Improved Traffic Signal Warrants for Crash Avoidance at Intersections

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Synopsis

In many jurisdictions, over 40% of all road crashes take place at or near intersections. One of the ways planners attempt to reduce the number and severity of crashes at intersections is to install traffic signals. Traffic signals seek to improve the flow of vehicles by reducing potential traffic conflicts and associated crashes.

Manual on Uniform Traffic Control Devices warrants cite lack of safety as an overriding concern for the introduction on signals at intersections. Lack of safety is expressed in terms of the number of crashes reported by police at or near the intersection over a given period of time for a given volume of traffic.

The fundamental problem with using historical crash occurrence to justify the introduction of traffic signals is that this approach ignores the rare random nature of crashes. Basically, what took place last year may not be a good indicator of what is likely to take place in the immediate future. The approach also ignores “near misses”. Given the practical need for consistency, the existing warrant structure needs to be modified to make it less dependent on historical crash variations and more reflective of potential “unsafe” conditions faced by drivers at a given location with and without signalization.

The use of microscopic traffic simulation over the last two decades has essentially focused on the analysis of system transportation efficiency such as signalized intersections, arterial networks and freeway corridors. The potential of microscopic simulation in traffic safety and traffic conflict analysis became to be investigated more frequently since the beginning of 2000. This paper introduces a micro-level behavioural model to estimate crash potential at intersections for different traffic scenarios and geometric attributes. The 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. The paper speculates on how the model can be used to provide insights into crash reductions causes by signalization.

Improved Traffic Signal Warrants for Crash Avoidance at Intersections

Intersections are a critical component of road safety. In 2002, about 45% of recorded crashes in Ontario took place at or near intersections (Ontario Road Safety Annual Report, 2002). The high potential for reducing these crashes has fostered considerable research on cost-effective traffic and control devices that seek to optimize flow under conflicting situations. This research has lead to improvements in guidelines for the introduction of traffic signals at intersections in order to reduce associated traffic conflicts and the expected number of intersection-related crashes.

The Manual on Uniform Traffic Control Devices (MUTCD) cites 8 major conditions or warrants that need to be considered before signals are introduced at an intersection:

1. Eight-hour vehicular volumes on all approaches
2. Four-hour vehicular volumes on all approaches
3. Peak-hour volumes (any 4 consecutive 15 min periods)
4. Pedestrian volume
5. School crossing
6. Traffic signal coordination
7. Crash or crash experience
8. Road network coordination

In practice, if one or more of these warrants is exceeded we may still decide against installing a traffic signal. Such a decision is normally based on sound engineering principles and research that indicate signals would not compromise safety or disrupt progressive traffic flow. Safety becomes the over-riding concern in the MUTCD warrants.

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. The impact of signalization on the number of crashes at intersections has been investigated by Pernia (*et al.,* 2002), Persaud (*et al.* 2003), Oh (*et al.* 2004), Abdel-Aty *et al., (*2005) and Lyon (*et al.,* 2005), among others. 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.

The use of microscopic traffic simulation over the last two decades has essentially focused on the analysis of transportation efficiency such as signalized intersections, arterial networks and freeway corridors. The potential of microscopic simulation in traffic safety and traffic conflict analysis was initially recognized by Darzentas et al (1980) and has gained increasing interest in recent years. According to Archer (2000), existing micro-simulators are not designed for safety assessment due to the complex and multi-disciplinary nature of road-user behaviour. Furthermore, available car-following, gap-acceptance and lane change models are sufficient to represent driver behaviour in a “normative” way. To evaluate the safety demands one might need a more complex driver behaviour model with a higher level of variance including errors in the driver’s perception, decision-making and action process.

Crashes represent a complex hierarchical process of inter-related causes and consequences for different driving situations, locations and time intervals. Therefore, 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. 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).

OBJECTIVES OF THE PAPER

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. AWST, TWSC, conventional fixed cycle traffic signals).

The research described in this paper has three 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 behaviour 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.

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 Archer (2000), Minderhoud and Bovy (2001), Kosonen and Ree (2000) and Barceló, et al (2003) and 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 movement 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-à-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.

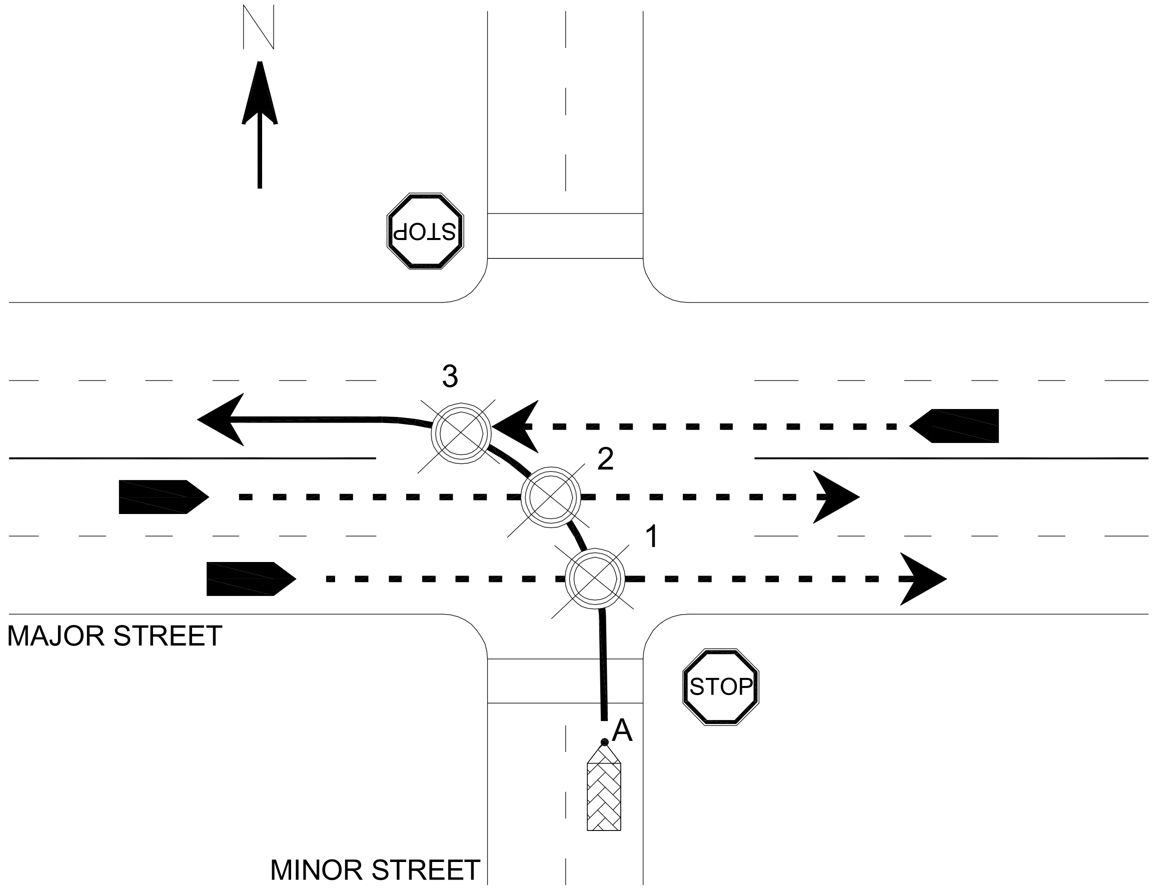

Figure 1: Single conflicting interaction for a left-turn manoeuvre.

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.

As illustrated in Figure 1, for a simple LT case potential crashes are assumed to result from erroneous 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, 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. The applicability of others safety indicators will be investigated, such as: deceleration to safety time (DTS), post-encroachment time (PET), potential time to collision (PTTC), time exposed time to collision (TIT) and time to accident (TTA), among others.

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 provides 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.

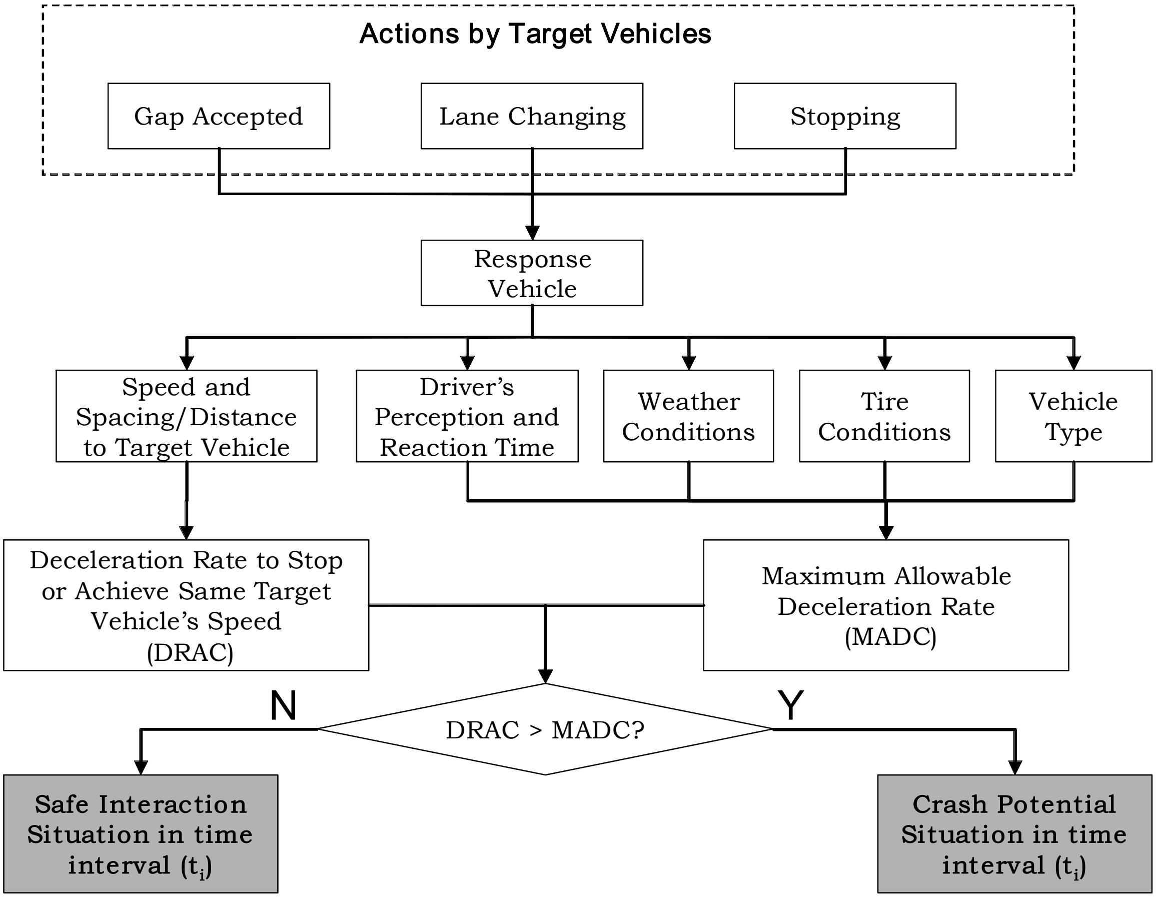

Figure 2: Framework to determine a crash potential situation in time (ti).

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. Table 1 summarizes the traffic conflicts considered 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.

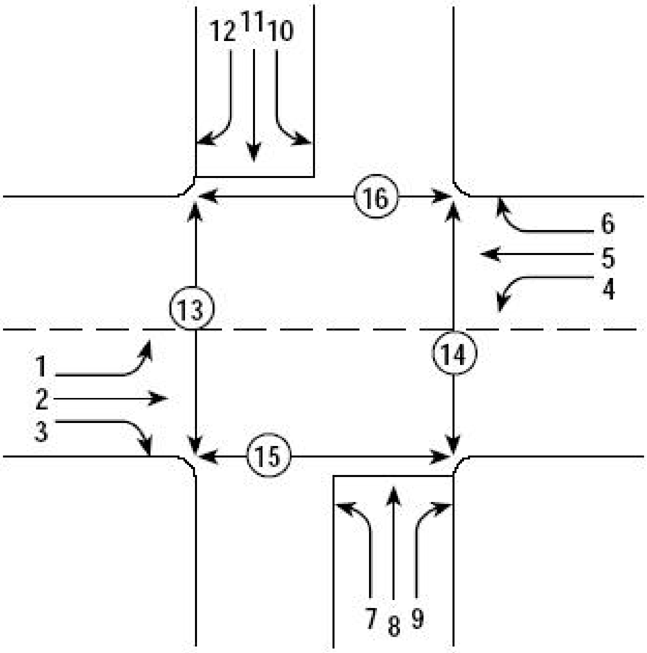

Figure 3: Manoeuvre numbering scheme for two-way stop controlled intersections (Source: HCM 2000)

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 being 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.

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.

SIMULATION RESULTS

The preliminary analysis presented in this work comprises a set of 4 scenarios each one with 1 hour 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.

Tab 1: Crash potential situations and pertinent micro-level model for unsignalized intersection.

Target Vehicle (TV)		Response Vehicle (RV) movements involved and micro-level model used to represent		
Movement	Manoeuvre/Action	Car-following (CF)	Lane-Change (LC)	Gap-acceptance (GA)
1	Decelerate to adequate speed to begin left turn	1, 2	-	-
	Turn left when gap is accepted.	-	-	5, 6
2	Decelerate to adequate speed when traveling on median lane due to movement 1.	1, 2	-	-
	Change lane when traveling in median lane to avoid excessive delay due to movement 1	-	2, 3	-
3	Decelerate to adequate speed to begin right turn manoeuvre.	2, 3	-	-
4	Decelerate to adequate speed to begin left turn	4, 5	-	-
	Turn left when gap is accepted.	-	-	2, 3
5	Decelerate to adequate speed when traveling on median lane due to movement 4.	4, 5	-	-
	Change lane when traveling in median lane to avoid excessive delay due to movement 4	-	5, 6	-
6	Decelerate to adequate speed to begin right turn manoeuvre.	5, 6	-	-
7	**Decelerate to stop and wait for a acceptable gap.**	**7, 8, 9**	**-**	**-**
	Turn left when gap is accepted.	**-**	**-**	**1, 2, 4, 5**
8	Decelerate to stop and wait for acceptable gap.	7, 8, 9	-	-
	Proceed straight ahead when gap is accepted.	-	-	1, 2, 4, 5, 6
9	Decelerate to stop and wait for acceptable gap.	7, 8, 9	-	-
	Turn right when gap is accepted.	-	-	2
10	Decelerate to stop and wait for a acceptable gap.	10, 11, 12	-	-
	Turn left when gap is accepted.	-	-	1, 2, 4, 5
11	Decelerate to stop and wait for acceptable gap.	10, 11, 12	-	-
	Proceed straight ahead when gap is accepted.	-	-	1, 2, 3, 4, 5
12	Decelerate to stop and wait for acceptable gap.	10, 11, 12	-	-
	Turn right when gap is accepted.	-	-	5

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

Tab 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

Tab 3: Results summary for different simulated scenarios.

Results	Scenario 1	Scenario 2	Scenario 3	Scenario 4
# vehicles in potential crash situations shoulder lane – WB	14	6	18	6
# vehicles in potential crash situations median lane WB	4	-	19	4
# vehicles in potential crash situations median lane EB	6	5	14	4
# Gaps accepted	138	150	158	158
# Generated vehicles	1466	1441	1494	1506
CP(secs)	36.6	6.8	57.7	10.1
% of simulated time under CP	1.02	0.19	1.60	0.28
CP/Veh (sec/veh)	0.025	0.005	0.038	0.007

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.

Several important results can be noted for the unsignalized intersection based on the safety indicator crash potential divided by the number of generated vehicles (CP/Veh) in Table 3:

- When the perception and reaction time is increased from 0.75 to 1.50 seconds, CP increases by corresponding 52% for wet pavement conditions, and 40% for dry pavement conditions.

- When pavement friction is reduced from 0.78 to 0.38, CP will increase by 400% for perception and reaction time of 0.75 seconds (alert drivers) and over 443% 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) CP is flagged for 6.8 secs of simulation, as compared to the worst case scenario 3 (1.50 seconds perception and reaction time and 0.38 coefficient of friction) where CP is flagged for 57.7 secs of simulation time. This reflects an increase in risk of over 650%.

Expected Changes in CP for a Signalized Intersection

The introduction of a traffic signal will eliminate all crash potential situations initiated by vehicles in movement 7 (attempting to turn left) since it reserves a specific un-conflicted time interval (directional green time) for each left turn movement. However, during the general green time vehicles attempting to turn left still have to wait for an acceptable gap from vehicles in the southbound approach. Obviously conditions that produce a CP must change for all movements. Table 4 summarizes what is considered to change in TV movements (actions) and the expected influence on CP when the intersection is upgraded from unsignalized to signalized. The conditions that produce change in CP for the complete set of movements in the unsignalized and signalized case will need to be explored further.

The introduction of a traffic signal (scenario 2 in Table 1) alters the crash potential for the RV at or near situations presented in Table 1. Manoeuvres 1 to 6 (major street) should keep all interactions (considering a permissive left-turn) and face a new disturbance represented by vehicles slowing down to stop for a amber/red light. This interaction could be represented using car-following models. On the minor street all gap-acceptance “situations” would be removed considering that vehicles seeking gaps now have a specific green phase to proceed. However, car-following “situations” must be added to mimic interactions between vehicles slowing down to stop under amber/red phases.

CONCLUSIONS

The use of micro-level behavioural models can provide valuable insights regarding the evaluation of safety at intersections for different geometric, operational and environmental conditions. However, a considerable amount of research is needed to establish a safety indicator that could be reasonable linked to “real” traffic accidents and the calibration and validation of the emerging micro-level “safety” models still an open question.

This paper presents 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 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. The introduction of a traffic signal is expected to make average deceleration manoeuvres to turn left/right more disciplined particularly during directional green phases and therefore providing safer interactions. However, straight movements in the major street should face a new interaction between themselves due to mandatory stop by amber/red phase. This model can serve as a practical guide to decision makers considering a range of countermeasures for a given intersection.

ACKNOWLEDGEMENTS

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Tab 4: Expected changes in CP for unsignalized and signalized intersection scenarios.

Movement (HCM-2000)	Action/Manouevre		Expected changes in CP from A to B
	Unsignalized - stop sign (A)	Signalized with left-turn phase (B)	
1 and 4	I Decelerate to adequate speed/rest to turn left in acceptable gap. II Turn left in acceptable gap.	I Decelerate to adequate speed to turn left when directional green phase. II Decelerate to adequate speed/rest to turn left in acceptable gap when general green phase. III Decelerate ro rest in amber/red phase. IV Turn left when directional green phase. V Turn left in acceptable gap.	Deceleration movements should be more organized due to the traffic signal. Acceptable gaps should be safe during directional green and more organized on general green phase.
2 and 5	I Decelerate to adequate speed/rest when traveling in median lane due to movement 1 or 4. II Decelerate to adequate speed/rest when traveling in shoulder lane due to movement 3 or 6. III Lane change when travellig in median lane to avoid excessive delay due to movement 1 or 4.	I Decelerate to adequate speed/rest when traveling in the median lane due to movement 1 or 4 when directional green phase. II Decelerate to adequate speed/rest when traveling in the median lane due to movement 1 or 4 when general green phase. III Decelerate to adequate speed/rest when traveling in shoulder lane due to movement 3 or 6 when general green phase. IV Lane change when travellig in median lane to avoid excessive delay due to movement 1 or 4 when general green phase. V Decelerate ro rest in amber/red phase.	Decelerations during directional and general green phase and lane change maneouvres tend to be safer due to traffic signal. However the mandatory stop manoeuvre in amber and red phase increase the overall CP due to the introduction of a conflict between movement 2 vehicles.
3 and 6	I Decelerate to adequate speed to turn right.	I Decelerate to adequate speed to turn right when general gree phase. II Decelerate ro rest in amber/red phase.	Deceleration movements should be more organized due to the traffic signal.
7 and 10	I Decelerate to rest to turn left in acceptable gap. II Turn left in acceptable gap.	I Decelerate to adequate speed to turn left when directional green phase. II Decelerate to adequate speed/rest to turn left in acceptable gap when general green phase. III Decelerate ro rest in amber/red phase. IV Turn left when directional green phase or in acceptable gap. V Turn left in acceptable gap.	Deceleration movements should be more organized due to the traffic signal. Acceptable gaps should be safe during directional green and more organized on general green phase.
8 and 11	I Decelerate to rest to proceed thru in acceptable gap. II Proceed thru in accpetable gap.	I Decelerate to adequate speed to proceed due to movement 7 and 10, 9 and 12, when directional green phase. II Decelerate to adequate speed/rest to proceed due to movement 7 and 10, 9 and 12 when general green phase. III Decelerate ro rest in amber/red phase. IV Proceed thru when green phase.	Deceleration movements should be more organized due to the traffic signal. All acceptable gap situations should be safe.
9 and 12	I Decelerate to rest to turn right in acceptable gap. II Turn right in accpetable gap.	I Decelerate to adequate speed to turn right due to movement 7 and 10 when directional green phase. II Decelerate to adequate speed/rest to turn right due to movement 7 and 10 when general green phase. III Decelerate to adequate speed/rest to turn right when general green phase. IV Decelerate ro rest in amber/red phase.	Deceleration movements should be more organized due to the traffic signal. All acceptable gap situations should be safe.

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