JOURNAL OF TRAFFIC AND TRANSPORTATION ENGINEERING (ENGLISH EDITION) 2019; 6 (2): 196–208

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Original Research Paper

Effects of winter weather on traffic operations and optimization of signalized intersections

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HIGHLIGHTS

- Adverse weather events largely affect traffic parameters at signalized intersections.
- Weather-specific signal plans are best with intersections of medium traffic demand.
- Weather-specific signal plans largely reduce delay at coordinated intersections.

ARTICLE INFO

Article history:
Received 29 March 2017
Received in revised form
12 January 2018
Accepted 9 February 2018
Available online 6 February 2019

Keywords:
Signal optimization
Inclement weather
Traffic simulation
Signal coordination

ABSTRACT

Adverse winter weather has always been a cause of traffic congestion and road collisions. To mitigate the negative impacts of winter weather, transportation agencies are under increasing pressure to introduce weather responsive traffic management strategies. Currently, most traffic signal control systems are designed for normal weather conditions and are therefore suboptimal regarding efficiency and safety for controlling traffic during winter snow events due to changes in traffic patterns and driver behaviors. The main objective of this research is to explore how to modify pre-timed traffic signal control parameters under adverse weather conditions to increase traffic efficiency and road safety. This research consists of two main components. First, we examine the impacts of winter weather on three key traffic parameters, i.e., saturation flow rate, start-up lost time, and free flow speed. Secondly, we investigate the potential benefits of implementing weather-specific signal control plans for uncoordinated intersections as well as coordinated corridors. Two case studies are conducted, each with varying levels of traffic demand and winter event severity, to compare the performance of different signal plans. Evaluation results from both Synchro and VISSIM show that implementing such signal plans is most beneficial for intersection with a medium level of traffic demand. It is also found that the benefit of implementing weather-responsive plans was more compelling at a coordinated-corridor level than at an uncoordinated-intersection level.

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Peer review under responsibility of Periodical Offices of Chang'an University.
https://doi.org/10.1016/j.jtte.2018.02.002

1. Introduction

Adverse weather has always been a cause of traffic congestion and a threat to road safety. In the U.S., inclement weather (snow, ice, and fog) causes delays of 544 million vehicle-hours annually, accounting for 23 percent of the total non-recurrent delay on highways (Franzese et al., 2002). According to National Highway Traffic Safety Administration (NHTSA), from 2002 to 2012, 1,311,970 crashes occurred in US annually in adverse weather, among which 540,931 occurred in snowy days (on snowing or snowy/slushy pavement) (Hanbali and Kuemmel, 1993). To mitigate these negative weather impacts, transportation agencies can deploy weather-responsive traffic management (WRTM) strategies in adverse weather conditions. Among common WRTM strategies, weather-responsive signal control is one of the most cost-effective options, as except for weather or traffic monitoring devices, no additional equipment is needed for this operation. Only the signal timing plans are adjusted under various adverse weather conditions. A weather-responsive signal control system deployed by the Utah Department of Transportation (UDOT) is described to reduce travel time and stop time by 4.3% and 11.2%, respectively (Perrin et al., 2001).

Generally, traffic signal timing plans are often designed to optimize traffic operations under normal weather conditions (Goodwin, 2002, 2003; Goodwin and Pisano, 2004). However, poor weather could have a significant impact on traffic pattern and driver behavior, rendering these signal plans suboptimal or even unsafe for these conditions (Agarwal et al., 2005). One study conducted in Salt Lake City, Utah found that on signalized arterial roads, saturation flow rates were up to 20 percent lower in adverse weather conditions than in normal weather conditions (Perrin et al., 2001). In this study, average speed was found to be 30% lower on slushy pavement than on dry pavement. Start-up lost time can be increased by 5%–10% depending on the weather condition. Thus, signal control plan designed for normal weather condition may not be appropriate under inclement weather conditions due to the different traffic patterns. Adapting signal control timing to adverse weather conditions can potentially increase traffic efficiency and road safety at signalized intersections. Specific measures include but are not limited to increasing cycle length, changing clearance interval, and adjusting coordination plans. Promisingly, latest advances in technologies have enabled real-time communication between a traffic control center and signal controllers. Implementing weather-responsive signal plans is more practical than ever.

For countries that are subject to long severe winter seasons, there is a significant need for cost-effective traffic control countermeasures to inclement weather. Despite the promising prospect, relatively few studies have been carried out to investigate weather-responsive signal control strategies. Perrin et al. (2001) suggested certain modifications on traffic signal parameters at isolated intersections under adverse weather conditions. The suggested measures included increasing amber time by 10%–15%, increasing all-red time by 1 s, decreasing the dry saturation flow rate by 20%, decreasing the average dry speed by 30%, and increasing the start-up lost time by 23%. Their suggestions were based on their field data measurements. However, their proposed inclement weather timing modification suggestions were not tested in simulation or field.

Sadek and Amison-Agolosu (2004) conducted a simulation study assessing potential benefits of weather-specific signal plans. Based on the reduction in saturation flow rate and free flow speed statistics under adverse weather conditions, they developed optimal signal timing plans using TRANSYT-7F and SYNCHRO for various weather conditions. The signal plans were evaluated using both macroscopic and microscopic simulation models. Evaluation results suggested that significant operational benefits were to be expected from implementing weather-specific timing plans. In one case study, the weather-optimal plan brought a 30.8% decrease in signal delay. However, there was little discussion on what aspects of signal timing they have considered to modify under adverse weather conditions.

Brennan et al. (2011) characterized traffic operations during winter weather conditions along with normal weather conditions. The study site was a 1.6-mile corridor of SR 37 in Noblesville, IN, USA. It was a coordinated system consisting of four intersections. High-resolution signal controller data and Bluetooth probe vehicle travel times were available along the corridor. From this information, they compared patterns of travel time, headway, and platoon shift and dispersion in normal and winter weather conditions. They found that travel time was increased by 83 s in median, platoons were shifted by 15, 25, and 30 s at three intersections, and design speed was decreased by 7–11 miles per hour (mph) in snowy events.

Asamer and Van Zuylen (2011) investigated changes of saturation flow rate in inclement weather conditions. They collected video recordings at three intersections in Vienna, Austria, and then estimated saturation flow rates by training a vehicle-behavior model using data extracted from videos. They obtained values of saturation flow rate in different road surface conditions (dry, wet, and snowy) and precipitation conditions (none, light, and heavy). Their results suggested that the effect of snowfall intensity is marginal and snow-weather saturation flow rates are similar to each other at different locations despite their various saturation flow rates in normal conditions.

Balke and Gopalakrishna (2013) described the implementation of a weather responsive traffic signal management system by UDOT. The goal of the system was to allow traffic signal operators to anticipate when weather conditions deteriorate to the point of impacting travel speeds and, once aware of the impending deterioration, to allow the operators to adjust offsets along the study corridor. The evaluation showed that the weather responsive timing plans reduced cumulative travel time by 4.3% and reduced the cumulative stop time by 11.2%. This research describes a real-world case study. However, the logic of weather-responsive signal control is relatively simple; furthermore, only coordination-related parameters are adjusted.

The FHWA study on developments in weather responsive traffic management strategies reviewed existing weather-responsive traffic signal control strategies (Gopalakrishna et al., 2011). It lists five specific weather-responsive signal control strategies: (1) redeploying signal control related detection systems; (2) changing clearance intervals (including yellow change intervals and all-red intervals); (3) modifying interval and phase durations; (4) adapting signal timing coordination plans; (5) deploying weather-responsive ramp metering measures. The report also mentions that certain measures (e.g., modified green interval length for isolated intersections) are still in the conceptual/research stage and most of these measures lack quantitative benefit evaluation.

In summary, the research and practice of weather-responsive signal control strategies are still in a preliminary stage with few comprehensive guidelines being developed. Adjustments on signal timing (e.g., cycle length, inter-green time, offset) are usually discussed separately; their combined effects on improving winter traffic performance, especially, safety, have not been investigated.

The purposes of this research are twofold: first, to quantify weather impacts on signal-design-related traffic parameters at signalized intersections; and second, to systematically investigate how to adjust pre-timed signal timing parameters to adapt to the adverse-weather traffic to increase traffic efficiency and road safety. Following the introduction, this paper first describes a field study on quantifying weather impacts on traffic parameters, and then demonstrates how to modify signal control plans under adverse weather conditions through two case studies. The last section concludes the findings from this research and proposes the future research.

2. Weather impacts on traffic parameters

The first step towards developing any weather-responsive traffic management strategies is to understand how drivers behave differently under various weather conditions (Ibrahim and Hall, 1994; Kwon et al., 2013; Zhang et al., 2004). Optimal traffic signal timing settings are affected by prevailing traffic flow patterns and driving behaviors. For example, longer cycle length is generally required to increase road capacity when saturation flow rates are lower and red clearance interval should be increased when drivers drive at a lower speed. These phenomena are expected to be observed under adverse weather conditions. This section describes a field study quantifying weather impacts on some signal-related traffic parameters.

2.1. *Field data collection*

We selected the intersection of University Avenue and Seagram Drive in the City of Waterloo, Ontario, Canada, as the study site. This is a four-leg signalized intersection with lane configurations shown in Fig. 1. Traffic parameters were extracted from video footage collected at the study site. Under normal as well as adverse weather conditions, we collected two types of data at the site: traffic video footage and road surface conditions. We collected video data in the winter of 2015 using a commercial portable video data collection device called Miovision Scout, which can elevate a video camera to 21 feet above the road surface. We collected 16 h of video footage from a total of eight days (Feb 2nd, Feb 4th, Feb 9th, Feb 11th, Feb 24th, Mar 3rd, Mar 4th, and Mar 5th) covering various weather conditions. Most of the video data were collected in rush hours (between 8:00 to 11:00 and between 16:00 and 18:15, in Eastern Standard Time) to ensure the ample sample size for estimating traffic parameters. During the videotaping, we also continuously monitored and recorded road surface conditions by field observations. Road surface conditions were initially categorized into five levels, i.e., dry, wet, wet and slushy, slushy in the wheel paths, and snowy and sticking. The numbers of valid cycle observations in each category are 26, 57, 36, 44, and 33.

2.2. *Methodology*

Three traffic parameters, i.e., saturation flow rate, start-up lost time, and free flow speed are extracted from the video data. All these parameters have significant impacts on signal timing design at intersections. The first two parameters are extracted from manually annotated video recordings and free flow speed is measured with aid of an automated video processing software (Fu et al., 2015). The detailed methodology of measuring these parameters and of applying automated video processing tools are described in the following sections, which is similar to the traditional method for the same purpose (Li and Prevedouros, 2002).

2.2.1. *Saturation flow rate*

Saturation flow rate indicates the flow rate at which vehicles could be discharged at maximum for a certain lane or approach during effective green time. We adopted the field measurement techniques of saturation flow rate described in Highway Capacity Manual (TRB, 2010) to measure saturation flow rate from traffic video footages. First, the saturation headway is estimated as the average of headways between vehicles from the fifth vehicle in the initial queue and continuing until the last vehicle that was in the initial

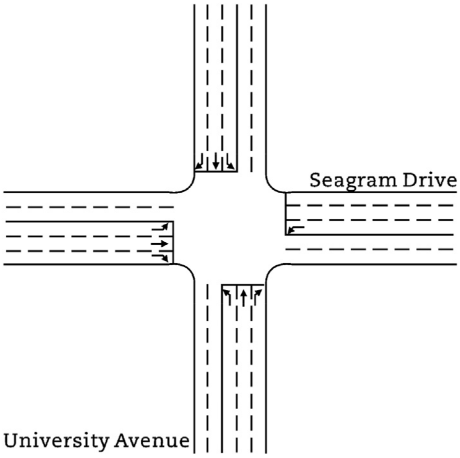


Fig. 1 – Lane configuration of the intersection of University Avenue and Seagram Drive.

queue. Then, the saturation flow rate can be converted from the saturation headway using Eq. (1).

$$s = 3600/h \tag{1}$$

where s is the saturation flow rate in vehicle/h and h is the saturation headway in second.

2.2.2. *Start-up lost time*

The first several departure headways from the start of green in every cycle are expected to be longer than the followings. As described in HCM, the start-up lost time is calculated as the sum of the first four lost time (the ith lost time is defined as the difference between the ith headway and saturation headway).

2.2.3. *Vehicle trajectory*

This paper extracts free-flow speed and average initial acceleration rate from vehicle trajectories. A software package called traffic intelligence (Saunier, 2016) is used to track individual vehicle trajectories from video data. The software has been applied in several other studies with its feature-based tracking technique described in study of Saunier and Sayed (2006). First, individual pixels' trajectories (features) are detected using the robust Kanade-Lucas-Tomasi feature tracker. Second, those features are grouped into objects, each representing a moving vehicle. The grouping of features is based on their relative distance and motion to each other. $D_{\text{connection}}$ and $D_{\text{segmentation}}$ are two parameters defining the maximum relative distance and motion threshold for features to be grouped as one object. Values of these two parameters can be adjusted by users to adapt various video filming heights, angels, and resolutions. The final output form is the temporal series of individual vehicle positions in world coordinates.

2.2.4. *Free flow speed*

Free flow speed is drivers' desired speed in low traffic volume conditions and without traffic control measures. In this paper, vehicles traveling at desired speed (not hindered by other factors) were identified and marked from the video recordings. Their trajectories were analyzed to derive free flow speed information. Specifically, the average speed of each one of these vehicles was calculated by dividing the traversed trajectory length by its travel time. This average speed was regarded as the driver's desired speed.

2.3. *Study results*

Initially, the measurements of saturation headway are categorized by five pre-defined road surface conditions. However, an analysis of variance (ANOVA) test and a subsequent Tukey's range test suggest that a revised categorization of road surface conditions would signify and simplify the results. Specifically, a road surface condition category "normal" is created to combine "dry" and "wet", and a category "slushy" is created to combine "wet & slushy" and "slushy in wheel paths". For simplicity reasons, the category "snowy and sticking" is renamed as "snowy". Hence, "normal" refers to surface conditions with no slush or snow accumulating on the ground; "slushy" refers to road surface partly or fully covered by slush; "snowy" refers to road surface fully covered by sticking or packed snow. The results under revised road surface condition categories are shown in Table 1. The corresponding saturation flow rates are 1825 veh/h/lane, 1509 veh/h/lane, and 1363 veh/h/lane on normal, slushy, and snowy road surface conditions, respectively, which are consistent with those from Asamer and Van Zuylen (2011).

Results of start-up lost time are shown in Table 2. Results show no clear pattern of how start-up lost time reacts to different road surface conditions. Also, start-up lost time does not vary largely under different road surface conditions. It is worth mentioning that negative values show up for start-up lost time of some cycles. It means that in those cycles, the average headway of first four vehicles is smaller than the saturation headway. It is not common to see, but it is possible to happen when in a particular cycle, first several vehicles move quite fast or follow each other quite close.

Due to the relatively small sample size and consistency with the results of saturation flow rate, we analyzed the relationship between free flow speed and road surface conditions at three levels: normal, slushy, and snowy. Mean of the sample desired speed in each category is regarded as the free flow speed under each weather condition. The sample sizes are 80, 77, and 30, respectively, and the means are 49.0, 40.7, and 37.6 km/h.

We compared the results of this study to research findings from literature. Table 3 lists the percent reduction in saturation flow rate under various road surface conditions from five previous studies and this research. The comparison shows that the results of weather impact on saturation flow rate from our research highly agree to the results from existing literature. The only relatively large discrepancy occurs when the road surface is in snowy and sticking condition. The higher reduction in saturation flow rate may be attributed to drivers' being more cautious in severe winter events in Canada than in the U.S.

As for the weather impacts on start-up lost time, the results of this research (the influence is not clear) conforms to some of the previous studies (Bernardin Lochumueller and Associates, Inc., 1995; Sadek and Amison-Agolosu, 2004). Meanwhile, some other studies claim that start-up lost time increases in inclement weather conditions (Perrin et al., 2001). Such inconsistency may be resulted from different techniques applied to estimate start-up lost time. In terms of free flow speed, the findings from this research agree to the results found in Perrin et al. (2001).

Table 1 – Statistics of saturation headway under revised road surface condition categories.

	Normal	Slushy	Snowy
Sample size	83	80	33
Average (s)	1.973	2.385	2.641
Standard deviation (s)	0.161	0.187	0.246
Maximum (s)	2.313	2.880	3.187
Minimum (s)	1.571	1.971	2.283

Table 2 – Statistics of start-up lost time under various road surface conditions.

	Dry	Wet	Wet & slushy	Slushy in wheel paths	Snowy & sticking
Sample size	26	57	36	44	33
Average (s)	3.320	3.129	2.864	2.648	2.777
Standard deviation (s)	1.878	1.376	1.438	1.646	2.068
Maximum (s)	7.249	6.927	5.860	7.984	8.216
Minimum (s)	−0.173	0.393	−0.160	0.099	−1.151

It should be noted that the study results found in Waterloo, Ontario, Canada, probably cannot be extended to areas where snowfall is infrequent during winter seasons. Canada is well known for its severe winter weather. In Waterloo, more than one-third of the winter months are snowy days (Government of Canada, 2017). Thus, most drivers are familiar with driving in snow events and winter tires are very popular. A survey shows that 65% of drivers use winter tires for their car during the winter (Tire and Rubber Association of Canada, 2016). These phenomena usually cannot be expected to occur in areas with less snowy days. Therefore, the effects of winter weather on traffic may vary dramatically in these areas from the effects found in this study.

3. Design of signal control for adverse weather conditions

This section explores how signal control systems can utilize road weather information to adjust their timing plans under adverse weather conditions for the purposes of increasing road efficiency and safety (Kittelson & Associates, Inc., 2008). We investigated this research problem through two case studies. In the case studies, we assumed that the results from the previous section could be applied to the case studies. We developed two specific weather signal alternatives tailored for slushy surface condition and snowy surface condition, respectively. Subsequently, these two plans are compared with the normal-weather signal plan regarding the performance under adverse weather conditions. The evaluation is conducted using both empirical methods and simulation models.

3.1. *Case study description*

The considerations and procedures of developing weather responsive plans are illustrated by two case studies: one on a single uncoordinated intersection and the other on a coordinated corridor, both of which are located in the City of Waterloo, Ontario, Canada. The first case is a typical four-leg intersection - intersection of Columbia St and Philip St. The second case is a 1.35 km corridor along the Columbia Street consisting four signalized intersections. Figs. 2 and 3 show the aerial maps of the two case study sites. In each case, we considered two adverse weather conditions (slushy vs. snowy road surface condition). Under each weather condition, we created three levels of traffic demand (high, medium, and low) for the uncoordinated intersection case, and two (high and medium) for the coordinated corridor case. The corresponding overall volume to capacity (V/C) ratios (in normal weather) for high, medium, low are around 0.95, 0.60, and 0.30, respectively. The reason why we did not consider low traffic demand for the coordinated corridor case is that it is usually suggested to coordinate intersections when the volumes between them are relatively large (Urbanik et al., 2015). Therefore, there are in total six scenarios (two weather conditions times three demand levels) for the uncoordinated intersection case and four scenarios (two weather conditions times two demand levels) for the coordinated corridor case.

3.2. *Development of signal timing plan alternatives*

Depending on the extent of utilizing external detector information about user demand, traffic signal control is categorized into three modes: pre-timed, actuated, and adaptive. The latter two modes are both adaptive to local traffic demand variations by using real-time demand information from road detectors. In contrast, pre-timed controllers use no real-time detection information to adapt operations. They use fixed signal timing plans that contain timing parameter values calculated and programmed into the controller based on historical data. Adverse weather can cause incorrect feedback from the detectors. For example, snow accumulation on road surface may obscure pavement markings. This issue can cause vehicles to stop at unsupposed locations or to move on the wrong lanes at the intersection. The loop detectors are usually designed and installed to count vehicles when they stop and move in a normal manner. Thus, the unexpected

Table 3 – Comparisons between research results on saturation flow rate reduction under adverse weather conditions.

Road surface condition	Reduction in saturation flow rate (%)					
	Fairbanks, Alaska	Anchorage, Alaska	Minneapolis, Minnesota	Salt lake city, Utah	Burlington, Vermont	Waterloo, Ontario
Dry	0	0	0	0	0	0
Wet	NA	NA	NA	6	2–3	3
Wet and snowing	14*	12*	11*	11	4–7	NA
Wet and slushy	14*	12*	11*	18	7–15	19
Slushy in wheel path	14*	12*	11*	18	21	20
Snowy and sticking	14*	12*	11*	20	16	27

Note: *average value from categories ranging from wet and snowing to snowy and sticking.

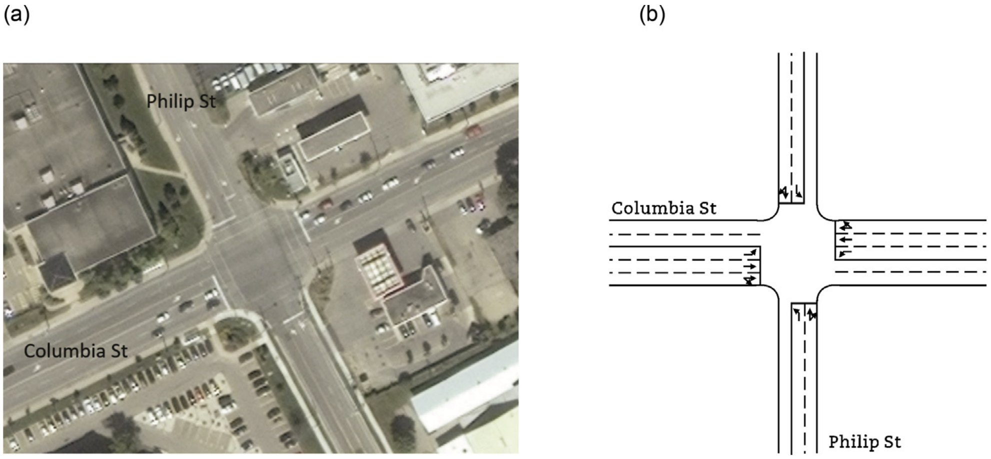


Fig. 2 – Uncoordinated intersection: Columbia St and Philip St, Waterloo. (a) Aerial map. (b) Lane configuration diagram.

trajectories of vehicles can cause detection errors. Therefore, this research only considers the application of pre-timed signal control under adverse weather conditions.

Time-of-day (TOD) signal control is one of the most widely used control modes in non-adaptive traffic signal systems. In essence, TOD control segments a day into multiple time intervals based on the variations of traffic volume within a day and uses different timing plan for each time interval. In the case studies, it is assumed that the signal control systems at intersections are operated in TOD mode. Different demand levels imitate the time intervals in a day with different traffic-volume patterns. Thus, a normal signal plan was designed for each demand level in case studies. The normal plan is supposed to be most suitable pre-timed signal timing plan operated in normal weather conditions. Moreover, for each scenario (combination of demand level and road surface condition), we developed two weather-specific signal plan alternatives: efficient plan and safe plan. First, it is designed as the most efficient plan in specific adverse weather conditions (keeping inter-green time unchanged), and second, it has longer inter-green time to ensure safety.

For pre-timed control, signal timing variables include yellow change, red clearance, cycle length, green split, and offsets (only applicable for the coordinated arterial case). How these variables are designed for all signal timing plan alternatives (normal, efficient, and safe) in this research is discussed as follows.

3.2.1. *Yellow interval*

One common consideration for determining yellow change length is that the interval should provide sufficient time for drivers to stop the vehicle before the stop line when they feel safe to do so at the start of the yellow indication (Urbanik et al., 2015).

Based on the idea, the Institute of Transportation Engineers (ITE) offers Eq. (2) for computing the minimum yellow interval.

$$Y = t + \frac{0.91v}{2(3.28a + 32.2g)} \tag{2}$$

where Y is yellow interval (s), t is perception-reaction time to the onset of a yellow indication (s), v is approach speed (km/h), a is deceleration rate in responsive to the onset of a yellow indication (m/s^2), g is grade, with uphill positive and downhill negative (percent grade/100).

A perception-reaction time of 1.0 s and a deceleration rate of 3.05 m/s^2 are widely used by practitioners in calculating the minimum yellow change interval. Based on Eq. (2) and the recommended values, for the normal weather signal plan, yellow intervals are set to 3.5 s.

Fig. 3 – Aerial map of the coordinated corridor: Columbia street corridor, Waterloo.

Table 4 – Summary of the component of signal control.

Case study	Plan	Yellow change	Red clearance interval	Cycle length	Green split	Offset
Uncoordinated intersection	Efficient	N	N	Y	Y	NA
	Safe	Y	Y	Y	Y	NA
Coordinated corridor	Efficient	N	N	Y	Y	Y
	Safe	Y	Y	Y	Y	Y

Note: Y is yes; N is no; NA is not applicable.

As discussed earlier, both approaching speed and deceleration rate decrease in adverse weather conditions. We have measured free flow speed in different weather conditions in the previous section (normal: 49 km/h, slushy: 40.7 km/h, and snowy: 37.6 km/h); however, deceleration rate data in these weather conditions are unavailable to this research (the automated video processing can hardly provide reliable trajectory tracking when the speed is decreasing to values close to zero). As a result, we used values from a previous study (Garber and Hotel, 1998), which indicates that drivers' comfortable deceleration rate drops from 2.65 m/s^2 on dry surface to 1.95 m/s^2 on slippery road surface in snow events.

Using the values of approach speed and deceleration rate in adverse weather conditions, Eq. (2) suggests a 0.5 s increase in yellow change. This increase is adopted for safe signal plans in adverse weather conditions.

3.2.2. *Red clearance interval*

As suggested by Urbanik et al. (2015), we choose 0.5 s as the red clearance interval for the normal plan and 1 s for the slushy- and snowy-safe plans according to the approach speed (free flow speed measured at different weather conditions) and intersection size of our study site.

3.2.3. *Cycle length and green split*

This study utilizes Synchro to conduct the optimization of cycle length and green split. Synchro is a commonly used software to design signal control plans. The general strategy of signal control design is to equalize the volume-to-capacity ratios for critical lane groups. Specifically, the effective green time is allocated to each lane group in proportion to its flow ratio (traffic volume divided by saturation flow rate) and cycle length is designed to either clear the critical percentile traffic or minimize the delay (Trafficware, Ltd., 2011). Saturation flow rate is a crucial input to both cycle optimization and green split. As saturation flow rates are found to be very different in severe winter events (normal: 1825 veh/h/lane; slushy: 1509 veh/h/lane; snowy: 1363 veh/h/lane), the optimal signal plans for normal weather and for adverse weather are very different. We used these values of saturation flow rate as inputs to Synchro and designed the signal plans in terms of cycle length and green splits using Synchro for normal weather condition and adverse weather conditions.

3.2.4. *Offsets*

As mentioned earlier, drivers are found to be driving more slowly in adverse weather conditions (for example, in our particular field study, the average free-flow speeds are as follows, normal: 49.0 km/h, slushy: 40.7 km/h, snowy: 37.6 km/h). The reduced speed causes the coordination plan designed for normal weather to be suboptimal in adverse weather conditions. Thus, for the coordinated intersection case, we adjusted the offsets for weather-specific signal plans as well as adjusting cycle length, green splits, and inter-green time (only for safe plans) using Synchro.

3.2.5. *Traffic signal timing plan alternatives*

Combining considerations on yellow change, red clearance interval, cycle length, and green splits, we designed signal plans for adverse as well as normal weather conditions with the aid of Synchro. Table 4 shows a summary that components of signal control are adjusted for each signal timing alternative.

3.3. *Evaluation of signal plan alternatives*

All signal plan alternatives were evaluated in both Synchro and VISSIM in terms of control delay. Traffic parameter measurements from the previous section were utilized in both Synchro and VISSIM to model weather effects on traffic.

Synchro provides deterministic intersection performance evaluation based on a collection of theoretical and empirical equations from Highway Capacity Manual (TRB, 2010). To reflect the weather effects, measurements of saturation flow rate, start-up lost time, and desired speed from the previous section were set as inputs to Synchro models of different weather conditions.

VISSIM evaluates the signal performance in inclement weather from a microscopic perspective considering random variation. To achieve credible evaluation results from VISSIM, proper calibration of simulation models is vital, especially for models simulating traffic under different weather conditions. This paper adopts a method described in Lu et al. (2016) to conduct the simulation calibration of each weather simulation model (normal, slushy, snowy). For each weather condition, saturation flow rate measured from the collected video data was set as the measure of effectiveness (MOE) for calibration. To select calibration parameters in VISSIM, we conducted sensitivity analysis on six parameters: desired speed μ_s, desired speed distribution range r_s, desired initial acceleration rate a_0, desired initial deceleration rate d_0, and two safe following distance parameters bx_{new}, and bx_{mult}. The relationships between these parameters and the MOE, saturation flow rate, were examined as shown in Fig. 4. It can be observed that μ_s, a_0, and bx_{new} have a strong effect on the MOE, whereas the influences of r_s, d_0 and $bx_{mult.}$ are negligible. Therefore, the former three parameters were selected as the calibration parameters. Then, values of the

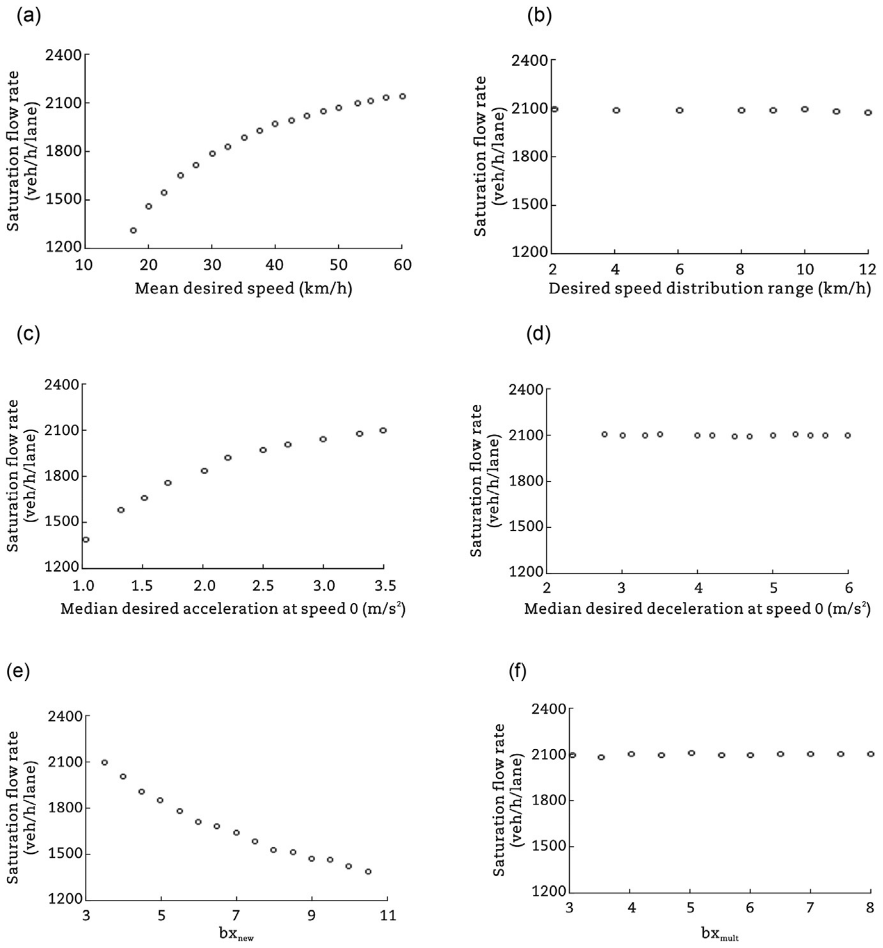


Fig. 4 – Sensitivity analysis results between MOE and the parameters. (a) Mean desired speed. (b) Desired speed distribution range. (c) Median desired acceleration at speed 0. (d) Median desired deceleration at speed 0. (e) bx_{new}. (f) bx_{mult}.

desired speed and desired initial acceleration rate in each weather condition were derived from the vehicle trajectories (extracted from the field video data). The optimal values for the safe following distance were subsequently obtained using the golden section search algorithm to minimize the error between the simulated MOE (average saturation headway) and the field-observed MOE in each weather condition model. After the model calibration, each weather model was validated based on two criteria. First, an observation on the animation of the calibrated model was performed to check whether there was obvious discrepancy between the simulation and field videos. Second, field measurements and simulation results of saturation flow rate were compared to evaluate the simulation credibility. This metric of field-measured saturation flow rate was collected from the video dataset other than the one used for calibration. It should be noted that the calibration and validation process in this research was conducted on the data-collection intersection, and valid simulation models of this intersection with normal, slushy, and snowy road surfaces were built. It is assumed that the calibration results (values of calibration parameters in different weather conditions) can be applied to the two case studies.

3.3.1. *Case study of the uncoordinated intersection*

(1) Synchro evaluation result

Table 5 shows the evaluation results at both intersection and approach levels. We found that implementing efficient plans can help reduce intersection delay when the traffic demand is at medium or high level (up to 19.3%), but when the traffic demand level is low, implementing efficient plans does not have tangible benefits in terms of traffic efficiency. With extended inter-green time, safe plans usually have higher intersection delay compared to efficient plans (5%–20%). Moreover, the percentage of change in delay after implementing weather-specific plans varies over approaches.

(2) VISSIM evaluation result

Average delays at both intersection level and movement level were used to evaluate the signal plan performance. For each signal alternative to be evaluated, results were average values from 10 simulation runs and each simulation was set to run for 6300 simulation seconds. The first 300 s of the

Table 5 – Evaluation results of signal plan alternatives designed for the uncoordinated intersection.

Weather	Demand	Signal plan	Average intersection delay (s)	Average eastbound (EB) approach delay (s)	Average westbound (WB) approach delay (s)	Average northbound (NB) approach delay (s)	Average southbound (SB) approach delay (s)
Slushy	High	Normal	115.6	109.1	134.5	91.5	117.7
		Efficient	114.1	107.2	123.4	128.1	99.1
		Safe	124.1	116.7	134.8	131.5	113.7
	Medium	Normal	41.2	55.1	33.5	29.8	39.8
		Efficient	37.3	44.3	34.4	36.0	32.4
		Safe	45.8	56.2	45.7	38.8	36.3
	Low	Normal	16.8	19.0	16.3	14.4	16.1
		Efficient	16.9	19.2	17.5	14.5	14.1
		Safe	17.8	19.3	17.8	15.6	17.1
Snowy	High	Normal	163.3	158.6	186.9	128.1	164.0
		Efficient	151.3	143.4	185.6	143.3	117.4
		Safe	164.2	162.0	186.8	156.2	138.8
	Medium	Normal	61.0	85.9	46.8	38.3	60.8
		Efficient	49.2	60.6	43.0	41.1	47.2
		Safe	57.9	69.9	46.3	53.6	60.0
	Low	Normal	17.9	20.3	17.3	15.3	17.2
		Efficient	18.0	20.5	18.8	15.4	15.0
		Safe	19.1	20.7	19.1	16.6	18.5

simulation were used as a warm-up period and thus were excluded from generating subsequent evaluation results. Evaluation results are presented in Table 6. It should be noted that a warning occurred when the high traffic demand was served by the normal and safe plans in VISSIM because of the oversaturated situation. However, all demands were served using the optimal plan. This proves that the optimal plan is superior to normal and safe plans in term of efficiency. The delays for high demand scenarios are not evaluated as in oversaturated situations a significant portion of the vehicles are not able to complete their trips within the simulation period, making it challenging to compute comparable performance metrics. The general patterns in terms of the benefits achieved by implementing weather-specific plans found in the VISSIM results agree to those found in the Synchro results. However, the efficiency benefits are much less tangible found from the VISSIM evaluation than the benefits found from the Synchro evaluation. For example, the VISSIM results show that implementing the optimal plan at medium traffic demand on snowy road surface can only decrease the intersection delay by 6.3%, while in the Synchro evaluation, this statistic is 19.3%.

(3) Evaluation result summary

The Synchro and VISSIM evaluation results show similar patterns in terms of the direction of effect of weather-specific signal control. It can be observed from the evaluation results above that the largest benefit is achieved when the optimal plan is used in snowy conditions and traffic demand is at an intermediate level. In general, the benefits of implementing weather-specific plans are larger in snowy conditions than in slushy conditions. In terms of traffic demand, it is most beneficial to implement weather-responsive strategies at medium demand. In low or high demand conditions, the efficiency improvements are relatively low. Poor weather conditions also require changing the duration of yellow change and red clearance intervals for safe traffic operations, which would then lead to reduced efficiency or longer delays. In conclusion, weather responsive signal control is highly beneficial for both safety and efficiency and the suitable plan should be selected on the basis of weather severity and traffic.

3.3.2. *Case study of the coordinated corridor*

(1) Synchro evaluation result

The main purpose of the coordination plan is to ensure corridor progression. Thus, delay experienced by travelers traveling along the coordinated direction (i.e., east and west) is an important indicator to evaluate the coordination plan. Also, overall traffic performance needs to be examined to prevent significant exacerbation on minor street movements brought by coordination. In this study, average delay (in seconds) experienced by eastbound or westbound travelers at each intersection was selected as the corridor progression indicator. Total network delay in one hour, which is the expected sum of delays experienced by all vehicles traveling within the network (the coordinated corridor) in one hour, was used to quantify the overall traffic performance. Moreover, average delays experienced by travelers at all intersections were also provided as evaluation criteria. It should be noted that these values were calculated by built-in deterministic models in Synchro. The evaluation results listed in Table 7 show that the efficiency benefits of implementing weather-specific plans on a coordinated corridor are significant, especially for coordinated directions. The magnitude of benefits is much larger

Table 6 – VISSIM results of average delay in seconds at intersection level and movement level.

Weather	Demand	Signal plan	Intersection	EB			WB			NB			SB		
				Left	Through	Right	Left	Through	Right	Left	Through	Right	Left	Through	Right
Slushy	Medium	Normal	22.6	16.4	30.3	21.9	23.0	21.9	16.0	18.8	20.9	10.8	17.5	25.9	19.5
		Optimal	21.9	19.4	27.2	25.2	22.1	33.8	18.5	6.0	22.8	15.4	15.6	24.5	19.2
		Safe	29.1	27.2	36.8	28.5	32.9	31.8	26.9	22.3	31.6	14.8	19.2	27.1	18.6
	Low	Normal	14.7	12.6	18.4	11.0	13.5	17.0	9.3	11.6	17.8	4.9	12.0	17.2	5.5
		Optimal	14.9	13.7	18.5	12.4	14.3	18.1	10.5	11.4	17.8	4.8	11.3	15.6	5.0
		Safe	15.1	13.7	18.5	12.4	14.3	18.1	10.6	11.8	17.0	4.6	12.6	16.4	5.2
Snowy	Medium	Normal	33.3	17.7	58.0	51.2	27.6	24.1	18.4	26.2	23.4	12.3	20.0	35.3	30.9
		Optimal	31.2	29.2	37.8	32.0	30.2	31.5	14.9	41.5	30.6	27.3	21.3	30.7	23.8
		Safe	33.4	26.3	43.6	34.5	27.6	31.9	34.1	34.5	34.9	16.4	23.7	33.3	25.6
	Low	Normal	15.3	12.6	20.6	10.5	14.5	17.3	10.4	11.4	17.2	4.7	11.9	16.8	5.5
		Optimal	15.2	13.0	20.9	10.6	14.3	17.8	10.1	11.3	17.2	4.6	11.2	15.3	5.0
		Safe	15.9	13.0	20.9	10.4	14.3	17.8	10.0	12.0	19.4	4.7	13.0	18.4	7.1

Table 7 – Synchro evaluation results of signal coordination plans.

Demand	Weather	Signal plan	Network total delay in one hour (h)	Intersection 1			Intersection 2			Intersection 3			Intersection 4		
				Average intersection delay (s)	Average EB delay (s)	Average WB delay (s)	Average intersection delay (s)	Average EB delay (s)	Average WB delay (s)	Average intersection delay (s)	Average EB delay (s)	Average WB delay (s)	Average intersection delay (s)	Average EB delay (s)	Average WB delay (s)
Medium	Slushy	Normal	121	44.3	73.5	27.3	25.8	21.0	40.0	32.8	50.3	21.7	46.8	25.7	100.0
		Optimal	107	36.9	58.5	17.9	21.9	14.5	31.0	28.0	33.9	21.4	44.3	10.2	74.5
		Safe	122	42.7	63.4	17.7	27.2	20.7	38.2	27.8	29.1	12.6	52.0	17.4	80.9
	Snowy	Normal	173	64.0	113.2	40.5	34.6	24.5	63.1	51.2	95.3	24.3	65.7	36.5	143.0
		Optimal	138	48.8	71.9	31.7	28.5	17.8	40.1	31.0	35.8	13.8	59.6	25.0	103.2
		Safe	156	54.3	78.4	33.4	30.5	21.5	38.3	36.0	41.2	16.6	68.2	38.0	114.4
High	Slushy	Normal	449	109.9	153.4	54.3	65.4	26.9	114.7	107.7	137.5	84.7	122.1	28.4	207.8
		Optimal	424	104.0	148.6	50.5	58.6	23.1	94.1	102.9	125.2	86.1	116.4	25.1	207.5
		Safe	474	116.9	161.8	68.2	65.4	34.0	89.4	115.3	133.1	93.3	130.0	39.5	211.7
	Snowy	Normal	647	159.0	210.0	104.5	103.9	70.3	171.8	156.1	190.9	137.4	168.1	59.2	266.0
		Optimal	578	140.9	188.8	58.0	82.5	39.3	126.7	140.8	159.6	109.0	157.3	40.4	270.0
		Safe	638	152.5	211.5	73.1	91.1	30.8	140.8	158.5	181.4	136.4	173.5	64.3	273.2

Table 8 – VISSIM evaluation results of signal coordination plans at medium demand level.

Weather	Signal plan	Total delay in one hour (h)	Average EB delay (s)	Average WB delay (s)
Slushy	Normal	69.5	99.4	113.8
	Optimal	66.4	84.9	75.8
	Safe	72.8	91.2	92.1
Snowy	Normal	91.3	165.7	141.4
	Optimal	86.2	113.0	131.3
	Safe	90.9	162.9	141.2

compared to implementing weather-responsive plans on an uncoordinated intersection. In snowy conditions, the weather-responsive plan have the potential of decreasing total delay experienced by road users by up to 20% (implementing the optimal plan at medium traffic demand on snowy road surface condition). Most benefit patterns found in the uncoordinated intersection case apply to this coordinated corridor case as well. For example, in this coordinated corridor case, the efficiency benefit is also most compelling when the traffic demand is at medium level.

(2) VISSIM evaluation result

We evaluated the signal plan alternatives in all scenarios based on the total delay in one hour (same definition as explained in Synchro evaluation) and the average delay experienced by vehicles traveling along Columbia St from Columbia St/Philip St to Columbia St/King St (EB) and from Columbia St/King St to Columbia St/Philip St (WB). Results presented in Table 8 are average values from 10 simulation runs, and the simulation period of each run is 6000 simulation seconds (from 300 to 6300). It should be noted that due to the over-saturated situations, VISSIM cannot output reliable delay information for high demand scenarios. Hence, only the aggregated results from the simulation period at medium-demand level are presented in Table 8. Generally, the VISSIM simulation results are consistent with the Synchro results. Same as in the uncoordinated intersection case, the efficiency benefits found by VISSIM (percentage of change in delay ranging from −5.5% to 4.8% after implementing weather-specific plans at medium traffic demand) is still less than those found by Synchro (ranging from −11.6% to 0.8%).

(3) Evaluation result summary

The benefits of implementing weather responsive signal plans are much more compelling at a coordinated-corridor level than at an uncoordinated-intersection level. Similar to the results from uncoordinated intersection studies, the benefits are largest at the medium demand level and lowest at the low demand level. Also, the benefits of implementing weather specific plans are larger in snowy conditions than in slushy conditions.

4. Conclusions and future research

Weather responsive signal control is a cost-effective measure to mitigate weather-related impacts on traffic operations. This research focuses on measuring how traffic affect signal-related traffic parameters and exploring how to modify pre-timed signal control under adverse weather conditions. A field study found that the saturation flow rate was 17% and 25% lower on slushy and snowy road surface than on normal road surface, respectively. Also, the study showed that road surface condition had limited impacts on start-up lost time. Free flow speed is 16.9% lower on slushy surface than on dry surface and it is 23.3% lower on snowy surface than on dry surface. All these results are consistent with the literature findings. Using these results as inputs, we developed weather-specific signal plans with aid of Synchro for one uncoordinated intersection and one coordinated corridor for adverse weather conditions. Inter-green time, cycle length, green split, and offsets were adjusted accordingly. Subsequently, these plans were evaluated using both Synchro and VISSIM. It is recommended that inter-green time be increased by 0.5–1.0 s for improved safety under adverse weather conditions. This improved safety margin would however result in reduced overall efficiency. It was found that the additional inter-green time would increase the total intersection delay by 5%–20% as compared to the weather-specific plans that keep the same inter-green time as normal signal plans. However, safety is always paramount in signal timing design. The evaluation results also show that implementing weather-specific signal plans is most beneficial in terms of traffic efficiency for intersection with a medium level of traffic demand with an overall degree of saturation in the range of 0.4–0.7. Also, the benefits are more obvious in snowy conditions than in slushy conditions. Lastly, the benefits are much more compelling at a coordinated-corridor level than at an uncoordinated-intersection level.

Some limitations of this study and future research topics on the subject are listed as follows. First, the results of weather impact on traffic in this research are all based on video data collected at one intersection in 2015 winter (February–March). Due to the limited sample size, the relationship between traffic performance and meteorological variables needs to be further investigated. Also, there is no data available from other intersections that can be used to validate the findings. In the future, it is suggested more data should be collected with a wider temporal and spatial coverage for more robust conclusions. Second, this research only theoretically discusses the benefits of customizing signal plans for winter conditions. Our future research will focus on explore how to shift signal plans and verify the benefits in field. Third, this research focuses on evaluating the efficiency measures (delay), which should be extended to include safety measures. Fourth, this research briefly discusses the general unreliability of detectors in inclement weather. In the future, efforts can be made to quantify the weather influence on various types of detectors (e.g., inductive loop, video camera) and to investigate methods to mitigate the influence, such as adjusting detector settings or altering detection zones in inclement weather.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

Acknowledgment

This research was supported by Ontario Research Fund – Research Excellence (ORF-RE) through a Round 8 project entitled “Intelligent Systems for Sustainable Urban Mobility (ISSUM)”, National Sciences and Engineering Research Council of Canada, and Hubei Province “Hundred Talents Plan”.

REFERENCES

Agarwal, M., Maze, T.H., Souleyrette, R., 2005. Impacts of weather on urban freeway traffic flow characteristics and facility capacity. In: 2005 Mid-continent Transportation Research Symposium, Ames Iowa.

Asamer, J., Van Zuylen, H.J., 2011. Saturation flow under adverse weather conditions. Transportation Research Record 2258, 103–109.

Balke, K., Gopalakrishna, D., 2013. Utah DOT Weahter Responsive Traffic Signal Timing. Federal Highway Administration, Washington DC.

Bernardin Lochumueller and Associates, Inc., 1995. Anchorage Signal System Update. Bernardin Lochumueller and Associates, Inc., New York.

Brennan Jr., T.M., Day, C.M., Wasson, J.S., et al., 2011. Assessing signal timing plans for winter conditions. Journal of Transportation of the Institute of Transportation Engineers 1 (1), 59–76.

Franzese, O., Greene, D.L., Hwang, H.L., et al., 2002. Temporary Losses of Highway Capacity and Impacts on Performance. Oak Ridge National Laboratory, Oak Ridge.

Fu, T., Zangenehpour, S., St-Aubin, P., et al., 2015. Using microscopic video data measures for driver behavior analysis during adverse winter weather: opportunities and challenges. Journal of Modern Transportation 23 (2), 81–92.

Garber, N.J., Hotel, L.A., 1998. Traffic and Highway Engineering. West Publishing Company, St Paul.

Goodwin, L.C., 2002. Weather Impact on Arterial Traffic Flow. Available at: http://ops.fhwa.dot.gov/weather/best_practices/ArterialImpactPaper.pdf. (Accessed 7 November 2015).

Goodwin, L.C., 2003. Best Practices for Road Weather Management (Version 2.0). Federal Highway Administration, Washington DC.

Goodwin, L.C., Pisano, P.A., 2004. Weather-responsive traffic signal control. ITE Journal 74 (6), 28–33.

Gopalakrishna, D., Cluett, C., Kitchener, F., et al., 2011. Developments in Weather Responsive Traffic Management Strategies. Federal Highway Administration, Washington DC.

Government of Canada, 2017. Canadian Climate Normals: 1981-2010 Climate Normals & Averages. Available at: http://climate.weather.gc.ca/climate_normals/index_e.html. (Accessed 2 June 2017).

Hanbali, R.M., Kuemmel, D.A., 1993. Traffic volume reductions due to winter storm conditions. Transportation Research Record 1387, 159–164.

Ibrahim, A.T., Hall, F.L., 1994. Effect of adverse weather conditions on speed-flow-occupancy relationships. Transportation Research Record 1457, 184–191.

Kittelson & Associates, Inc., 2008. Traffic Signal Timing Manual. Federal Highway Administration, Washington DC.

Kwon, T.J., Fu, L., Jiang, C., 2013. Effect of winter weather and road surface conditions on macroscopic traffic parameters. Transportation Research Record 2329, 54–62.

Li, H., Prevedouros, P.D., 2002. Detailed observations of saturation headways and start-up lost times. Transportation Research Record 1802, 44–53.

Lu, Z., Fu, T., Fu, L., et al., 2016. A video-based approach to calibrating car-following parameters in VISSIM for urban traffic. International Journal of transportation Science and Technology 5 (1), 1–9.

Perrin, H.J., Martin, P.T., Hansen, B.G., 2001. Modifying signal timing during inclement weather. Transportation Research Record 1748, 66–71.

Sadek, A.W., Amison-Agolosu, S.J., 2004. Validating Traffic Simulation Models to Inclement Weather Travel Conditions with Applications to Arterial Coordinated Signal Systems. NETCR47. Project No. 02-7. The New England Transportation Consortium, Storrs.

Saunier, N., 2016. Traffic Intelligence Project. Available at: https://bitbucket.org/Nicolas/trafficintelligence/wiki/Home. (Accessed 21 March 2016).

Saunier, N., Sayed, T., 2006. A feature-based tracking algorithm for vehicles in intersections. In: The 3rd Canadian Conference on Computer and Robot Vision, Quebec City, 2006.

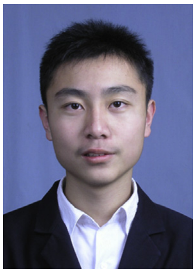
Tire and Rubber Association of Canada, 2016. 2016 TRAC Winter Tire Report. Available at: http://www.tracanada.ca/files/TRAC_winter_tire_report_2016-compressed2.pdf. (Accessed 2 June 2017).

Trafficware, Ltd., 2011. Synchro Studio 8 Traffic Signal Software – User Guide, 2011. Trafficware, Ltd., Sugar Land.

TRB, 2010. Highway Capacity Manual. Transportation Research Board of the National Academies, Washington DC.

Urbanik, T., Tanaka, A., Lozner, B., et al., 2015. Signal Timing Manual. NCHRP Report 812. Transportation Research Board, Washington DC.

Zhang, L., Holm, P., Colyar, J., 2004. Identifying and Assessing Key Weather-Related Parameters and Their Impacts on Traffic Operations Using Simulation. Federal Highway Administration, Washington DC.



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