EVALUATION OF SAFETY COUNTERMEASURES AT INTERSECTIONS USING MICROSCOPIC SIMULATION

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RESUMO
Em várias jurisdições, mais de 40% dos acidentes de trânsito ocorrem nas proximidades das interseções. A necessidade de reduzir tais tipos de acidentes tem incentivado pesquisas visando o desenvolvimento e avaliação de medidas de engenharia mais eficientes. Engenheiros de Transporte procuram tomar decisões que influenciem o padrão de segurança viária baseados em diferentes modelos estatísticos e/ou através de análises do tipo "antes" e "depois". Sabe-se que esse tipo de conhecimento não é fácil de ser obtido seja estatisticamente ou empiricamente. Esse trabalho apresenta um modelo de micro-simulação comportamental para a estimativa do potencial de acidente em interseções para diferentes configurações de tráfego e geometria em interseções. O modelo foi aplicado em uma conversão à esquerda em interseção não semaforizada. Neste caso, o aumento no tempo de percepção e reação e a redução no coeficiente de atrito aumentaram o potencial de acidente consideravelmente.

ABSTRACT
In many jurisdictions, over 40% of all road crashes take place at or near intersections. The need to reduce these crashes has fostered considerable research on the development and evaluation of cost-effective countermeasures. Safety engineers have been trying to make decisions affecting safety based on the knowledge extracted from different types of statistical models and/or observational before-after analysis. It is generally recognized that this type of factual knowledge is not easily obtained either statistically or empirically. This paper introduces a micro-level behavioural model to estimate crash potential at intersections for different traffic scenarios and geometric attributes. This model has been applied to a simple left turn movement for a four-leg unsignalized intersection. For this situation, increases in driver perception and reaction times and reduction in the pavement surface friction were found to increase crash potential significantly.

1. BACKGROUND

Intersections are a critical component of road safety. In Ontario, about 45% of reported crashes for 2002 took place at or near intersections (Ontario Road Safety Annual Report, 2002). The need to reduce these crashes has fostered considerable research on the development and evaluation of cost-effective countermeasures based on improvements in intersection geometry and real-time traffic control (Persaud *et al*, 2003, Zennaro and Misener, 2003, Cody, 2005, and Lyon *et al.*, 2005).

Geometric improvements include countermeasures such as the construction of exclusive or dedicated left-turn and right turn lanes, improvements in turning radii and removal of obstacles in the vehicle trajectory. These types of improvements could include capital intensive "grade separation" options or the replacement of intersections with roundabouts. Real-time traffic control attempts to modify the pattern of traffic conflicts at intersections by providing directional vehicle guidance that could have significant potential to reduce certain types of crashes. These controls could include the introduction of signal devices with a range of directional protocols and advanced driving warning systems that are operational in real time.

Before introducing a given countermeasure at an intersection, the net safety gain (crash reduction) of this option needs to be established *vis-à-vis* its implementation cost for different geometric and traffic conditions. Safety engineers have been trying to make decisions affecting safety based on the factual knowledge extracted from different types of statistical models and/or observational before-after analysis. It is generally recognized that this type of factual knowledge is not easily obtained either statistically or empirically. Davis (2004) and Hirst et al. (2004) cite a number of shortcomings associated with these types of approaches as applied to the evaluation of countermeasures at a specific location over different periods of time. These include:

1. Discrepancies between predicted and actual crash rates following the implementation of a countermeasure could occur normally as a result of historical trends in crash occurrence regardless of the countermeasure. This is frequently referred to as the "regression-to-the-mean" phenomenon.

2. These methods fail to consider driver behavioural factors and other variables that influence a site's level of safety.

3. Variables that are identified as been potentially significant for reducing crashes may fail to meet minimum thresholds for inclusion in statistical models. Their contribution to crashes may be plagued by problems of co-linearity.

4. Due to the rare random nature of crashes and data availability, the effect of an important variable may not be large enough to be detected reliably in a before and after observational data, despite the fact that its effect cannot be denied intuitively.

5. Under-reporting of crashes in police reports, especially those with low severity and failure to consider "near misses".

6. Mis-specification of the causes and consequences of the crashes in the historical data.

In an ideal world, a complete picture of lack of safety at a given location only emerges following a detailed "mechanistic analysis" of the causes and consequences of crashes at a given location and point in time at a given location and point in time. Crashes represent a complex hierarchical process of inter-related causes and consequences for different driving situations, locations and time intervals. For a highly circumscribed crash (e.g. rear-end crashes in non-merging freeway flows without lane changes, left turn manoeuvres at intersections, etc), researchers are beginning to explore different mechanistic approaches that can provide valuable insights into how crashes take place with their corresponding likelihood of occurrence (Mehmood *et al.*, 2002 and Cody, 2005).

2. OBJECTIVES

The main purpose of this paper is to present an overview of a mechanistic micro-level model for evaluating safety at isolated intersections subjected to the introduction of different countermeasures. In order to accomplish this objective left turn movements are considered for unsignalized and signalized situations at a hypothetical two-lane four-leg intersection with major and minor approaches. For the unsignalized case the minor approach is equipped with a stop sign, while for the signalized case the intersection is equipped with a three phase traffic light with advanced green interval for left turn maneuvers. It is worth noting that such a micro-level mechanistic analysis of vehicle movements can account for different driving and traffic conditions, including changes in the average daily traffic volume, effect of driver behaviour, road geometry and different intersection control devices (e.g. all-way-stop controlled, two-way-stop controlled and conventional fixed cycle traffic signals).

The research described in this paper has three specific objectives:

1. Develop a micro-level traffic simulation model that can identify potentially unsafe vehicle interactions for different vehicle movements based on three types of traffic behaviors protocols, car-following, lane change and gap acceptance.

2. Link the traffic simulation model to a Crash Potential (CP) component based on real-time analysis of traffic conflicts for different vehicle movements, driver perception and reaction times, and vehicle speed/deceleration profiles.

3. Investigate variations in CP resulting from the introduction of traffic signal controls for LT vehicles entering the minor approach. Two traffic signal options can be considered: stop signs on the minor approach and full traffic signal installation with directional advanced green phases.

3. MODELLING POTENTIAL INTERSECTION CRASHES

The usual representation for considering crashes at intersections is based on identifying "traffic conflicts" for various vehicle movements. A traffic conflict is defined as a juxtaposition of vehicle trajectories (more than one vehicle occupying the same space at the same time). In this paper, potential traffic conflicts are determined using micro level simulation and the overall lack of safety at intersections is obtained using three components of driver behaviour: car-following, lane-changing and gap-acceptance. Such an approach was considered by Gettman and Head (2003) in their analysis of surrogate safety indicators using traffic simulation models.

As illustrated in Figure 1, the identification of potential traffic conflicts is determined for a simple left turn movement where the left turn vehicle enters the intersection from the minor approach in the northbound direction. The LT vehicle is referred to as the Target Vehicle (TV), since it initiates the process leading to a potential crash at the intersection. The risk associated with this LT movements begins the moment that TV decides to proceed through the intersection after coming to a full stop (Pt. A in Figure 1). The left turn manoeuvre for the TV is defined in terms of two phases: 1) Gap-acceptance for the vehicle entering the intersection from pt. A *vis-a-vis* eastbound vehicles proceeding through the intersection along the major road in both lanes. 2) Gap-acceptance of the TV moving into the westbound lanes from the center median storage area *vis-a-vis* westbound vehicles proceeding through the intersection in the median lane.

Vehicles proceeding through the intersection along the major road are considered as Response Vehicles (RV), since their drivers react or respond to the actions of the TV driver. In this hypothetical exercise only three RV movements are considered: eastbound vehicles travelling in both the near side and centre median lane, and westbound vehicles travelling in the center median lane. Initially, we ignore all potential rear end and head-on crashes situations that result from secondary vehicle interactions and/or southbound vehicles running the stop sign on the minor approach.

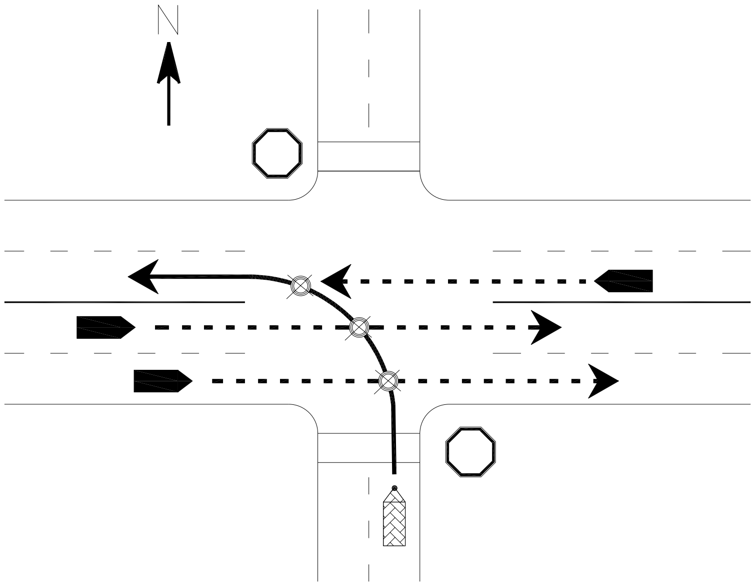

Figure 1: Single conflicting interaction for a left-turn manoeuvre.

As illustrated in Figure 1, for a simple LT case potential crashes are assumed to result from a combination of both erroneous TV gap acceptance and RV actions taken in response to TV stimuli. Traffic conflicts leading to a potential crash arise during three time-space intervals: 1) TV traverses the near side eastbound lanes in reaching the centre median storage area, 2) TV obstructs flow in the eastbound center median while it awaits a suitable gap in the center median westbound lane, and 3) TV enters the centre median westbound lane if a suitable gap arises creating a potential conflict with vehicles travelling westbound on the major road. In this example it is assumed that the TV driver speculates on the distance and time-to-crash posed by the various RV using insights gained from observed average speeds, headways and assumptions about RV driver behaviour.

A crash potential (CP) arises when the response vehicle (RV) deceleration rate needed to avoid a crash (DRAC) with the TV exceeds the RV maximum allowable deceleration rate (MADR). DRAC is determined over the simulation in 0.1 sec time intervals using actual RV speeds and distances established with respect to the “crash zone”. The crash zone as shown in Figure 1 reflects an area in the intersection where the target vehicle (TV) trajectory overlaps with the expected trajectory of each RV. As defined in this paper, the crash zone is assumed to form a discrete time-space window associated with each traffic conflict. The size of this window will depend on the relative speeds of the vehicles, their dimensions and lane width.

Logically we would assume CP to vary with respect to differential vehicle speeds and accelerations, and spacing. For example, vehicles with higher speed differentials travelling close to each other are more likely to be involved in crashes than vehicles with lower speed differentials travelling further apart. This relationship needs to be explored further. For this paper, we have assumed that a CP situation will arise anytime the DRAC exceeds MADR needed to avoid the crash.

For a situation where the RV and TV are travelling in the same direction, the RV will not have to come to a full stop, but simply needs to match the speed of the TV in order to avoid the crash. For the case of RV and TV trajectories intersecting at some angle greater than zero, the RV speed needs be set to zero (stop). MADR is estimated using individual RV driver perception and reaction times and fundamental information concerning coefficients of friction based on prevailing pavement surface condition, tires and type of brake system.

Based on the definition of crash potential and actions taken by the TV driver, Figure 2 presents a framework to establish CP in real-time using micro-level simulation. In order to establish this potential, the algorithm shown this Figure can be applied repeatedly for different time intervals until the TV clears all three crash zones as defined in a gap acceptance model.

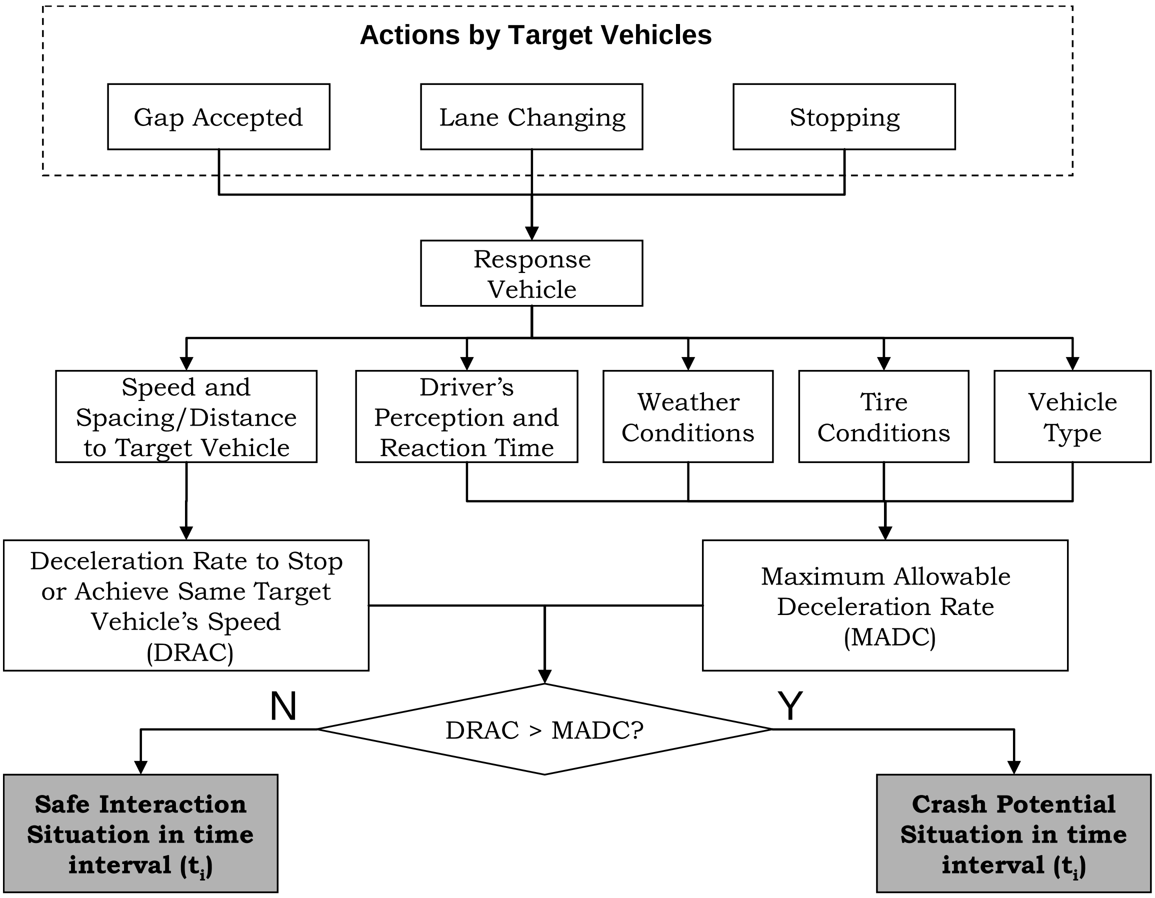

Figure 2: Framework to determine a crash potential situation in time (t_i)

The above discussion has focused on a simple LT vehicle movement from the minor approach. The Highway Capacity Manual (HCM) identifies 12 different vehicle movements for a typical four-leg intersection as showed in Figure 3. Each of these movements will need to be modeled separately.

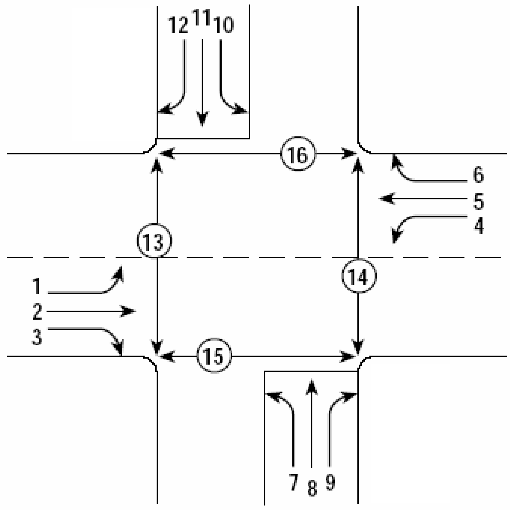

Figure 3: General manoeuvre numbering scheme for a four-legged intersection (Source: HCM 2000)

Table 1 summarizes the traffic conflicts used to establish crash potential for unsignalized intersections for the 12 movements cited in the HCM (2000) based on car-following, lane change and gap acceptance algorithms. For this analysis only TV movement 7 and RV movements 2 and 5 are considered.

The movements in Table 1 are for unsignalized intersections. The introduction of a traffic signal will alter the CP for each relevant RV movement in this Table. For an unsignalized intersection, the potential for a crash results from the RV on the major road be in conflict with the left-turn TV entering the intersection from the minor approach. For a signalized intersection, crash potential arises as a result of a rear end crash situation between vehicles moving on the major approaches stopping for the traffic light, acting as separate targets for vehicles moving in the same direction.

On the minor approach all gap-acceptance situations would be eliminated considering that vehicles seeking gaps now have a specific green phase on which to proceed. However, interactions between approaching vehicles and stopped vehicles on the minor approach are present for both signalized and unsignalized case. For the signalized case the difference would be the in number of interactions which depend on available gaps and on the traffic signal cycle (red/green/amber etc).

The RV is at risk of a crash with the left turning TV if the time required to complete each stage of the left turn movement exceeds the minimum time required for RV to reach the crash zone. The latter is based on observed vehicle location and speed/deceleration capabilities.

Table 1: Crash potential situations and pertinent micro-level models for unsignalized intersection.

Target Vehicle (TV) – Movements and Manoeuvres		Response Vehicle (RV) movements involved and micro-level model used to represent		
Movement	Manoeuvre	Car-following (CF)	Lane-Changing (LC)	Gap-acceptance (GA)
1	Stop and turn left when a gap is accepted	1, 2	-	5, 6
2	Stop and/or changing lane when traveling on the median lane due to movement 1 stop	1, 2	2, 3	-
3	Decelerating to turn right	2, 3	-	-
4	Stop and turn left when a gap is accepted	4, 5	-	2, 3
5	Stop and/or changing lane when traveling on the median lane due to movement 1 stop	4, 5	5, 6	-
6	Decelerating to turn right	5, 6	-	-
7	**Stop and turn left when a gap is accepted**	**7, 8**	**-**	**2, 5**
8	Stop and proceed straight ahead when a gap is accepted	7, 8, 9	-	2, 5
9	Stop and turn right when a gap is accepted	8, 9	-	2
10	Stop and turn left when a gap is accepted	10, 11	-	2, 5
11	Stop and proceed straight ahead when a gap is accepted	10, 11, 12	-	2, 5
12	Stop and turn right when a gap is accepted	11, 12	-	5

In the next section of the paper, micro-level simulation is used to explore the above left turn movement in terms of changes in CP for the unsignalized intersection case. The implications of introducing a directional traffic signal device will then be discussed.

4. SIMULATION RESULTS

The preliminary analysis presented in this work comprises a set of 4 scenarios each one with 15 minutes simulation time. In the simulation for specific scenarios were considered: 1) the presence of alert drivers and wet pavement, worn tires with a perception and reaction time of 0.75 secs and a coefficient of friction between tires and pavement of 0.38, 2) Alert drivers and dry pavement, good tires with a perception and reaction time of 0.75 secs and a coefficient of friction between tires and pavement of 0.78, 3) Non alert drivers and wet pavement, worn tires with a perception and reaction time of 1.50 secs and a coefficient of friction between tires and pavement of 0.38 and 4) Non alert drivers and dry pavement, good tires with a perception and reaction time of 1.50 secs and a coefficient of friction between tires and pavement of 0.78. For this simulation a volume on the major approach of 400 vphpl was assumed.

Table 2 summarizes the different drivers perception-reaction times and weather characteristics used in the scenario. The simulation algorithm was implemented in visual basic.

Table 2: Different drivers and weather characteristics used on the simulations

Scenario	RV Average Perception and reaction time (s)	Average Coefficient of friction	Volume on major (vphpl)	Obs
1	**0.75**	**0.38**	**400**	**Alerted drivers, wet pavements and worn tires**
2	**0.75**	**0.78**	**400**	**Alerted drivers, dry pavement and good tires**
3	**1.5**	**0.38**	**400**	**Un-alerted drivers, wet pavement and worn tires**
4	**1.5**	**0.78**	**400**	**Un-alerted drivers, dry pavement and good tires**

In order to run the simulation and evaluate CP the following assumptions were made:

1. Time headways were generated according to Poisson distribution. Individual RV speeds were generated using a Normal distribution with an average speed of 40km/h with a standard deviation equal to 20% of the mean. This situation reflect speeds of 80km/h for free-flow conditions and a jam-density following Greenshield's model of 80 vehicles/km per lane.

2. Perception and reaction times and coefficients of friction that follow a Normal distribution with a mean as shown in Table 1 and standard deviation equal to 20% of the mean.

3. To calculate the perceived time for the RV to reach the crash zone, the average speed of vehicles on the major approach and the distance to the crash zone plus a given perception error fixed at 20% of the true distance.

4. The true time required for the TV to clear the crash zone is determined using a fixed acceleration rate of 5.3 km/h per sec, lane widths of 3.5m, uniform car length equals to 4 meters and distance from the front bumper to the intersection approach line of 1m.

5. The perceived time for the TV to clear the crash zone is assumed to be the true time to clear the crash zone reduced by a perception error of 20%.

6. A specific gap is accepted if the perceived time needed for the TV to clear the crash zone is less than the perceived time for the RV to reach the same crash zone.

Table 3 presents the number of vehicles involved and the number of seconds under CP for each of the scenarios described above.

Table 3: Results summary for different simulated scenarios

Results	Scenario 1	Scenario 2	Scenario 3	Scenario 4
# vehicles in crash situations. shoulder lane – WB	1	1	2	5
# vehicles in crash situations median lane WB	6	-	6	3
# vehicles in crash situations median lane EB	3	3	7	2
CP(secs)	**10.5**	**1.9**	**14.6**	**7.2**

The introduction of a traffic signal will eliminate all crash potential situations presented in Table 3 since it reserves a specific un-conflicted time interval (green time) for each left turn movement. However, car-following algorithms in the model must be modified to represent possible interactions between vehicles slowing down or stopping in the amber/red phases. Additionally other TV scenarios from Table 1 will need to be considered.

In Table 3 several important results can be noted for the unsignalized intersection case:

- When the perception and reaction time is increased from 0.75 to 1.50 seconds, CP increases by corresponding 39% for wet pavement conditions, and over 200% for dry pavement conditions.

- When pavement friction is reduced from 0.78 to 0.38 the CP will increase by over 400% for perception and reaction time of 0.75 seconds (alert drivers) and over 100% for a perception and reaction time of 1.5 seconds (non alert drivers).

- At the two extremes for the best case scenario 2 (0.75 seconds perception and reaction time and 0.78 coefficient of friction) a CP situation occurs in 1.9 secs of simulation, as compared to the worst case scenario 3 (1.50 seconds perception and reaction time and 0.38 coefficient of friction) with a CP situation for 14.6 secs of simulation time for an increase in risk of over 600%.

For the signalized case conditions that produce a CP situation for the intersection need to be explored and is outside the scope of this paper.

5. CONCLUSIONS

This paper has presented some preliminary results of a micro-level mechanistic model of intersection vehicle movements. The model can be used to identify potential traffic conflicts and establish corresponding CP measures for different vehicle interactions and traffic conditions. In this paper CP situation was assumed to take place when the perceived TV time intervals for crash avoidance exceeds actual time available for the given traffic conditions and RV volumes. This model can serve as a practical guide to decision makers considering a range of countermeasures for a given intersection.

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