Development of Collision Adjustment Factors for the Canadian Traffic Signal Warrant Matrix Procedure

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Paper prepared for presentation
at the Emerging Topics in Road Safety session
at the 2020 TAC Conference & Exhibition.

Acknowledgements

Special thanks are extended to Dr. Jim Christie and Dr. Yuri Yevdokimov for their guidance on the methodology used in this study, as well as the Natural Sciences and Engineering Research Council of Canada, New Brunswick Innovation Foundation, and the University of New Brunswick for their financial support of this research.

ABSTRACT

Traffic signal warrants (TSWs) are important tools for traffic engineers because they provide an objective shorthand means of identifying whether a net benefit would result from signalizing an intersection. This decision can impact numerous operational facets; consequently, most TSW systems consider several factors when estimating an overall impact.

The Canadian Traffic Signal Warrant Matrix Procedure, originally published by the Transportation Association of Canada (TAC) in 2003 with subsequent minor adjustments, does not have a collision history component: a common feature in other TSWs. This creates challenges for practitioners investigating the safety impacts of signalization because the lack of a standardized approach can lead to inconsistency in their findings.

This research developed collision adjustment factors (CAFs) that convert the collision history for a site into points that supplement the existing TAC warrant procedure score outputs. The CAFs were developed based on recent research that estimates expected changes in collision severity and frequency in North America due to signalization, with the intent that they can be broadly used by all Canadian jurisdictions. Additionally, the procedure used to develop the national CAFs in this research can be employed by jurisdictions analyze their intersections based on local data.

INTRODUCTION

Traffic engineers and planners often must consider whether changing the type of traffic control at an intersection would improve the intersection's operational performance. Depending on the types of traffic control being considered there are numerous tools that can be used to assess the net impacts but the primary resource employed is normally a traffic signal warrant (TSW) analysis.

TSWs are shorthand tools that are intended to help practitioners easily identify stop-controlled intersections that may benefit overall from signalization. There are numerous reasons why a practitioner may want to signalize an intersection, though the most common warrants deal with the reduction of delays for lower rank movements and collision history *(1-3)*. TSWs are normally developed for use at a national or regional level to provide consistent, objective justification for the signalization of stop-controlled intersections across large road networks.

The TSW guideline published by the Transportation Association of Canada (TAC) in 2003 with subsequent modifications, the Canadian Traffic Signal and Pedestrian Signal Head Warrant Matrix Procedure *(1)*, follows a cumulative-factors methodology. The TAC warrant procedure uses a calculation based on conflicting vehicle-vehicle movements, vehicle-pedestrian movements, and a few other intersection and regional characteristics to calculate a score that provides both a warrant threshold (100 or more points indicates that signals should have a net benefit) and a priority ranking system for intersections (higher scores indicate higher priority).

The TAC warrant procedure does not include a collision history component *(1)*, which further differentiates it from other contemporary TSW systems *(4, 5)*. The authors of the TAC warrant procedure provide several arguments for why they chose not to include collision history in their system; however, this has not relieved practitioners from being obligated to assess the safety implications from signalizing stop-controlled intersections. Since the TAC warrant procedure does not provide guidance on how to compare collision history to their warrant score, practitioners are left with the task of determining how to best accomplish this themselves, which can lead to inconsistency in application.

This research presents a methodology that practitioners can employ to empirically compare collision histories to TAC warrant scores at stop-controlled intersections through the creation of a *Collision Adjustment Factor* (CAF). The collision analysis used in the development of the CAFs *(6)* was based on analyses of intersection collision frequency *(7)* and severity *(8)* across North America. The CAFs developed were intended to be supplemental to the existing TAC warrant procedure. Provincial and municipal road authorities that have their own models for predicting the change in collision expectation due to signalization, collision cost analysis, and/or valuation of the importance of collisions and delays can also use the framework outlined in this research to develop their own CAFs to supplement the TAC warrant procedure.

LITERATURE REVIEW

To provide a foundation for this research, a literature review was conducted covering the details of the TAC warrant procedure, how collisions have been accounted for in TSWs, and the common methods used to evaluate the externalities of signalizing an intersection.

Canadian Traffic Signal and Pedestrian Signal Head Warrant Matrix Procedure

There are two general approaches that have been used in the development of TSW systems: discrete-factors methodology (DFM) and cumulative-factors methodology (CFM). DFM warrants, such as those published by the FHWA *(3, 4)* and the Province of Ontario *(2)*, provide a set of individual warrants for varying intersection characteristics, where if any one of the warrant criteria are met then signalization may be warranted. CFM warrants, like the one published by TAC *(1)*, provide one overall recommendation for installing signals at an intersection based on a confluence of several distinct facets being considered.

The TAC warrant procedure calculates a score for an intersection based on the number of vehicle-vehicle and vehicle-pedestrian conflicts and a few other physical, demographic, and traffic characteristics of the intersection. The scoring system provides both a warrant threshold (100 or more points indicates that signals may be beneficial) and a priority ranking system for intersections (higher scores indicate higher priority). The scoring system was originally calibrated against other conflicting-movement traffic delay-based traffic signal warrants used in Canada at the time of its creation to provide results that were consistent with the expectations of practitioners *(9)*. The method for calculating the TAC warrant score is shown in Equation 1.

$$W = \left[\frac{C_{bt}X_{V-V}}{K_1} + \frac{X_{V-P}FL}{K_2}\right] C_s C_{mt} C_v C_p \quad (1)$$

Where:
W is the score output from the calculation;
X_{V-V} is the cross-product of all vehicle-vehicle conflicts in the intersection;
X_{V-P} is the cross-product of all vehicle-pedestrian conflicts in the intersection;
F is a pedestrian demographics factor;
L is the number of lanes that pedestrians must cross on the main road;
C_s is an intersection spacing factor;
C_{mt} is a main street truck factor;
C_v is a posted speed limit factor;
C_p is a population demographics factor, and;
K_1 and K_2 are scaling factors.

The TAC warrant procedure requires counting all through, left turning, and right turning vehicles from each approach for 6-hours, typically covering the morning, midday, and evening peak periods. The hourly counts are then averaged before being used to calculate the TAC warrant score. In addition to the equation, TAC provides a methodology to account for intersection configurations where right turning vehicles from the minor road are not impeded by the other minor road traffic, such as when there are exclusive right turn lanes. This methodology adjusts the product of right turning and conflicting through volumes within the X_{V-V} component of the equation.

Notably, the TAC warrant procedure does not incorporate a collision history component. The authors of the TAC warrant procedure chose to exclude collision history because of the random fluctuations of collisions around a mean, that most warrants based on collision history do not anticipate future safety issues, and because collision expectations are dependent on the vehicle conflict analysis that was already included in the TAC warrant procedure *(1, 9)*. The first two of these concerns can be addressed by employing statistical methods for analyzing collision expectations that were not widely in use when the TAC warrant procedure was first created in 2003. The third concern is an issue of calibration; traffic conflict models can be used to predict intersection safety, but the TAC warrant procedure was not calibrated to achieve this result so it is unlikely that an additional collision analysis would be double-counting collisions.

Collision Analysis in Traffic Signal Warrants

The lack of a collision history component separates the TAC warrant procedure from the industry norm, as the majority of other TSW systems do account for collision history in some manner. This includes the previous system published by TAC in 1988, wherein collision priority points were determined by cross-referencing the police reported collision frequency for an intersection on a chart *(10)*. Despite other TSWs having a collision history component, most of these warrants are quite dated and the methods used to develop them are unknown to the authors of this study, including the 1988 TAC TSW.

The majority of TSWs with collision history components that were found in this literature review were based on the criteria from the original 1935 edition of the Manual of Uniform Traffic Control Devices (MUTCD) *(11)*. The 1935 MUTCD indicated that signalizing an intersection may be warranted if there were 5 or more angle collisions at the intersection during a one-year period and if a trial of alternative safety collision reduction measures did not improve overall intersection safety. Slight modifications to this criteria were made in subsequent editions of the MUTCD; however, the only substantial addition by the 2009 edition was that 80% of the threshold requirements from one of two delay-based warrants also needed to be met to justify signalization based on collision history *(3)*. Other jurisdictions that use similar collision-based TSWs include Ontario, Canada; the UK; and Australia *(2, 12-17)*. Like the 1988 TAC TSW, there is no known empirical justification for these TSWs *(11)*.

The upcoming edition of the MUTCD will contain an overhauled collision based TSW that was developed using the Highway Safety Manual predictive tools to establish new collision rate thresholds *(4)*. These updated thresholds are a substantial improvement over the previous methodology, though the predictive tools in the HSM themselves are dated and had a narrow geographical scope; making them potentially unreliable for the development of TSWs that will see nation-wide application. Additionally, MUTCD presents a DFM warrant, so the updated methodology would still require substantial reworking to be incorporated into a CFM warrant like the current TAC warrant procedure.

Comparison of Signalization Externalities

When an intersection is signalized, it is generally expected that the average delay for conflicted movements at the intersection will decrease, traffic volumes will increase for conflicted movements due to the reduced delay, and that the severity and frequency of collisions will change. This follows the previous discussion of traffic signal warrant systems, wherein vehicle delays and collisions are the main variables considered.

Several externalities are often recommended for consideration in addition to travel time, collisions, and the cost of infrastructure for the general transportation project, including vehicle costs, health, parking, congestion, roadway land value, traffic services, transportation diversity, air pollution, noise, resource consumption, barrier effect, land use impacts, water pollution, and waste disposal *(18)*. These additional externalities are often omitted when developing traffic signal warrant systems in the interest of developing simplified tools that focus on the localized operational effects of signalizing an intersection.

Direct comparison of the externalities involved in transportation projects is challenging due to the nature of the variables being considered. The most common way to overcome this has been through the economic comparison of costs and benefits, and numerous resources are available to assist practitioners with evaluating the economic costs and benefits of changes to their transportation networks *(18-21)*. In the context of TSWs, a combination of empirical analysis and expert opinion is typically used in their development *(4, 11)* as the priorities of practitioners do not always align with the results of a cost-benefit analysis.

METHODS

There were two main components to this research: quantifying the change in annual collision costs due to signalization and converting the resulting change into TAC warrant points. The intent was to create the CAFs for the TAC warrant procedure in a framework with substantial flexibility, allowing practitioners to make modifications and develop their own CAFs if desired. The general method being used to calculate the CAF is shown in Equation 2 and it is intended that the resulting CAFs can be added directly to the score output from the TAC warrant procedure. The equation was formulated such that a decrease in overall collision costs due to signalization results in a positive CAF.

$$W_C = (F_B C_B - F_A C_A) * S \tag{2}$$

Where:
W_C is the collision adjustment factor;
F_B and F_A are the collision frequencies before and after signalization;
C_B and C_A are the average cost of a collision before and after signalization, and;
S is a scaling factor used to convert the net collision costs into TAC warrant points.

To assist with converting the net collision costs into TAC warrant points, an analysis of the change in annual delay costs associated with the TAC warrant procedure was conducted. This was not a perfect comparison because the warrant calculation includes several components that do not specifically correspond to expected changes in vehicle delay; however, it allows for an order-of-magnitude comparison between the two most significant externalities associated with signalizing an intersection. It is further notable that the CAFs developed through this process are useful at the network screening level for identifying candidate intersections for further study, not as a replacement for the safety study that should be conducted prior to signalizing an intersection.

Change in Collision Cost Estimation

This research relied on a previous effort for the estimation of the change in collision costs due to signalization *(6)*, which used SPFs for annual collisions developed through the aggregate analysis of SPFs from 28 jurisdictions across North America *(7)* and collision costs developed through a study of the average severity of intersection collisions in the United States *(8)* to estimate the change. This prior study phase analyzed the change in collision costs for signalizing intersections exhibiting traffic volumes of 5000 to 15000 AADT on the major road and 1500 to 6000 AADT on the minor road, and a summary of the intersection configurations that resulted in either collision cost increases (+), decreases (-), or mixed results within the range of traffic volumes (+ / -) is shown in Table 1. It was notable that this analysis predicted an increase in collision costs after signalization for most intersection configurations; this finding was in contrast to collision cost analyses based on collision modification factors, which typically show a collision cost reduction due to signalization, because the underlying SPFs were developed based on random intersections as opposed to CMFs which are developed based on intersections where practitioners expect to see a benefit (either through delay or collision reduction) from signalization.

TABLE 1: Summary of the change in net collision costs due to signalization *(6)*

Category					Collision Analysis Inputs					Change in Total Collision Costs
					SPFs for Annual Collision Prediction and Stop-Controlled Dispersion Parameter *(7)*			Average Collision Cost (2010 US$) *(8)*		
Severity	Legs	Land Use	PSL	Divided	Signal	Stop	Disp.	Signal	Stop	
Casualty	3	Rural	-	No	$e^{-7.629}AADT_{maj}^{0.619}AADT_{min}^{0.222}$	$e^{-11.051}AADT_{maj}^{0.828}AADT_{min}^{0.381}$	0.702	$346,545	$483,333	+ / -
			-	Yes	$e^{-7.629}AADT_{maj}^{0.619}AADT_{min}^{0.222}$	$e^{-11.051}AADT_{maj}^{0.828}AADT_{min}^{0.381}$	0.702	$414,293	$357,168	+ / -
		Urban	-	No	$e^{-9.044}AADT_{maj}^{0.755}AADT_{min}^{0.233}$	$e^{-12.224}AADT_{maj}^{0.879}AADT_{min}^{0.380}$	0.894	$244,977	$652,947	+
			-	Yes	$e^{-9.044}AADT_{maj}^{0.755}AADT_{min}^{0.233}$	$e^{-12.224}AADT_{maj}^{0.879}AADT_{min}^{0.380}$	0.894	$276,725	$414,962	+
	4	Rural	-	No	$e^{-7.227}AADT_{maj}^{0.591}AADT_{min}^{0.240}$	$e^{-10.174}AADT_{maj}^{0.652}AADT_{min}^{0.572}$	0.923	$346,545	$483,333	-
			-	Yes	$e^{-7.227}AADT_{maj}^{0.591}AADT_{min}^{0.240}$	$e^{-10.174}AADT_{maj}^{0.652}AADT_{min}^{0.572}$	0.923	$414,293	$357,168	-
		Urban	-	No	$e^{-9.596}AADT_{maj}^{0.833}AADT_{min}^{0.264}$	$e^{-10.149}AADT_{maj}^{0.781}AADT_{min}^{0.314}$	0.585	$244,977	$652,947	+
			-	Yes	$e^{-9.596}AADT_{maj}^{0.833}AADT_{min}^{0.264}$	$e^{-10.149}AADT_{maj}^{0.781}AADT_{min}^{0.314}$	0.585	$276,725	$414,962	+
Total	3	Rural	Low	-	$e^{-5.476}AADT_{maj}^{0.536}AADT_{min}^{0.198}$	$e^{-10.022}AADT_{maj}^{0.747}AADT_{min}^{0.442}$	0.556	$115,448	$124,011	+
			High	No	$e^{-5.476}AADT_{maj}^{0.536}AADT_{min}^{0.198}$	$e^{-10.022}AADT_{maj}^{0.747}AADT_{min}^{0.442}$	0.556	$139,515	$214,592	+ / -
				Yes	$e^{-5.476}AADT_{maj}^{0.536}AADT_{min}^{0.198}$	$e^{-10.022}AADT_{maj}^{0.747}AADT_{min}^{0.442}$	0.556	$139,515	$222,724	+ / -
		Urban	Low	-	$e^{-9.457}AADT_{maj}^{0.896}AADT_{min}^{0.265}$	$e^{-11.697}AADT_{maj}^{0.899}AADT_{min}^{0.453}$	0.841	$110,751	$124,011	+
			High	No	$e^{-9.457}AADT_{maj}^{0.896}AADT_{min}^{0.265}$	$e^{-11.697}AADT_{maj}^{0.899}AADT_{min}^{0.453}$	0.841	$140,713	$214,592	+
				Yes	$e^{-9.457}AADT_{maj}^{0.896}AADT_{min}^{0.265}$	$e^{-11.697}AADT_{maj}^{0.899}AADT_{min}^{0.453}$	0.841	$140,713	$222,724	+
	4	Rural	Low	-	$e^{-5.960}AADT_{maj}^{0.601}AADT_{min}^{0.229}$	$e^{-9.162}AADT_{maj}^{0.660}AADT_{min}^{0.498}$	0.615	$115,448	$124,011	+
			High	No	$e^{-5.960}AADT_{maj}^{0.601}AADT_{min}^{0.229}$	$e^{-9.162}AADT_{maj}^{0.660}AADT_{min}^{0.498}$	0.615	$139,515	$214,592	+ / -
				Yes	$e^{-5.960}AADT_{maj}^{0.601}AADT_{min}^{0.229}$	$e^{-9.162}AADT_{maj}^{0.660}AADT_{min}^{0.498}$	0.615	$139,515	$222,724	+ / -
		Urban	Low	-	$e^{-8.926}AADT_{maj}^{0.889}AADT_{min}^{0.271}$	$e^{-8.355}AADT_{maj}^{0.723}AADT_{min}^{0.309}$	0.402	$110,751	$124,011	+
			High	No	$e^{-8.926}AADT_{maj}^{0.889}AADT_{min}^{0.271}$	$e^{-8.355}AADT_{maj}^{0.723}AADT_{min}^{0.309}$	0.402	$140,713	$214,592	+
				Yes	$e^{-8.926}AADT_{maj}^{0.889}AADT_{min}^{0.271}$	$e^{-8.355}AADT_{maj}^{0.723}AADT_{min}^{0.309}$	0.402	$140,713	$222,724	+

Since the prior analysis was based on SPFs, the general method shown in Equation 2 was modified to the formulation shown in Equation 3. This formulation follows the standard procedure for predicting the change in collision frequency based on SPFs and using the EB method to account for the regression-to-the-mean effect.

$$W_C = \left[\left(\frac{SPF_B * \left(F_B + \left(\frac{1}{\alpha}\right)\right)}{\left(\frac{1}{\alpha}\right) + nSPF_B}\right)\left(C_B - \frac{SPF_A}{SPF_B} C_A\right)\right] * S \tag{3}$$

Where:
SPF_B and SPF_A are the collision expectations from before and after signalization calculated from the aggregate SPFs;
α is the dispersion coefficient associated with the stop-controlled intersection SPF, and;
n is the number of years worth of collisions predicted by the SPFs.

Change in Traffic Delay Cost Estimation

Developing an estimate of the change in traffic delay costs due to signalization was a two-step process. First, a set of traffic volume conditions at stop-controlled intersections that would result in TAC warrant scores of around 100 points had to be developed. The 100-point value was used because it is the threshold in the TAC warrant procedure between intersections warranting or not warranting signalization, indicating that the delay reduction benefit observed at this threshold is sufficient to justify signalization. To obtain an adequate sampling of conditions around the 100-point threshold, sets of conditions that resulted in scores of 90 to 100 points were identified. Once a set of these traffic volume conditions were determined, total intersection delays were approximated and delay costs could be calculated. Many assumptions were made in the development of the estimations, which are documented in the following subsections.

Predefined intersection geometries were used to simplify the calculation procedures while still covering most real-world scenarios. Both 3- and 4-leg intersections were considered, the main road had either one or two through lanes in each direction plus a dedicated left turning lane at the intersection, and the minor road had one lane in each direction under stop control and a dedicated left turn lane was added when signalized. All dedicated left turn lanes were assumed to have capacity for four vehicles. The remaining assumptions were taken from the standard assumptions in the Highway Capacity manual, including that the intersections have 12-foot lane widths, were at a level grade, did not have flared lanes, and that there was no skew.

Identification of Traffic Volume Conditions

There were several inputs to the TAC warrant procedure that could have substantial variation between intersections, so a Monte Carlo Simulation was conducted to identify sets of inputs that resulted in output scores of 90 to 110. In a Monte Carlo Simulation, the input parameters to a model are varied randomly within specified ranges across thousands of iterations (10,000 iterations were used in this research) to determine the range and distribution of possible outputs from the model *(22)*, making this an ideal analytical tool to identify combinations of input parameters that resulted in TAC warrant scores of 90 to 110.

The inputs to the TAC warrant procedure were traffic and pedestrian volumes, the distance to the nearest intersection on the main road, main road heavy vehicle percentage, main road posted speed limit, and the population of the surrounding area. Heavy vehicle percentage was set at 3%, following guidance in the Highway Capacity Manual *(23)*, turning volume proportions were drawn from research conducted in Toronto, Canada in the 1980s *(24)*, and the population of the surrounding area was randomly set to one of the three levels designated by TAC. The remaining variables were varied randomly within upper and lower limits in the Monte Carlo analysis as summarized in Table 2. These ranges were set to allow the Monte Carlo simulation to generate sets of inputs that would be typical of stop-controlled intersections that are in consideration for signalization. To simplify the analysis, it was assumed that opposing approaches had the same traffic volumes and that equal numbers of pedestrians crossed on each side of the intersection.

TABLE 2: Parameter estimates for the TAC warrant procedure Monte Carlo Simulation

Number of Intersection Legs	**3-Leg**		**4-Leg**	
Number of Lanes on the Main Road	**3-Lane**	**5-Lane**	**3-Lane**	**5-Lane**
Traffic Volume per approach: Main Road (vph)	300 – 525	300 – 600	225 – 450	200 – 400
Traffic Volume per approach: Minor Road (vph)	125 – 200	125 – 200	100 – 175	100 – 175
Turning Proportions: Main Road	Left: 10% Right: 10%	Left: 10% Right: 10%	Left: 10% Right: 10%	Left: 10% Right: 10%
Turning Proportions: Minor Road	Left: 50% Right: 50%	Left: 50% Right: 50%	Left: 35% Right: 35%	Left: 35% Right: 35%
Pedestrian Crossing Volume Per road (pph)	0-50	0-50	0-50	0-50
Nearest Intersection on Main Road (m)	100 - 800	100 - 800	100 - 800	100 - 800
Posted Speed Limit on Main Road (km/h)	40-80	40-80	40-80	40-80

Traffic Delay Estimation and Delay Costs

The change in annual traffic delay due to signalization was then calculated for the hypothetical intersections with the input parameters resulting in TAC warrant scores of 90 to 110 identified in the Monte Carlo Simulation. Traffic delays were estimated using the procedures outlined in the Highway Capacity Manual (HCM) *(23)*. Stop-controlled delays were calculated following the core methodology outlined in Chapter 20 and the signal-controlled delays were calculated following the construction of queue accumulation polygons as outlined in Chapter 31. To follow these procedures and simplify the analysis, numerous assumptions were made as follows.

One of the more substantial assumptions made in this analysis was that the traffic volumes at the intersection did not change after signalization. In areas with few alternative routes bypassing the intersection this assumption would have a negligible effect; however, signalizing a single intersection can result in a redistribution of latent traffic demand. Review of the literature did not reveal typical expectations for how traffic volumes are redistributed due to the highly site- and context-specific nature of the redistributions, so the traffic volumes were assumed to remain constant.

For the stop-controlled delay it was assumed that crossing and left-turn movements from the minor road occurred in a single stage, critical and follow-up headways were the HCM default values, u-turns are not allowed, and no capacity adjustments were made due to platoons from upstream signals.

The signalized intersection was assumed to have an 80 second cycle length with 4 second inter-green periods. The signal operates with 2-phases with all movements permissive under green and no protected movement phases. Time was allocated between the two phases in proportion to the approach volumes, with a 20 second minimum phase length for the minor road. Base saturation flow rates were assumed as per the HCM recommendations. Arrivals are assumed to be random on the minor road, with platoon ratios on the main road corresponding to the distance between intersections and assuming a coordinated signal network. The initial queue and incremental delays were assumed to be negligible, due to the low vehicle volumes. The intersection is assumed to not be in a central business district. Additionally, it was assumed that there were no right turns on red, initial queues from previous cycles, on-street parking, bus stopping, work zones, downstream lane blockages, and no sustained spillback.

The HCM procedures are designed to yield per-vehicle delay estimate, typically for a peak 15-minute or hour interval on a weekday. The TAC warrant procedure is a segmented six-hour period that covers the typical morning, midday, and evening peak traffic periods. The per-vehicle delay estimates calculated from the HCM analysis were converted into yearly per-intersection delay estimates that align with the TAC warrant procedure by multiplying the approach delays by their respective average hourly traffic volumes, the duration of the analysis period per-day (6 hours), a growth factor of 2.17 to account for delays experienced at the intersection outside of the 6-hour study period, and the typical number of days in a year (365 days). The growth factor was calculated based on a chart published in the ITE Transportation Planning Handbook *(25)* which illustrated that 46% of daily delays in the United States are experienced during the combined 7am-9am, 11am-1pm, and 4pm-6pm period (a 6-hour period that coincides with the typical period for the TAC warrant procedure).

While this approach to estimating the yearly per-intersection delays will provide an order-of-magnitude estimate of annual delays to ultimately compare to collision costs, there were some notable drawbacks to this scaling method. The assumption that each of the six study hours experiences the same traffic volume likely underestimates total delays given they typically increase exponentially as traffic volumes increase. Conversely, the assumption that the same delays would be experienced each weekday likely overestimates total delay. The TAC warrant system does not specify a day of the week on which to collect the traffic counts for the analysis, but the analysis is primarily targeted to weekday commuter traffic patterns due to the 6-hour count methodology. Intersections with substantial commuter traffic on weekdays typically exhibit a reduction in volumes on weekends and better distribution of traffic throughout the day, so the rush hour peaks where most delays are experienced are not as common. The impacts of these opposing assumptions depend on local traffic fluctuations and there was notably no guidance found in the literature to account for these impacts accurately at a national level.

To convert the delay estimates into costs, average valuations of travel time were required in units that matched the collision cost units (2010 US dollars). Values of travel time were obtained from US Department of Transportation guidelines in 2009 US dollars and inflated to 2010 US dollars. The recommended average value of travel time for all purposes surface mode trips for local travel was \$12.71 per person hour (\$12.50 in 2009) and for intercity trips was \$18.30 per person hour (\$18.00 in 2009) *(26)*. A vehicle occupancy of 1.62 persons per vehicle was assumed, which was the Canadian average for light vehicles as published in the 2009 Canadian Vehicle Survey *(27)*.

Determination of a Scaling Factor

There are two main methods that can be used to determine an appropriate scaling factor for converting the change in collision costs from signalization into TAC signal warrant points: an economic comparison of the change in collision costs and value of TAC warrant points based on delay costs or expert opinion on the value of collisions relative to delays. The economic comparison has the advantage of being the most objective assessment method, though can produce results that are at odds with the priorities of practitioners if the collision costs outweigh the value of TAC warrant points based on delay. TSWs that incorporate delay and collision components typically prioritize improved traffic flow and often explicitly set collision criteria such that very few intersections would merit installing signals solely based on collision history *(3, 4, 10)*.

The main justification for using expert opinion in creating scaling factors for the CAFs is the substantial variability of collision frequency and severity between jurisdictions and even between intersections within the same jurisdiction. Due to this issue of variability, the change in collision cost results developed in the prior research *(6)*, being an estimate based on North American averages, cannot perfectly predict the actual change in collision costs due to signalization at any randomly selected Canadian intersection. Expert opinion can be used to mitigate this issue by discounting the change in collision costs from signalization such that the CAFs do not hold their full economic weight against delays but still provide a meaningful adjustment to TAC warrant scores based on the changes in collision frequency and severity due to signalization that would be expected at the average Canadian intersection.

For these reasons, this research examined the applicability of both a direct economic comparison of delays and collisions and expert opinion in the development of scaling factors for the CAFs.

RESULTS AND DISCUSSION

The results and discussion cover three main subjects: the changes in collision and traffic delay costs from signalization, the recommended CAFs for the TAC warrant procedure, and the opportunities for jurisdictions to modify this procedure to create CAFs that correspond to their local priorities.

The collision cost and CAF analyses are both functions of traffic volume. To simplify the results and discussion, the range of traffic volumes considered was 5000 to 15000 AADT on the major road and 1500 to 6000 AADT on the minor road, to be consistent with the AADT ranges used in developing the most recent traffic signal warrant guidelines in the United States *(4)* and in the development of the aggregate SPFs applied in this study *(28)*.

Magnitude of Change in Collision Costs

While the change in collision costs used in this analysis was published in previous work *(6)*, the magnitude of the expected change in collision costs due to signalization is important for comparison to the change in delay costs. Within the proposed CAF structure the change in collision costs is calculated based on the specific information for the intersection, but Table 3 provides a summary of the range of expected change in collision costs for intersections with collision histories of 0, 5, and 10 collisions per year as a reference for comparison to the change in delay costs. It is important to note that the change in collision costs with a collision history of 0 per year is due to the analysis assuming that future collision frequencies will regress upwards towards the average collision frequency for intersections with similar traffic volumes.

TABLE 3: Range of the Increase in Collision Costs due to Signalization

Category					Change in Average Collision Cost at Varying Annual Collision Frequencies (thousands of 2010 US dollars)					
					Existing Collision History (per year)					
					0		5		10	
Severity	Legs	Land Use	PSL	Divided	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Casualty	3	Rural	-	No	-86	18	-388	82	-689	145
			-	Yes	-153	3	-690	14	-1226	25
		Urban	-	No	42	70	232	385	422	699
			-	Yes	46	76	250	417	455	758
	4	Rural	-	No	-221	-56	-1239	-313	-2258	-570
			-	Yes	-323	-97	-1815	-544	-3306	-992
		Urban	-	No	27	67	105	263	183	458
			-	Yes	26	69	104	271	181	473
Total	3	Rural	Low	-	24	75	92	283	160	491
			High	No	-45	54	-171	204	-297	353
				Yes	-55	50	-207	187	-358	325
		Urban	Low	-	39	81	205	424	370	766
			High	No	20	68	106	354	192	641
				Yes	16	63	82	328	149	593
	4	Rural	Low	-	35	94	142	383	250	671
			High	No	-36	52	-145	211	-254	370
				Yes	-45	45	-185	181	-324	318
		Urban	Low	-	53	145	159	436	266	726
			High	No	21	101	64	305	107	508
				Yes	14	91	41	273	69	456

Traffic Delay Cost Estimation

The initial run through the Monte Carlo simulation and traffic delay analysis found that traffic delay costs at the hypothetical intersections increased when the intersection was signalized. The main reason for this was that those operating with the right of way experience no, or very little, delay, but after signalizing the intersection these vehicles experience some delay. Even though the change in delay time per vehicle was minimal, the volume of traffic it was applied to was large enough to produce a significant difference.

Most delay-based TSWs are focused on reducing delays for impeded movements at stop controlled intersections *(2, 3)*. This makes sense when considering the Level of Service (LOS) metric that is often used in assessing intersection delays *(23)*; the increase in per vehicle delays for the unimpeded movements due to signalization typically still results in these movements being categorized as LOS A, which is the highest LOS that can be achieved, whereas the decrease in delays for the impeded movements is typically significant enough to improve their LOS rating. Even though the total traffic delay for the intersection may not be improved, this is still a desirable result for practitioners. As a result, the delay analysis in this study was modified to only assess the delays for the impeded movements under stop control (left turns on the main road and all minor road movements).

The results of the TAC warrant procedure Monte Carlo Simulation and subsequent traffic delay cost estimation for impeded movements are shown in Table 5. The data presented identify the number of iterations from the Monte Carlo Simulation that resulted in TAC warrant scores of 90 to 110 (out of 10,000 iterations), the average delay per vehicle under stop and signal controlled conditions, the average annual traffic delay savings in total hours and dollars, and the incremental value of a TAC warrant point within the 90 to 110 point range. The incremental value was the slope of a linear regression fit of TAC warrant points to annual savings in dollars, representing how much each additional point is worth within the range of 90 to 110 TAC points. The range of costs corresponds to using the local and intercity travel time costs as lower and upper bounds for the average, respectively.

TABLE 5: Change in traffic delay costs for impeded movements due to signalization

Category			Avg. Delay per vehicle (s)		Avg. Annual Savings		Value of an Incremental TAC Warrant Point (2010 US Dollars)
Legs	Lanes	Cases	Stop	Signal	Hours	2010 US Dollars	
3	3	1913	48.1	19.7	14932	\$317,136 - \$456,474	\$8,239 - \$11,860
	5	1749	60.5	19.4	21845	\$463,947 - \$667,787	\$11,719 - \$16,867
4	3	2759	20.1	18.2	934	\$19,233 - \$27,691	\$1,497 - \$2,156
	5	2677	19.5	18.4	519	\$10,690 - \$15,392	\$1,265 - \$1,823

It was notable from Table 5 that the travel time and cost savings were substantially greater for 3-leg intersections than 4-leg intersections. Since a 3-leg intersection has one fewer approach than a 4-leg intersection, more vehicles were required on each of the 3 approaches to obtain TAC warrant scores of 90 to 110 than at a 4-leg intersection and the increase in vehicles per approach directly led to increased delays under stop and signal control.

Further, it appears that the TAC warrant system has been calibrated (intentionally or unintentionally) such that 4-leg intersections achieve 100 points when they are right at the threshold of achieving a reduction in delays for impeded movements resulting from signalization. While this is a good objective measure, it does not effectively balance the benefits of delay savings against the increased capital and maintenance costs that arise when signalizing an intersection. The average annual savings for 3-leg intersections, being much more substantial than the 4-leg intersection results, suggest that signalizing a 3-leg intersection with a TAC score of about 100 would pay back the infrastructure costs of signalization within a few years.

Comparing the Changes in Annual Delay and Collision Costs Due to Signalization

The magnitudes of the change in collision costs due to signalization shown in Table 3 were, in general, equivalent to the average annual delay cost savings for 3-leg intersections and much greater than the savings for 4-leg intersections as shown in Table 5. This suggests that for an objective warrant system, the safety implications of signalization should hold at least equal weight to vehicle delay considerations.

It is also important to note that the results shown in Table 3 are applicable to any randomly selected stop-controlled intersection, as opposed to strictly stop-controlled intersections that are being seriously considered for signalization. This means that while the results shown in Table 3 are applicable to most intersections, some intersections will exhibit drastically different changes in collision severity and frequency from the average intersection when signalized. For this reason, it is recommended that all intersections being considered for signalization be subject to an in-service road safety review.

Scaling Factors based on an Economic Evaluation

Scaling factors for the CAFs were calculated based on the incremental TAC score costs shown in Table 5. The midpoint incremental TAC score costs for 3-leg and 4-leg intersections were about \$12,000 and \$1,600, respectively. To convert the collision costs into TAC scores the collision costs must be divided by the cost of a TAC point, so the inverse of the incremental TAC score costs were calculated. This resulted in scaling factors of 8.33×10^{-5} points per 2010 US dollar for 3-leg intersections and 6.25×10^{-4} points per 2010 US dollar for 4-leg intersections. Applying these scaling factors to the results shown in Table 3 results in the CAFs that are presented in Table 4.

TABLE 4: Range of CAFs using Scaling Factors based on an Economic Evaluation

Category					Collision Adjustment Factors using Scaling Factors of 8.33×10^{-5} for 3-leg intersections and 6.25×10^{-4} for 4-leg intersections					
					Existing Collision History (per year)					
					0		5		10	
Severity	Legs	Land Use	PSL	Divided	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Casualty	3	Rural	-	No	-2	7	-7	32	-12	57
			-	Yes	0	13	-1	58	-2	102
		Urban	-	No	-6	-4	-32	-19	-58	-35
			-	Yes	-6	-4	-35	-21	-63	-38
	4	Rural	-	No	35	138	196	774	356	1411
			-	Yes	61	202	340	1134	620	2066
		Urban	-	No	-42	-17	-164	-66	-286	-114
			-	Yes	-43	-16	-169	-65	-296	-113
Total	3	Rural	Low	-	-6	-2	-24	-8	-41	-13
			High	No	-5	4	-17	14	-29	25
				Yes	-4	5	-16	17	-27	30
		Urban	Low	-	-7	-3	-35	-17	-64	-31
			High	No	-43	-13	-221	-66	-401	-120
				Yes	-39	-10	-205	-51	-371	-93
	4	Rural	Low	-	-59	-22	-239	-89	-419	-156
			High	No	-33	23	-132	91	-231	159
				Yes	-28	28	-113	116	-199	203
		Urban	Low	-	-91	-33	-273	-99	-454	-166
			High	No	-63	-13	-191	-40	-318	-67
				Yes	-57	-9	-171	-26	-285	-43

The results in Table 4 show that even relatively modest collision histories can have a substantial impact on TAC warrant scores through this CAF process. This impact could create a barrier for implementation of the CAFs due to how dramatically they will change the results of an analysis using the TAC warrant procedure. Ideally this would be mitigated by recalibrating the existing TAC warrant procedure to better reflect the economic impacts of signalization on traffic delays or creating a separate economic-based warrant procedure that could be used in conjunction with these CAFs.

Scaling Factors based on Expert Opinion

The best reference for expert opinion on the inclusion of collision history in TSWs comes from a survey conducted as part of the development of the new collision justification for the MUTCD in the United States *(4)*. This survey identified attitudes that practitioners had towards the existing MUTCD warrant (trial of alternatives to reduce collisions, at least 5 collisions per year reducible through signalization, meeting 80% of one of two traffic volume-based warrants) as well as ways that practitioners felt that the warrant could be improved. The respondents did not propose changes to the criteria of meeting 80% of a volume-based warrant with the most common request being the inclusion of a longer collision history period than one year.

Following the results of this survey and the general practice for collision-based TSWs globally, the criteria used for creating scaling factors based on expert opinion were that 5 casualty collisions per year were equivalent to 20 TAC warrant points. For this analysis, 5 casualty collisions per year were used instead of 5 reducible collisions per year to simplify the analysis procedure for practitioners, and because casualty collisions are more likely to result from 'reducible' angle collisions as opposed to 'non-reducible' rear-end or other types of intersection collisions. The 20 TAC warrant points equivalence was used because that constitutes 20% of the TAC warrant points required to justify signalization (the remaining portion of points after 80% of the points are awarded through the delay-based analysis).

From Table 4, the highest expected change in collision costs for 5 casualty collisions per year was $1,815,000, and equating this to 20 TAC points results in a value of $90,750 per point. A scaling factor based on this TAC point value is $1.102x10^{-5}$ points per 2010 US dollar. Notably, this scaling factor represents collision costs being discounted to about 1/8 for 3-leg intersections and 1/60 for 4-leg intersections of their economic value within the warrant system. Table 5 shows the range of expected CAFs for collision histories of 0, 5, and 10 collisions per year using this scaling factor.

TABLE 5: Range of CAFs using Scaling Factors based on an Economic Evaluation

Category					Collision Adjustment Factors using a Scaling Factor of $1.102x10^{-5}$					
					Existing Collision History (per year)					
					0		5		10	
Severity	Legs	Land Use	PSL	Divided	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Casualty	3	Rural	-	No	0	1	-1	4	-2	8
			-	Yes	0	2	0	8	0	14
		Urban	-	No	-1	0	-4	-3	-8	-5
			-	Yes	-1	-1	-5	-3	-8	-5
	4	Rural	-	No	1	2	3	14	6	25
			-	Yes	1	4	6	20	11	36
		Urban	-	No	-1	0	-3	-1	-5	-2
			-	Yes	-1	0	-3	-1	-5	-2
Total	3	Rural	Low	-	-1	0	-3	-1	-5	-2
			High	No	-1	0	-2	2	-4	3
				Yes	-1	1	-2	2	-4	4
		Urban	Low	-	-1	0	-5	-2	-8	-4
			High	No	-1	0	-4	-1	-7	-2
				Yes	-1	0	-4	-1	-7	-2
	4	Rural	Low	-	-1	0	-4	-2	-7	-3
			High	No	-1	0	-2	2	-4	3
				Yes	0	0	-2	2	-4	4
		Urban	Low	-	-2	-1	-5	-2	-8	-3
			High	No	-1	0	-3	-1	-6	-1
				Yes	-1	0	-3	0	-5	-1

Recommended Scaling Factor for CAFs

Based on the analysis of scaling factors developed through economic comparison and expert opinion, it is recommended that the expert opinion-based scaling factor of $1.102x10^{-5}$ be used in conjunction with the current TAC warrant. While this scaling factor discounts collision costs substantially when compared to delay costs through the TAC warrant analysis, it provides a more meaningful adjustment to the existing TAC warrant procedure based on the expected collision expectations after signalization of the average Canadian intersection.

Figures 1 through 4 show graphs of the CAFs developed using a scaling factor of 1.102×10^{-5} with major road AADT of 15,000 and minor road AADT of 6,000. These graphical references are specific to traffic volume, so practitioners should determine CAFs for specific intersections by following Equation 3.

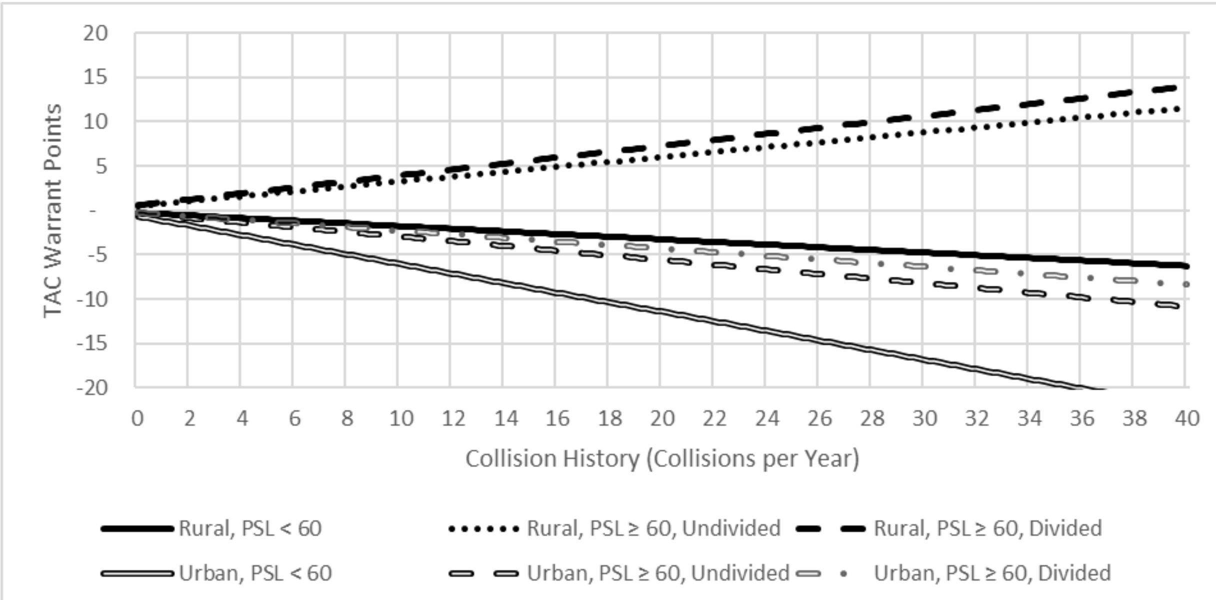

FIGURE 1: Graph of CAFs for total collisions at 3-leg intersections with major road AADT of 15,000, minor road AADT of 6,000, and scaling factor of 1.102×10^{-5}

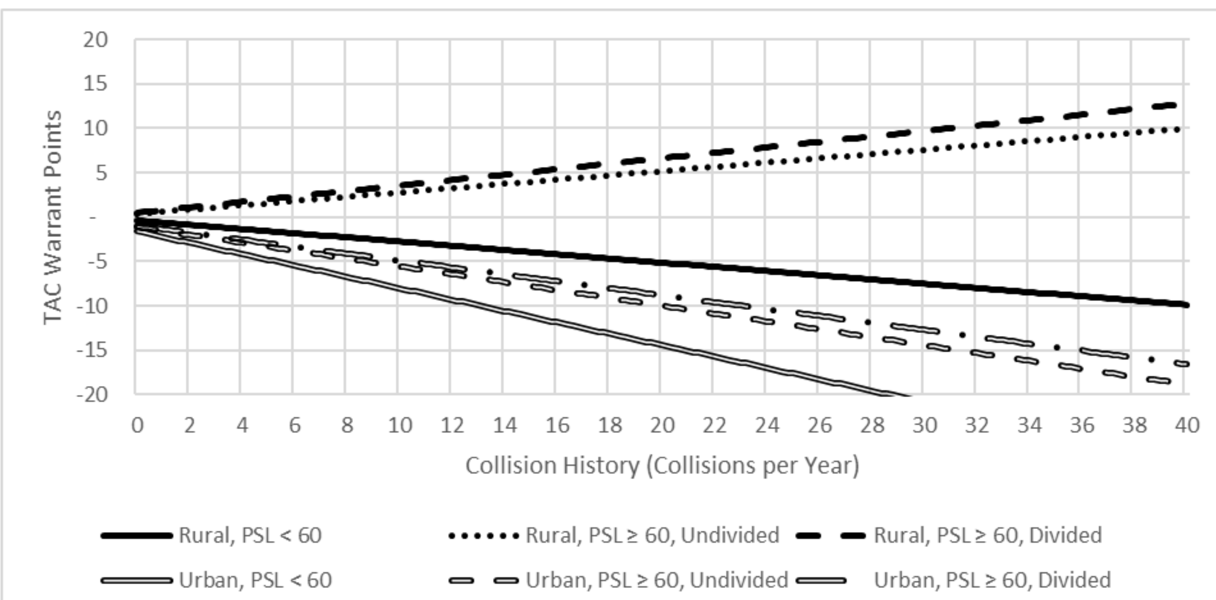

FIGURE 2: Graph of CAFs for total collisions at 4-leg intersections with major road AADT of 15,000, minor road AADT of 6,000, and scaling factor of 1.102×10^{-5}

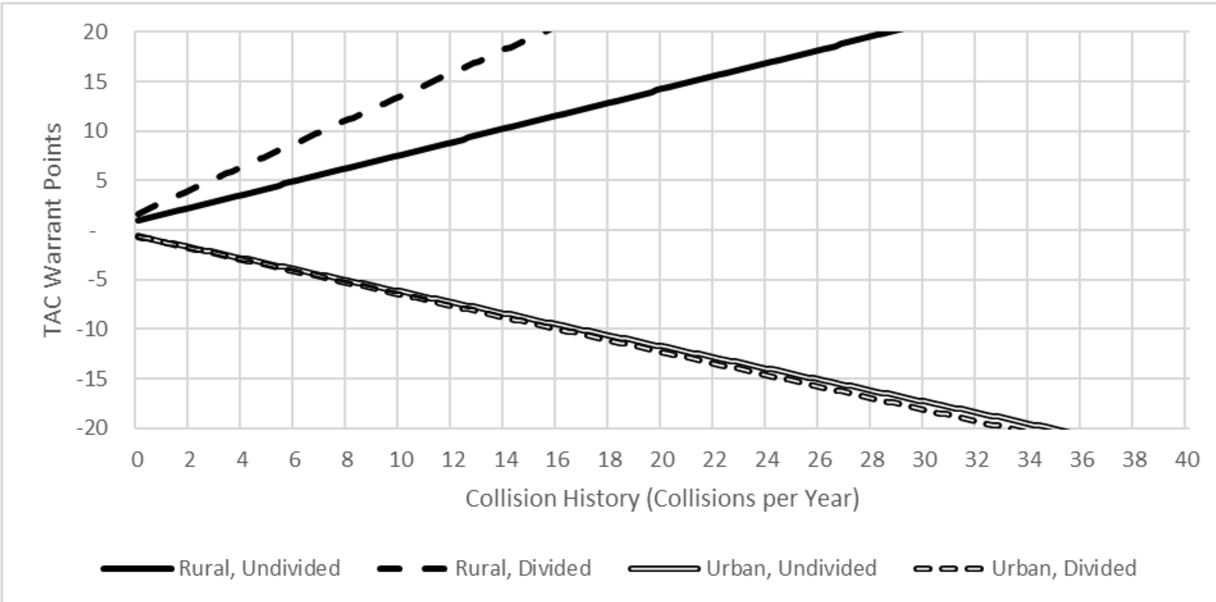

FIGURE 3: Graph of CAFs for casualty collisions at 3-leg intersections with major road AADT of 15,000, minor road AADT of 6,000, and scaling factor of 1.102×10^{-5}

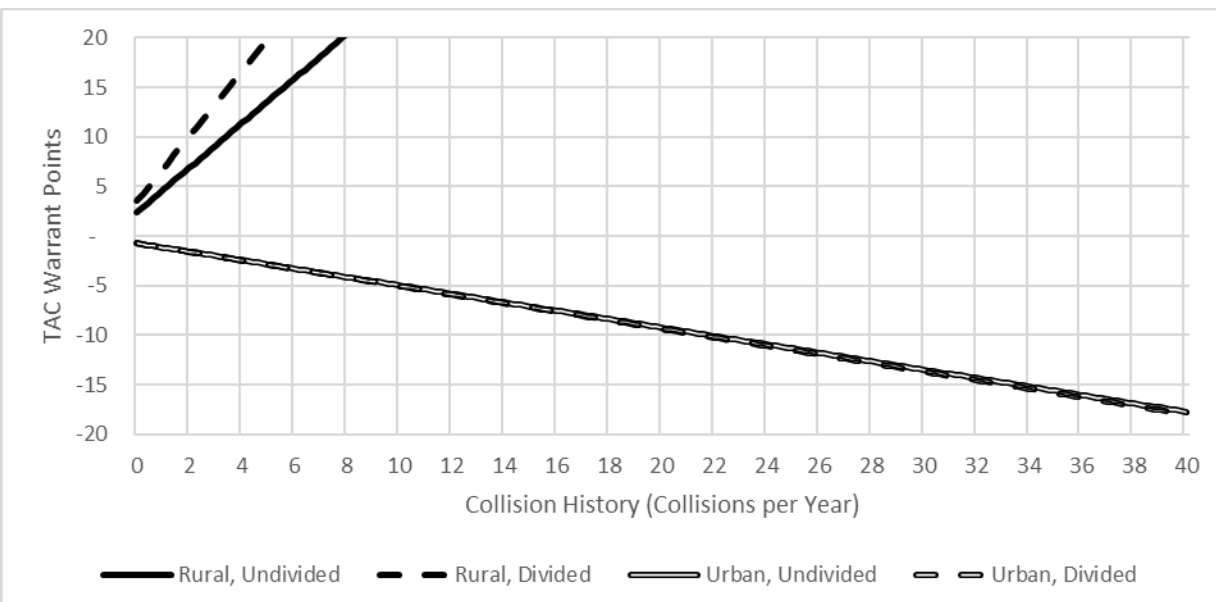

FIGURE 4: Graph of CAFs for casualty collisions at 4-leg intersections with major road AADT of 15,000, minor road AADT of 6,000, and scaling factor of 1.102×10^{-5}

Modifications for Jurisdiction CAFs

As discussed previously, the intent for TSWs is to provide consistent and objective justification for the signalization of stop-controlled intersections across large road networks. While the CAFs developed through this research are designed to provide consistent results across Canada, individual jurisdictions may be interested in developing CAFs that better match their local collision expectations or collision priorities.

The most obvious modification that jurisdictions could make would be to substitute their locally developed collision models into the methodology presented in this research. The benefit is that the resulting jurisdiction CAFs would better match the change in collision expectations for their jurisdiction, providing more accurate results. It is important to note that not all jurisdictions across Canada have the capacity to develop their own collision prediction models, which justifies the need for the CAFs presented in this research.

In addition to collision expectations, collision priorities can differ between jurisdictions. A common example is that some Canadian jurisdictions have adopted Vision Zero strategies that specifically strive to eliminate fatal and serious injury collisions from their roadways. CAFs could be locally tailored to such priorities by modifying the collision costs used to compare the different severities of collisions when developing average collision costs, modifying the values used in determining the scaling factor, or deciding to only count specific severities of collisions.

CONCLUSIONS

This research presented a methodology for incorporating a collision history element into the TAC warrant procedure by calculating CAFs. The CAFs are applicable to network analyses where the objective is to identify and prioritize stop-controlled intersections for further evaluation and are not a replacement for a safety audit that ought to be conducted before an intersection is signalized.

Additionally, it was found that there is a large discrepancy in the change in delay costs expected for 3-leg and 4-leg intersections with characteristics that result in TAC warrant scores of about 100 points. It is recommended that these be reconciled, or that a new delay-based analysis revolving around the change in delay costs be undertaken to allow more detailed refinement of the CAFs.

Lastly, while this research successfully achieved its objective of incorporating collision history into the TAC warrant procedure, it is important to recognize that collisions and delays are only two of many externalities of signalizing an intersection. An additional feature that should be studied for incorporation is the environmental footprint of signalization, particularly as efforts to mitigate climate change are increased over the coming years.

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