaluated using the TTC measurement which can be defined as the time until two objects, whose paths intersect and meet, collide, assuming that their trajectories and speeds remain unchanged (6). The TTC is used in this study because it is one of the most popular and appropriate indicators for intersections or ramps facilities, as in our case study. It can be extended to be robustly computed for all converging interactions with a likely collision course, in which case other indicators may not be needed (8). In situations where TTC does not exist (as the vehicles are not predicted to collide), but paths converge, we extract the PET measurement instead. Additionally, we also extract the position (x, y) of each predicted point of collision CP.

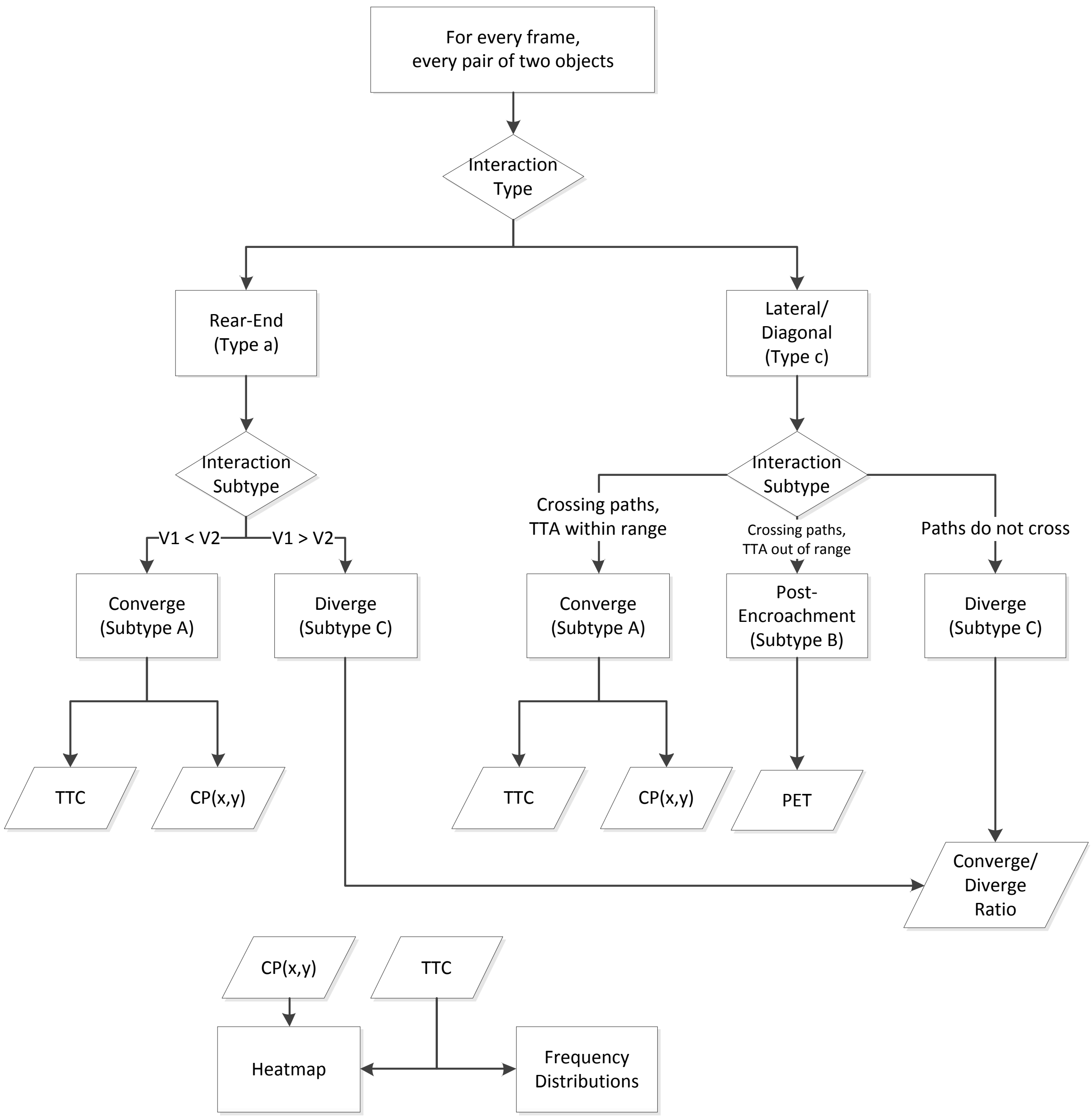

Figure 1 – Interaction classification and data extraction flowchart.

Feature Tracking

This study uses the video analysis tool developed at the University of British-Columbia to track vehicles from video data (10) (14). Individual pixels are tracked and followed over the course of many frames and recorded as features trajectories.

The positional analysis of vehicles requires accurate estimation of the camera parameters. The camera parameters calibrated in this study are six extrinsic parameters (that describe the location and orientation of the camera) and two intrinsic (that represent the projection on the image space). Once calibrated, it is possible to recover real-world coordinates of points in the video sequence 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 feature based on the shape, position, and length of remarkable objects in both image and world spaces (15). 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.

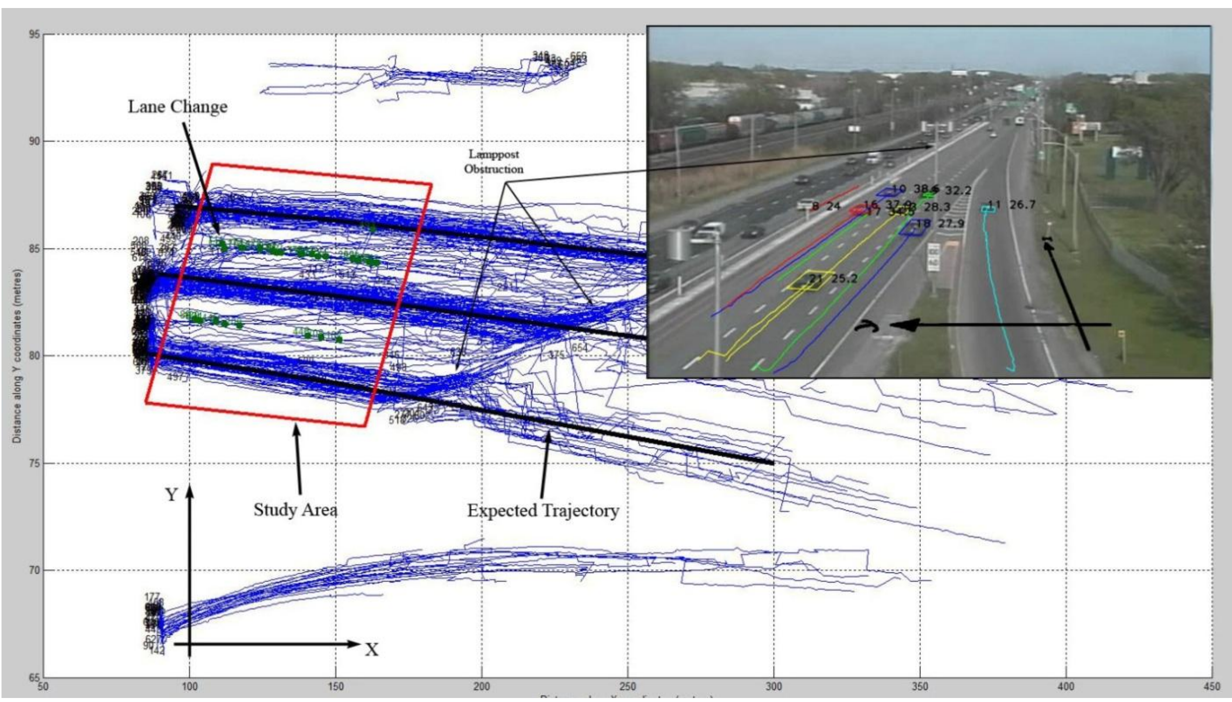

Figure 2 – Sample X,Y data for spatial analysis of entrance 56 (Bouchard), autoroute 20 eastbound, Dorval, Montreal. Datapoints are filtered to include only the study area (50 m long by 10 m wide).

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 flagging (such as duplicate objects, multiple vehicles per object, split objects, etc.) for manual review. These filtering routines were manually validated for each new site to a 95 % confidence level. **Figure 2** shows sample trajectories being extrapolated and the selection of a study area to remove unreliable trajectories. 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 associated with each lane.

Interaction classification and conflict measurement

The trajectory processing begins by analysing, frame by frame, every pair of objects and classifying their interaction type: rear-end (type A) for vehicles in the same lane, and diagonal-lateral converging (type C) for vehicles in different lanes. A flowchart of the general classification and data extraction algorithm is depicted in **Figure 1**Erreur ! Source du renvoi introuvable.. Then the point of conflict, i.e. the potential future collision point, is estimated from the vehicles' dimensions, positions, differential velocities, and angle of approach. See **Figure 3** and (6) for details on the conflict point prediction algorithm. The TTC is simply the time until both vehicles enter the predicted conflict scenario. The interaction algorithm uses a fifth interaction classification: diverging; however, other than providing a converging to diverging interaction ratio, this type of interaction is largely ignored as it does not generate any point of conflict.

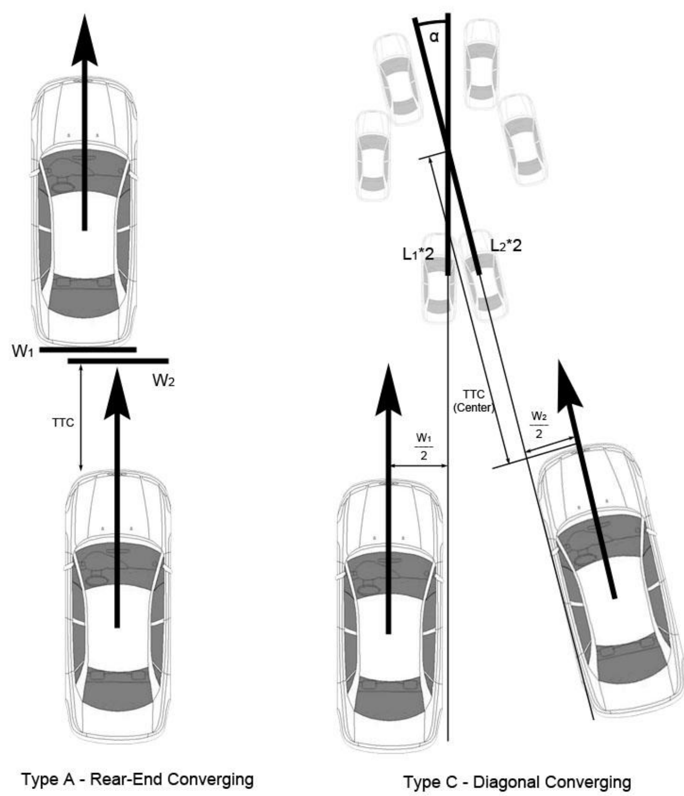

Figure 3 – Predicted conflict types. TTC is calculated from speed, position, width W, length L and angle of conflict α for converging interactions.

Summaries

Among the various ways in which we can summarize the TTC data, three particular ways are proposed: a coordinate-density conflict-point heatmap by building a two-dimensional weighted histogram of the CPs using the inverse of TTC as weight (until an exact relationship between accidents and TTC is validated); a distribution of all instantaneous TTC observation; or a distribution of the minimum TTC observed for every unique pair of objects or individual object. In practice, the TTC distribution associated with unique pairs is almost identical to the distribution associated with unique individuals.

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, where as < 50% would suggest a tendency of pulling the vehicles apart; the rear-end to diagonal interaction ratio, and PET distributions.

4. A CASE STUDY: FREEWAY RAMPS

The proposed methodology is illustrated using, as an application environment, 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**.

a) b)

Figure 4 – 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. This 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 (referred as design exceptions). For instance, ramps treated with this type of marking were those with poor approaching visibility, short weaving zones, or close proximity to other ramps. 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 (vehicle conflicts and collisions) has not been fully understood and the benefits are still debated.

This case study aims to illustrate the use of the proposed approach. For this purpose, various steps are observed and the outcome of this process determines the safety status of each freeway ramp. Each of the steps is detailed as follows:

i) ***Conflict measures definition:*** The conflict definitions are the same as those set out in the previous methodology defined in section 3.

ii) ***Site selection:*** The ramps involved in this case study are those for which video data was available as part of an attempted before-after LCGV1 treatment study. Video data was collected for the three test sites on the Montreal Island and their main characteristics are presented in **Table 1**. The sample analysis was performed just upstream of one LCGV1 entrance and two non-LCGV1 entrances. The 20E-Dorval site did not feature any treatment during video recording.

Site	**720E-Green**	**20E-Dorval**	**138W-Clement**
Type	Freeway Entrance	Freeway Entrance	Freeway Entrance
Lanes	4	3	2
Treatment	Yes	No*	No
Meas. Avg. speed	60 km/h	100 km/h	60 km/h
Meas. Avg. flow	2193 veh/h	2866 veh/h	1559 veh/h
Est. Loop Det. flow	3187 veh/h**	2636 veh/h**	1613 veh/h**
Sample frame			
Orientation	Looking downstream	Looking downstream	Looking downstream
Nearest upstream ramp	465m	502m	509m
Nearest downstream ramp	473m	506m	1019m
Study area	75m	50m	60m
Distance from pier-head	0m	75m	0m
Datapoints/h	364,600	320,000	272,000
CPs/h	96,000	45,000	90,000
Unique int./h	4,054	18,994	1,842
Hours analyzed	6 hours, off peak	5 hours, off peak	6 hours, off peak
Date	May 12, 2010	May 12, 2010	May 12, 2010

Table 1 – Characteristics of the three sites evaluated. **The loop detector flow is estimated from expansion factors.

iii) ***Video processing:*** 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 pier-head.

iv) ***Conflict measures:*** 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 an exit or entrance of other vehicles. It is theorized that the beginning of the lane-change-closure is a critical point of conflict for drivers as is the pier-head (see **Figure 5** for labels). The Highway Capacity Manual defines 762 meters upstream, 152 meters downstream of an exit or 152 meters upstream, 762 meters downstream of an entrance as the design influence zone (16) although comparing sites over this distance is not very practical particularly because most sites have a design influence zone which overlaps other entrances and exits.

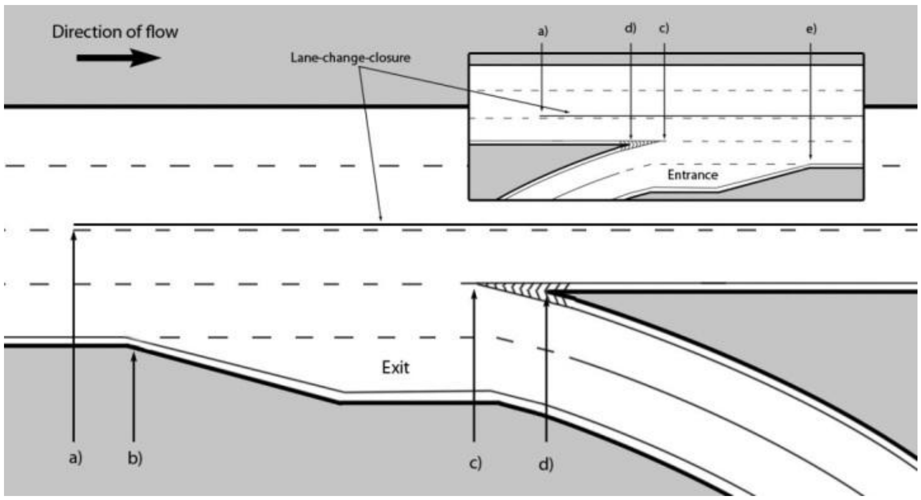

Figure 5 – a) critical point for lane-change-closure treatment; b) start of exit ramp merging section; c) pier-head (painted); d) pier-head (concrete); e) end of entrance ramp merge section. The distributions for unique pairs and unique individuals overlap.

5. EXPERIMENTAL RESULTS

The percentage of converging interactions was found to be 50.0% for the 720E-Green site, 49.5% for the 20E-Dorval site, and 50.5% for the 138W-Clement site indicating that it had the greatest proportion of conflicts overall and the 20E-Dorval had the smallest proportion of conflicts overall.

Also, the dominant conflict types found for the 20E-Dorval site were type A (rear-end) conflicts with more than twice the number of recorded type A conflict interactions as type C conflict interactions. The dominant conflict types found for the 720E-Green site were 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 to, but might also simply describe a behavioural tendency of more vehicle following in the 20E-Dorval and a more overtaking in the 720E-Green site.

The 720E-Green site's heatmaps and TTC distributions are shown in **Figure 6**. The 20E-Dorval site's heatmaps and TTC distributions are shown in **Figure 7**.

The heatmaps' density should be read as a **concentration of potential collision points with low TTC** measurement; however they are not yet calibrated to represent **probability of**

collision. 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. The positioning of the points along the alignment direction of the freeway appears to be highly dependent on the relationship of TTC over average speed.

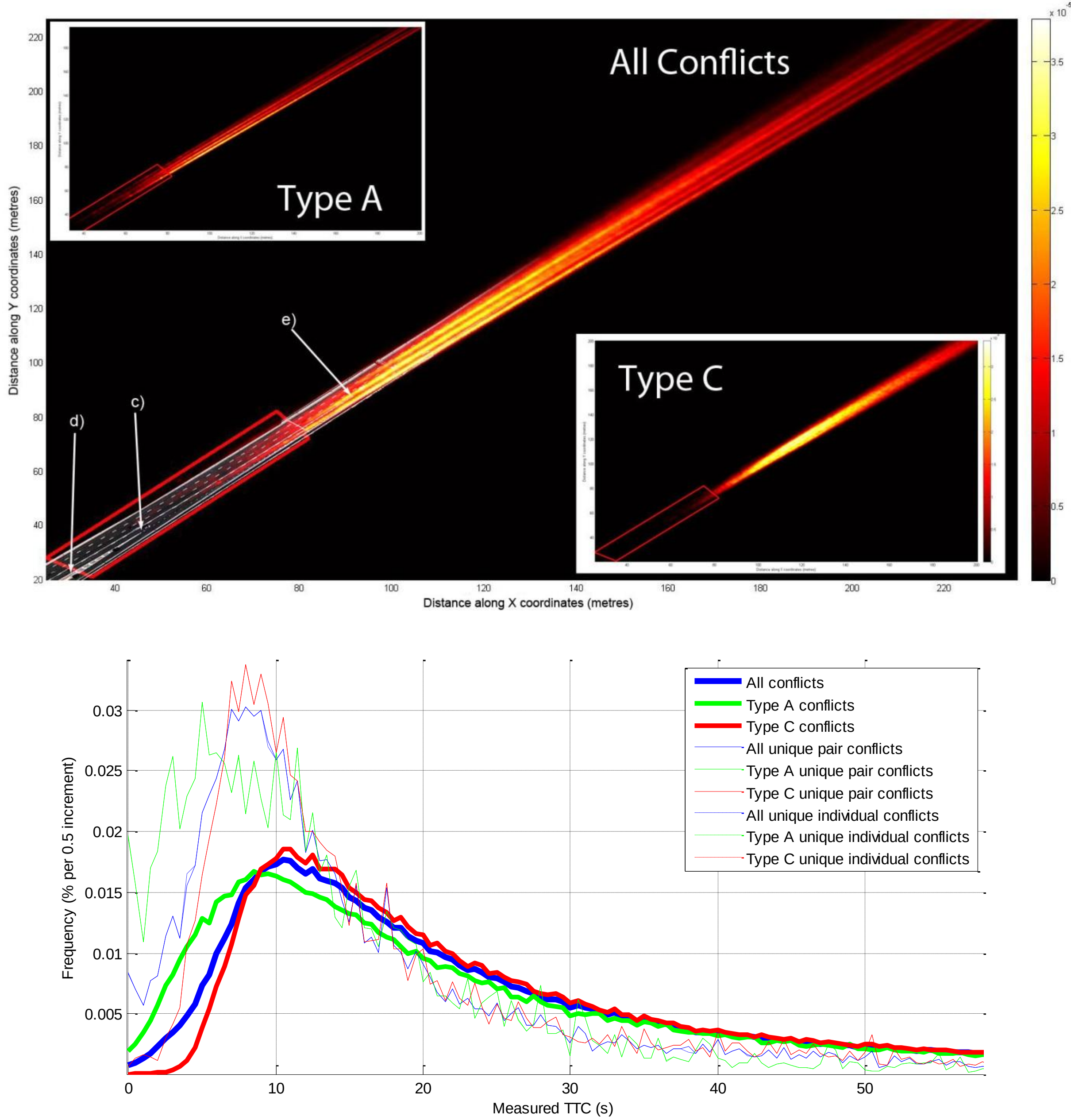

Figure 6 – Heatmap and TTC distribution for the 720E-Green site; heatmap distances in metres; c) pier-head (painted); d) pier-head (concrete); e) end of entrance ramp merge section as labeled in Figure 5. The distributions for unique pairs and unique individuals overlap.

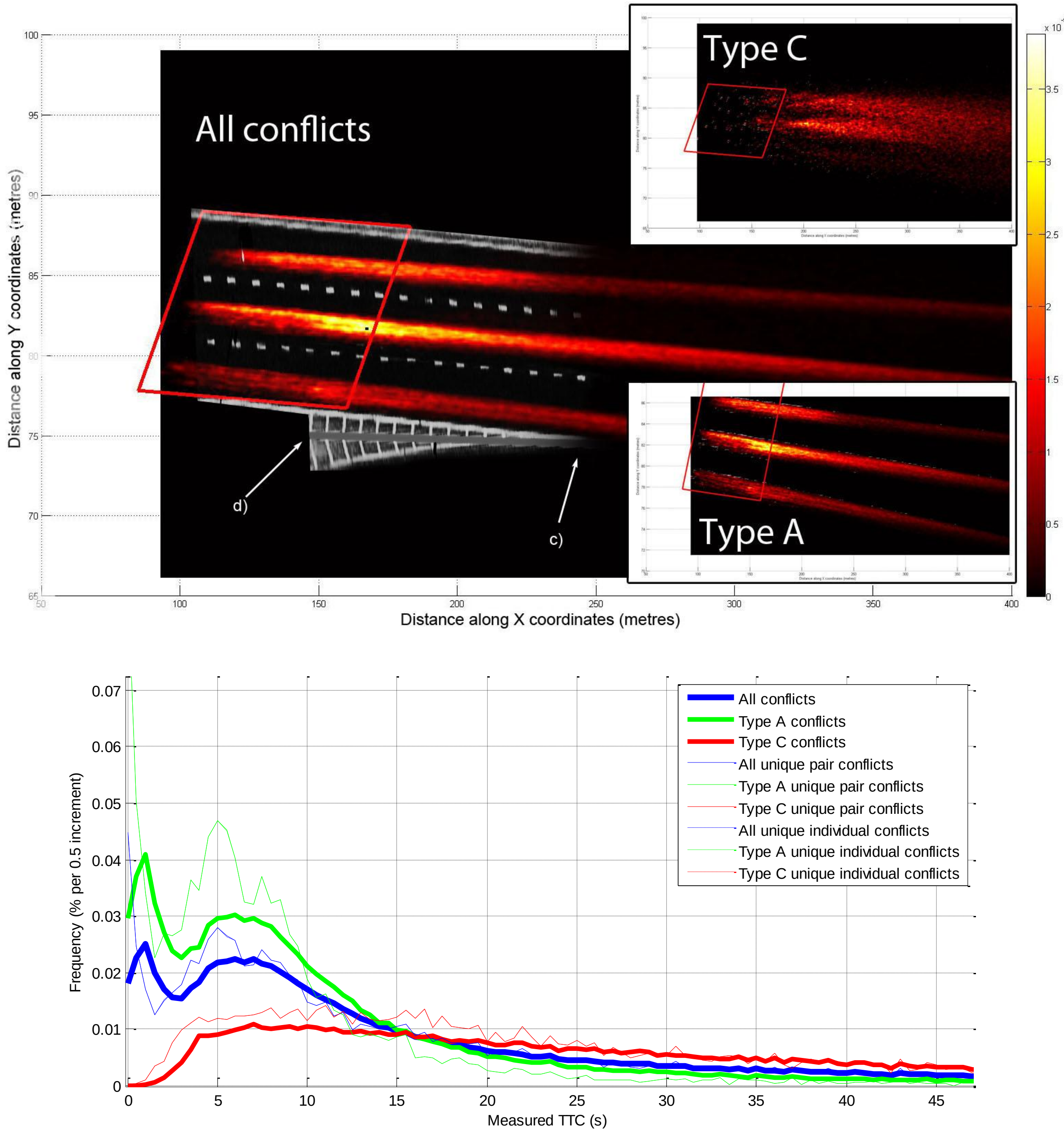

Figure 7 – Heatmap and TTC distribution for the 20E-Dorval site; heatmap distances in metres metres; c) pier-head (painted); d) pier-head (concrete) as labeled in Figure 5. The distributions for unique pairs and unique individuals overlap.

The TTC measures appear to be distributed according to a gamma distribution. The TTCs seem to be concentrated around different points for each site. 720E-Green has a concentration at 10 seconds while the concentrated of TTCs for 20E-Dorval is just above 5 seconds. We could simply attribute this difference in TTC to a reduced speed, however the 138E-Clement study area also had a TTC concentration around 3 seconds (not shown) despite having an average speed equal to that of the 720E-Green site. The distribution shapes are also markedly different between sites. Type A conflicts from the 20E-Dorval site demonstrate a secondary peak, suggesting that TTC measures are a composite of distributions. This is further reinforced by the difficulty we had in fitting a single gamma function to the observations, regardless of the type or aggregation.

The total lane changes were also recorded and their ratio, as a percentage of all observed drivers, calculated. 720E-Green shows the greatest rate or lane changing, likely due to the lower speed, slightly longer analysis area, shorter distances between merging sections and confirms a subjectively observed greater rate of freeway entering and exiting activity in the area. In the 20E-Dorval and 720E-Green sites, the rate of lane changing from the second to the first lane wasn't significantly lower, and for the 720E-Green site, which had the treatment applied this rate was the second-highest, suggesting that drivers do not obey the treatment.

Site	720E-Green		20E-Dorval		138W-Clement	
1 → 2	291	3.32%	379	2.94%	425	4.54%
2 → 3	555	6.32%	276	2.14%	-	-
3 → 4	350	3.99%	-	-	-	-
4 → 3	257	2.93%	-	-	-	-
3 → 2	289	3.29%	79	0.61%	-	-
2 → 1**	377	4.30%	150	1.16%	274	2.92%

Table 2 – Summary of lane changes. Left columns are total lane changes, right columns are a percentage of total objects. **Lane changes from the second to the first lane are those which the treatment is designed to forbid.

6. CONCLUSION

Building a study around video data means that the quality and depth of the analysis is constantly improving. The original observation data is never lost and can be revisited to perform new types of measurements. Many of the graphs and measures presented are only snapshots of the current development process. There is a lot of room for expansion and also for improvement.

This study demonstrates the methodology of TTC extraction and calculation. However, the data collected and analysed so far are insufficient to make conclusions for or against the implementation of this lane-change-closure treatment, particularly because the analysis sites were not identically located with respect to the ramp geometry. The case study will be further explored with a greater data sample in future research; statistical analyses between TTC curves and site characteristics will be attempted, as well as attempting to validate the usefulness of these curves by comparing them to real accident data, both on a macroscopic and microscopic scale. The usefulness in using TTC as an intermediary measure of risk lies in the ease of its collection, particularly in situations where data is unavailable for safety reasons, as well as a safety risk hotspot identification tool on a more microscopic level.

The steps needed to refine and expand this research are clear:

i. More video data will be collected, at higher resolutions, with less compression artefacts and at locations allowing for a greater coverage of merging sections and interaction zones.
ii. More conclusive statistical analysis of correlation between heatmaps and accident history.
iii. Refined road user tracking and point-of-conflict prediction. Particularly, use of improved filtering to take advantage of high polling rates to increase accuracy of speed and position measurements.
iv. TTC distribution curve fitting (i.e. gamma or gamma composite) and modeling with respect to geometry
v. Expanded diagonal collision prediction: collision paths adjusted for natural road alignment (for TTC's with respect to an "expected trajectory")
vi. Comparison of conflicts with actual outcomes for validation

7. ACKNOWLEDGMENTS

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