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RESILIENT INFRASTRUCTURE
June 1–4, 2016

RESILIENT INFRASTRUCTURE LONDON 2016

MODIFYING SIGNAL CONTROL AT INTERSECTIONS UNDER ADVERSE WEATHER CONDITONS

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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 such as adaptive control of signalized intersections and variable speed limits. Currently, most traffic signal control systems are designed for normal weather conditions and are therefore suboptimal in terms of efficiency and safety for controlling traffic during winter snow events due to the changing traffic patterns and driver behavior. The main objective of this research is to explore how to modify traffic signal control under adverse weather conditions. This research consists of two main components. First, we have examined the impacts of winter weather on two key traffic parameters, i.e., saturation flow rate and start-up lost time. Both parameters were measured from 16 hours of traffic video footage at one intersection. Secondly, we have investigated the potential benefits of implementing weather-specific signal control plans for isolated intersections as well as arterial corridors based on two case studies. Three traffic demand scenarios, i.e., high, medium, and low, were considered. We developed weather-specific signal plan alternatives for each scenario based on the traffic parameters measured in winter weather. Evaluation results show that implementing such signal plans is most beneficial for intersection with a medium level of traffic demand. It is also been found that the benefit of implementing weather-responsive plans was more compelling an arterial-corridor level with signal coordination than at an isolated-intersection level.

Keywords: weather-responsive traffic management, traffic signal operations

1. INTRODUCTION

Adverse weather, including rain, snow, sleet, fog, etc., 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 per year, 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 (snowing or snowy/slushy pavement). 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.

Generally, traffic signal timing plans are designed in response to traffic in normal weather. However, existing studies have indicated that weather conditions significantly impact urban mobility. 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. Average speed was found to be 30% percent lower on slushy pavement than on dry pavement. Start-up lost time can be increased by 5 to 10 percent depending on the weather condition

(Perrin et al. 2001). Thus, the normal-weather signal control plan may be inappropriate 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, the advances in technologies have enabled real-time communication between traffic control center and signal controllers. Implementing weather-responsive signal plans is more practical than ever.

Despite the promising prospect, relatively few studies have been carried to investigate weather-responsive signal control. For countries that are subject to long severe winter seasons, there is a significant need for cost-effective traffic control countermeasures to inclement weather. Canadian Capacity Guide for Signalized Intersections (CCG), a prevalent guidebook among Canadian traffic engineers, provides very limited guidance on signal operations in winter weather (Teply et al. 2008). It simply points out that typical winter saturation flows are about 5% to 20% lower than summer saturation flows; while, it provides no explicit advice on how traffic engineers should tackle this issue. The purposes of this paper are twofold: first, to quantify weather impacts on signal-design-related traffic parameters at signalized intersections; and second, to systematically investigate how to adjust signal timing parameters to adapt to the adverse-weather traffic. Following the introduction, the 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 condition through two case studies. The last section concludes the findings from this research and proposes the future research.

2. WEATHER IMPACTS ON TRAFFIC PARAMETERS

2.1 Field data collection

We selected the intersection of University Avenue and Seagram Drive in the city of Waterloo as 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. We collected 16 hours of video footage from eight days covering various weather conditions. During the videotaping, we also continuously monitored and recorded road surface conditions. Five categories of road surface condition were defined, i.e., dry, wet, wet and slushy, slushy in the wheel paths, and snowy and sticking.

2.2 Traffic parameter measurement

We extracted two traffic parameters, i.e., saturation flow rate and start-up lost time from the video data. Both parameters have significant impacts on signal timing design at intersections. The methodology of measuring these two parameters are described as follows.

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 situation flow rate described in Highway Capacity Manual (HCM) (Transportation Research Board 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 queue. Then, the saturation flow rate can be converted from the saturation headway using Equation 1:

[1] $s=3600/h$

Where,

s denotes the saturation flow rate in vehicle/hour, and

h denotes 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 i^{th} lost time is defined as the difference between the i^{th} headway and saturation headway).

2.3 Study results

The measurements of saturation headway are categorized by five pre-defined road surface conditions, as shown in Table 1. The general trend shows that the mean and standard deviation of the saturation headway increases as the road surface condition worsens. However, there are noticeable overlapping between some of the road surface condition categories, such as, the means between dry and wet. 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 & sticking" is renamed as "snowy". The results under revised road surface condition categories are shown in Table 2. The corresponding saturation flow rates are 1825, 1509, and 1363 on normal, slushy, and snowy road surface conditions, respectively.

Table 1: Statistics of saturation headway under various road surface conditions

	Dry	Wet	Wet&Slushy	Slushy in Wheel Paths	Snowy&Sticking
Sample Size	26	57	36	44	33
Mean (s)	1.926	1.995	2.365	2.408	2.641
Standard Deviation (s)	0.175	0.151	0.190	0.185	0.245
Maximum (s)	2.244	2.313	2.880	2.717	3.187
Minimum (s)	1.571	1.608	2.042	1.971	2.283

Table 2: 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)	1.161	0.187	0.246
Maximum (s)	2.313	2.880	3.187
Minimum (s)	1.571	1.971	2.283

Results of start-up lost time are shown in Table 3. 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 each road surface condition. As shown in Figure 1, a further analysis on individual headways within the cycle helps to explain this finding. It suggests that although it takes longer time for first several vehicles to leave the intersection in inclement weather than in normal weather, the additional time to saturation headway that each of these first vehicles takes is not longer because of the increased saturation headway in inclement weather.

Table 3: 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

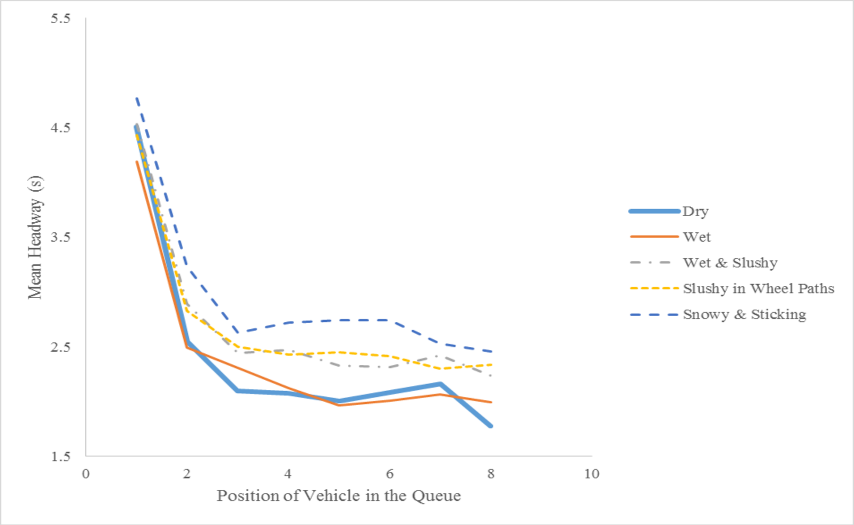

Figure 1: First eight mean vehicle headways under various road surface conditions

2.4 Comparison to the results from literature

We compared the results of this study to research findings from literature. Table 4 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.

Table 4: Comparisons between research results on saturation flow rate reduction under adverse weather conditions

Road Surface Condition	Reduction in Saturation Flow Rate (%)					
	Fairbanks, Alaska (Bernardin Lochumueller and Associates Inc. 1995)	Anchorage, Alaska (Bernardin Lochumueller and Associates Inc. 1995)	Minneapolis, Minnesota (Maki 1999)	Salt Lake City, Utah (Perrin et al. 2001)	Burlington, Vermont (Sadek and Amison-Agolosu 2004)	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				18	7-15	19
Slushy in Wheel Path				18	21	20
Snowy and Sticking				20	16	27

*Average value from categories ranging from wet and snowing to snowy and sticking.

As for the weather impacts on start-up lost time, the results of this research (the influence is not significant) 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 significantly in inclement weather conditions (Perrin et al. 2001). Such inconsistency may be resulted from different techniques applied to estimate start-up lost time.

3. MODIFYING SIGNAL CONTROL PLANS UNDER ADVERSE WEATHER CONDITIONS

This section explores how signal control systems can utilize road weather information to adapt their timing plans during adverse weather conditions. Regarding how the signal controllers respond to variation in traffic demand, signal controllers can be grouped into three types: pre-timed, actuated, and adaptive. However, adverse weather can impair the effectiveness of traffic detection system, causing incorrect feedbacks from the detectors (e.g., snow accumulation can obscure pavement markings and consequently cause detection errors). Thus, in the research, only pre-timed control is considered to operate in inclement weather.

3.1 Case study description

The considerations and procedures of developing weather responsive plans are illustrated by two case studies: one on an isolated intersection and the other on an arterial corridor. The selected isolated four-leg intersection is the intersection of Columbia Street and Philip Street, and the selected arterial corridor is a 1.35 km corridor along Columbia Street consisting four signalized intersections. All the sites are located in the city of Waterloo, Ontario. The arterial map of these locations are shown in Figure 2. In each case, we considered two adverse weather conditions (slushy, and snowy road surface condition). Under each weather condition, we developed three levels of traffic demand (high, medium, and low) for the isolated intersection case, and two (high and medium) for the arterial corridor case (as coordination plans are usually not used when the traffic demand is low). The corresponding overall norma;-weather volume to capacity (V/C) ratios for high, medium, low are around 0.95, 0.60, and 0.30, respectively. Therefore, there are in total six scenarios (two weather conditions times three demand levels) for the isolated intersection case and four scenarios (two weather conditions times two demand levels) for the coordinated corridor case.

Figure 2: Arterial map of case study locations

3.2 Development of signal timing plan alternatives

For each scenario (combination of demand level and road surface condition), we developed two weather-specific signal plan alternatives: optimal plan and safe plan. The first is designed as the most efficient plan in specific adverse weather conditions (keeping inter-green time unchanged), and the second 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 for the coordinated arterial case). How these variables can be modified under adverse weather conditions is discussed as follows.

3.2.1 Inter-green Time

Inter-green time consists of yellow change and red clearance interval. Both of these two intervals are displayed during phase changes. The proper lengths of yellow change and red clearance interval are highly dependent on approach speed. From the trajectory analysis on the recorded video footage, we found that free flow speed was 49.0 km/h on dry surface from 80 sample trajectories; on slushy surface, the speed was reduced to 40.7 km/h and on snowy surface, the speed further decreased to 37.6 km/h. The sample sizes are 70 and 30 respectively. According to the newly published signal timing manual (Urbanik et al. 2015), we suggest an increase of 0.5 seconds in both yellow change and red clearance interval based on the reduced speed. This suggestion is adopted in designing the safe plans for adverse weather conditions.

3.2.2 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, all effective green time are 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, the optimal signal plans for normal weather and for adverse weather are very different. We designed the signal plans in terms of cycle length and green splits using Synchro for normal weather condition and adverse weather conditions.

3.2.3 Offsets

As mentioned earlier, drivers are found to be driving more slowly in adverse weather conditions. 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.

3.3 Evaluation of signal timing plan alternatives

All signal plan alternatives were evaluated in Synchro in terms of control delay. Normal plan refers to the plan designed for normal weather conditions. Optimal and safety plans are designed based on the weather-specific traffic parameters. The difference is that the optimal plan uses the same inter-green time as the normal plan, while the safe plan adopts an increase in yellow change and red clearance interval time. Evaluation results are shown in Table 5 and Table 6. The comparisons between different plans for each scenario for the two case studies (isolated intersection and arterial corridor) are shown in Table 7 and Table 8 respectively. Results show that the safe plans always have 5%-20% higher delay than the optimal plans. The weather-specific plan achieves the largest benefit in terms of delay reducing in snowy conditions when the traffic demand is at an intermediate level (19.3% reduce in delay using the optimal plan compared to using the normal-weather plan). Moreover, this benefit is more appealing at a coordinated corridor level than at an isolated intersection level.

Table 5: Evaluation results of signal plan alternatives designed for the isolated intersection

Weather	Demand	Signal Plan	Intersection Delay (s)	EB Approach Delay (s)	WB Approach Delay (s)	NB Approach Delay (s)	SB Approach Delay (s)
Slushy	High	Normal	115.6	109.1	134.5	91.5	117.7
		Optimal	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
		Optimal	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
		Optimal	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
		Optimal	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
		Optimal	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
		Optimal	18.0	20.5	18.8	15.4	15.0
		Safe	19.1	20.7	19.1	16.6	18.5

Table 6: Evaluation results of signal plan alternatives designed for the arterial corridor

Demand	Weather	Signal Plan	Total Delay (hr)	Intersection 1 Delay (s)	Intersection 2 Delay (s)	Intersection 3 Delay (s)	Intersection 4 Delay (s)
Medium	Slushy	Normal	121	44.3	25.8	32.8	46.8
		Optimal	107	36.9	21.9	28	44.3
		Safe	122	42.7	27.2	27.8	52
	Snowy	Normal	173	64	34.6	51.2	65.7
		Optimal	138	48.8	28.5	31	59.6
		Safe	156	54.3	30.5	36	68.2
High	Slushy	Normal	449	109.9	65.4	107.7	122.1
		Optimal	424	104	58.6	102.9	116.4
		Safe	474	116.9	65.4	115.3	130
	Snowy	Normal	647	159	103.9	156.1	168.1
		Optimal	578	140.9	82.5	140.8	157.3
		Safe	638	152.5	91.1	158.5	173.5

Table 7: Changes in delay after implementing weather-specific signal plans at the isolated intersection

Weather	Demand	Signal Plan	Intersection Delay	EB Approach Delay	WB Approach Delay	NB Approach Delay	SB Approach Delay
Slushy	High	Optimal	-1.3%	-1.7%	-8.3%	40.0%	-15.8%
		Safe	7.4%	7.0%	0.2%	43.7%	-3.4%
	Medium	Optimal	-9.5%	-19.6%	2.7%	20.8%	-18.6%
		Safe	11.2%	2.0%	36.4%	30.2%	-8.8%
	Low	Optimal	0.6%	1.1%	7.4%	0.7%	-12.4%
		Safe	6.0%	1.6%	9.2%	8.3%	6.2%
Snowy	High	Optimal	-7.3%	-9.6%	-0.7%	11.9%	-28.4%
		Safe	0.6%	2.1%	-0.1%	21.9%	-15.4%
	Medium	Optimal	-19.3%	-29.5%	-8.1%	7.3%	-22.4%
		Safe	-5.1%	-18.6%	-1.1%	39.9%	-1.3%
	Low	Optimal	0.6%	1.0%	8.7%	0.7%	-12.8%
		Safe	6.7%	2.0%	10.4%	8.5%	7.6%

Table 8: Changes in delay after implementing weather-specific signal plans at the arterial corridor

Demand	Weather	Signal Plan	Total Delay	Intersection 1 Delay	Intersection 2 Delay	Intersection 3 Delay	Intersection 4 Delay
Medium	Slushy	Optimal	-11.6%	-16.7%	-15.1%	-14.6%	-5.3%
		Safe	0.8%	-3.6%	5.4%	-15.2%	11.1%
	Snowy	Optimal	-20.2%	-23.8%	-17.6%	-39.5%	-9.3%
		Safe	-9.8%	-15.2%	-11.8%	-29.7%	3.8%
High	Slushy	Optimal	-5.6%	-5.4%	-10.4%	-4.5%	-4.7%
		Safe	5.6%	6.4%	0.0%	7.1%	6.5%
	Snowy	Optimal	-10.7%	-11.4%	-20.6%	-9.8%	-6.4%
		Safe	-1.4%	-4.1%	-12.3%	1.5%	3.2%

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 exploring how to modify 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. All these results are consistent with the literature findings. Using these results as inputs, we developed weather-specific plans using Synchro for one isolated intersection and one arterial corridor for adverse weather conditions. Inter-green time, cycle length, green split, and offsets were adjusted accordingly. It is recommended that inter-green time be increased by 0.5-1.0 second 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% to 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 to 0.7. Also, the benefits are more obvious in snowy conditions than in slushy conditions. Furthermore, the benefits are much more compelling at an arterial-corridor level with signal coordination than at an isolated-intersection level.

This research only discusses how pre-timed signal timing parameters can be adjusted during adverse weather conditions due to the general unreliability of detectors in such conditions. Our future research will focus on explore how the interaction between detection systems and signal control can be modified under adverse weather conditions. Moreover, this research's evaluation part focuses on the efficiency measures (delay). In the future, it is suggested to include quantitative safety measures to evaluate signal plan alternatives.

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