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Modifying Signal Timing During Inclement Weather

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ABSTRACT

Most individuals living in cold weather climates realize that on snowy days their commute will take longer. While traffic volumes are often lower, the combination of reduced speeds and capacity cause severe congestion particularly in signalized urban networks. Signal coordination that reduces traffic congestion in typical clear conditions results in an uncoordinated and sub-optimal timing plan. This paper examines traffic parameters for developing signal timings during inclement weather conditions. With the completion of the Utah Department of Transportation (UDOT) Advanced Transportation Management System (ATMS), there is an opportunity to change signal timing plans by communicating with each controller from the Transportation Operations Center (TOC). With this ability, it has become feasible to have a library of special signal timing plans with one allocated for inclement weather conditions. Traffic flow data is collected over a range of seven inclement weather severity conditions at two intersections for the 1999/2000 winter season. The data indicates that the largest decrease in vehicle performance occurs when snow and slush begins to accumulate on the road surface. Saturation flows decrease by 20%, speeds decrease by 30%, and start-up lost times increase by 23%. UDOT is now developing and implementing modified inclement weather coordinated signal timing plans for the major signalized corridors in the Salt Lake Valley. The determination of when to implement an inclement weather signal timing plan is based on four general criteria: storm severity, projected duration, area of influence and immediately projected running speeds. With these considerations, traffic engineers can determine whether to implement an inclement weather signal timing plan.

INTRODUCTION

Drivers are more cautious during heavy rain and snow. These adverse road conditions cause drivers to travel and accelerate more slowly. Normal signal coordination plans become unsuitable during adverse weather because the traffic flow parameters used to develop the “dry weather” plans change. Ideally, a traffic signal coordination system should adapt to changing traffic flows and travel conditions as they occur. A compromise between the ideal control system and one that does nothing to accommodate signal coordination in adverse weather is to develop an “inclement weather plan”.

In the past, the implementation of such specialized plans was impractical because they required an operator to visit each traffic signal and manually change the signal timing plan at the signal controller. As more agencies develop real-time communication links to their traffic controllers, it makes the possibility of using a specialized signal coordination plan for inclement weather, special events or other atypical occurrences more practical.

An inclement weather signal coordination plan must be created using the traffic flow parameters specific to inclement weather. This paper describes how these traffic flow parameters are quantified for developing and implementing an inclement weather plan by the Utah Department of Transportation (UDOT) in the Salt Lake Valley.

To identify the change in traffic flow parameters, various data elements were collected over a range of weather conditions. Specifically, saturation flow, free flow speeds, and start-up lost times were collected at two intersections during dry weather and various intensity levels of rain and snow throughout the winter of 1999/2000. Comparisons of the data collected with other similar research done in Alaska and Minnesota provide validation for the Utah findings.

PRIOR RESEARCH IN INCLEMENT WEATHER SIGNAL TIMING

The limited research that focuses directly on inclement weather signal timing address how inclement weather affects saturation flows, capacities, pedestrian walking speeds, design of freeway interchanges, and other traffic parameters. Bernardin et al. (1) assess the changes in speeds and saturation flows during extreme winter weather on a 24-signal Anchorage, Alaska network. The study measured several traffic flow parameters in summer, winter, and severe winter conditions. During each of these conditions, saturation flow, vehicle speeds, lost time, and capacity were measured. The study asserts that signal timing parameters are inappropriate in winter and extreme conditions because of slower vehicle speeds. The traffic signal optimization packages SIGNAL 85, and TRANSYT-7F were used to develop optimized signal timing plans. Signal 85 was used to run chosen cycle lengths to generate final phase sequences and splits. TRANSYT-7F was used to generate offsets that yield better arterial progression in the network. The inclement timing plan in Anchorage decreased travel time by 13% and average delay by 23%.

Maki (2) describes a study for the Minnesota Department of Transportation to evaluate the feasibility of implementing a traffic signal timing plan for inclement weather. The following data was collected from 3 P.M. to 8 P.M. on several weekdays: current signal timing, intersection geometry, turning movement counts, travel time, volume and occupancy (system detectors) start-up delay, and saturation flow rates. The Minnesota study also collected weather related data from road weather information system (RWIS) devices, including air temperature, pavement temperature, relative humidity, and roadway condition (i.e. icy, plowed), and dew point. All of this was done on Trunk Highway 36 in Minneapolis, MN. The study defines “inclement weather” as being a storm with accumulation of 3 inches of snow or more. Data was also collected on fair-weather days for comparison purposes. A street network in Minneapolis was simulated in existing “normal” conditions to establish a basis of comparison. The SYNCHRO III traffic signal optimization software was used to create optimized signal timings for inclement conditions. In the simulation, adverse conditions were created by modifying the saturation flow rates, average speeds, and lost times of the traffic. Comparison data was then gathered from the software output under the signal timings in use and the signal timings optimized for inclement weather. The results of the Minnesota study were a 13% reduction in average vehicle delay and a 6% reduction in average stops per vehicle. An interesting ancillary conclusion of the study was that volumes during inclement weather was 15% to 20% lower than volumes collected during the same time period (3-8 PM) on a normal day and 15% to 30% lower during the peak hour (5-6 PM). The speeds were about 40% lower during inclement weather, falling from 71 kph (44 mph) to 42 kph (26 mph). The start-up delay increased from 2 seconds to 3 seconds. The saturation flow rate (measured in vehicles per lane per hour of green, vplphg) was also reduced by 11% from 1,800 vplphg to 1,600 vplphg.

The study also explored the possibility of having the inclement weather plan automatically activated by several RWIS sensors located near the intersections. The study concluded that there is not a strong enough correlation between RWIS data and the actual road conditions to do this reliably.

Parsonson (3) discusses the principles of signal timing for adverse weather recommending that a snowy corridor be "flushed" by setting all corridors signals to green at the same time. This is a similar management scheme for some heavily congested corridors.

FHWA (4) assesses the economic impacts of adverse weather on all types of highways. Some of these related impacts are extra fuel consumption and work delay. As supportive evidence to their findings, they also measured interstate speeds of vehicles in varying degrees of inclement weather. Their findings are provided in Table 1 where seven conditions are defined.

Table 1 Inclement Weather Speed Reductions

	Condition	Percent Reduction
1	Dry	0%
2	Wet	0%
3	Wet and Snowing	13%
4	Wet and Slushy	22%
5	Slushy in Wheel Paths	30%
6	Snowy and Sticking	35%
7	Snowing and Packed	42%

Source: (4)

Botha and Kruse (5) show how inclement weather reduces saturation flow rates. The study assesses the effects of residual ice and snow on saturation flow rates and start-up lost times at signalized intersections in Fairbanks, Alaska. The winter data collection and subsequent analysis are reported and compared with the saturation flow rates suggested in the Highway Capacity Manual (HCM) (6). The winter saturation flows measured were much less than those suggested in the HCM. It was found that when snow and ice were prevalent at signalized intersections, saturation flow rates were 19% lower than the recommended HCM rates.

Gilliam and Withill (7) demonstrate how to measure the increase in congestion of a signal network due to inclement weather. Levels of congestion are more likely to be found when road conditions are slick, and travel times are greater than that under normal weather conditions. Also, when a reduction in saturation flow is found on corridors, it becomes possible to relieve these areas of congestion due to poor weather conditions using a Split Cycle Offset Optimization Technique (SCOOT) system (8). To accomplish this, specially developed “wet” weather parameters (such as decreased saturation flow and longer travel times) can be input into SCOOT. Gilliam and Withill (7) expect that the SCOOT system will perform more appropriately and optimize traffic flow when “wet” parameters are applied. The precise monitoring of traffic conditions has allowed more attention to be focused on the operation of a SCOOT system, and its perceived ability to handle varying traffic conditions over long periods and under different weather conditions.

The results of the literature review support the need for inclement signal timing plans where snow and ice reduce saturation flows and travel speeds. Minnesota and Alaska benefit from their inclement weather timing plan implementations. The following research addresses several elements of other studies in one all-inclusive study. By identifying the traffic flow parameters specific to inclement weather, adjusted signal timings plans can be evaluated. This is preface work for the future evaluation of inclement weather using both fixed time signal plans and adaptive signal control systems.

TRAFFIC FLOW PARAMETERS IN VARYING WEATHER CONDITIONS

Data Collection

Researchers observed saturation flow, vehicle speed, and start-up lost time over a range of weather severity conditions on two intersections in Salt Lake City, Utah. These measurements determine how to change each parameter when developing the special timing plan and under what conditions a special timing plan should be in operation. The measured parameters are defined as follows (6):

- **Saturation Flow Rate**: The maximum rate of traffic flow for a single lane under prevailing conditions if it has 100% effective green time.
- **Lost Time**: The time that an intersection is not being used by any movement. This occurs at the beginning of a movement and during the clearance intervals.
- **Free-flow speed**: The uninhibited speed of a vehicle on a length of roadway.

A range of seven weather severity categories are incorporated from a 1977 FHWA study (4) as defined in Table 1.

Saturation flow and speed data was collected during all available weather events over the winter season of 1999-2000. For comparison purposes, data was also collected on several dry weather days to provide a base comparison. Over 30 hours of saturation flow and free-flow speed information was collected on 14 different inclement weather days. Data was primarily collected during the morning or evening peak hours. There were only a few heavy snowstorms that occurred during peak hours due to the unusually mild conditions during this winter. The two intersections selected for all data collection are: 700 East / 900 South and 1300 East / 500 South from Salt Lake City (SLC), Utah.

Saturation flow

Saturation flow decreases during inclement weather because of larger headways, slower speeds, and decreased acceleration rates. Saturation flow decreases as storm severity increases. The average measured values are shown in Table 2 along with the percent reduction from the dry saturation flow.

Table 2 Saturation Flow

Road Surface Condition	Severity	700 E 900 S		1300 E 500 S		Average % Reduction
		AM	PM	AM	PM	
Dry	1	1881	1736	1752	1902	0%
Rain	2	1680 (89%)	1711 (99%)	-	-	6%
Wet and snowing	3	1751 (93%)	1708 (98%)	1491 (85%)	1691 (89%)	11%
Wet and Slushy	4	-[a]	1476 (85%)	1321 (75%)	1647 (87%)	18%
Wheel Path Slush	5	-	1421 (82%)	-	-	18%
Snowy and Sticking	6	-	-	1395 (80%)	-	20%
Snow Packed	7	-	-	-	-	-

[a] No data available
(#) = Percent of Dry condition
values in vehicles per hour

Table 2 shows that saturation flows are inversely proportional to the degree of severity of inclement weather. There were no storms in the Salt Lake Valley during the 1999/2000 winter season severe enough to be classified as severity category seven. There were however, enough storms to collect saturation flows for all other categories. It is important to note that the largest drop between two adjacent categories (3 and 4) is 9%. The maximum reduction in saturation flow was 20%, which occurred during severity category 6 but that categories 4 and 5 are at an 18% reduction indicating that levels 4, 5 and 6 are very similar in their impacts on saturation flow. The measured SLC inclement value of 1,432 vehicles per hour is the mean saturation flow found between conditions 4-6. It is useful to compare these results to those found in similar studies from Fairbanks, Alaska; Minneapolis, Minnesota; and Anchorage, Alaska as shown in Table 3.

Table 3 Comparison of Saturation Flow Reduction

Weather Condition	SLC	Fairbanks, AK (5)	Anchorage, AK (1)	Minneapolis, MN (2)
Normal/clear	1,808	1,792	1,816	1,800
"Inclement"	1,432	1,538	1,600	1,600
Reduction	21%	14%	12%	11%

values in vehicles per hour

The higher reduction in saturation flow for the Salt Lake City area may be attributed to drivers being less accustomed to snow driving then drivers in Minnesota and Alaska.

Speed

Free-flow speeds decrease during rain or snowstorm events. Table 4 shows the average values of free-flow speeds collected on 18 different days during the winter of 1999-2000. Speeds were collected during the peak (AM or PM) hours at each intersection. There is no data, however, for speeds beyond condition 5 for either intersection.

Table 4 Average Speeds and Percent Reduction from Dry Condition

Road Surface Condition	Severity	700 E 900 S		1300 E 500 S		Average % Reduction
		AM	PM	AM	PM	
Dry	1	39.0	31.4	28.4	27.4	0%
Rain	2	34.3 (88%)		-	25.2 (92%)	10%
Wet and Snowing	3	31.4 (81%)	29.4 (93%)	-	23.5 (86%)	13%
Wet and Slushy	4	-*	22.0 (70%)	-	21.8 (79%)	25%
Slushy Wheel Paths	5	25.5 (65%)	23.4 (75%)	-	-	30%
Snowy and Sticking	6	-	-	-	-	-
Snow Packed Surface	7	-	-	-	-	-

No data available
(#) = Percent of Dry condition
values in miles per hour

The mean speed is inversely related to the severity of inclement weather. The largest drop in speeds is between conditions 3 and 4 (12%). This is consistent with the largest drop in saturation flows, which also saw the largest decrease between conditions 3 and 4. By condition 5, there was an average decrease in speeds of approximately 30%. This decrease is consistent with two other studies. Maki (2) found a decrease in speeds of about 40% during inclement weather. FHWA (4) found that interstate speeds are reduced by 36% during inclement weather. Table 5 shows the collected data of this study compared to the FHWA (4) findings.

Table 5 Speed Data Comparison to FHWA

Condition	Severity	% Reduction SLC	% Reduction FHWA
Dry	1	0%	0%
Wet	2	10%	0%
Wet and Snowing	3	13%	13%
Wet and Slushy	4	25%	22%
Slushy in Wheel Paths	5	30%	30%
Snowy and Sticking	6	-	35%
Snowing and Packed	7	-	42%

Source: (4)

The similarity in the results of the FHWA (4) study indicates that the data collected in Salt Lake City is consistent with previous findings and increases the confidence in the data.

Start-up Lost Time

The start-up speeds of each queue (procession of vehicles) will be much slower during inclement weather because vehicles will have less tire traction, thus stalling their initial movements. The Anchorage, 1995 (1) study found that inclement start-up times were equivalent to the summer conditions. The study reported that the additional time is accounted for in the saturation flow reductions and therefore no change to lost time was included in the revised signal timing. In Fairbanks, there was a small reduction but not appreciable from the 2 seconds recommended by the HCM (6). Maki (2) found a 50% increase in start-up lost time from 2 to 3 seconds.

In Salt Lake City, the start-up lost time increased by an average of 23% from 2.0 to 2.46 seconds. This corresponds to the increased headway for inclement saturation flow rates. This is based on observations of 112 dry weather samples and 134 snowy (severity condition 4-6) samples. The rain (condition 2) seemed to have little impact on start-up lost time as the 35 samples indicated that the average lost time changed from 2.0 seconds (dry) to 2.1 seconds (wet in conditions 2 and 3).

In addition to the start-up lost time, consideration must be given to the dilemma zone and amber time, all-red time and pedestrian crossing time. Pedestrian crossing times are often limiting factors in the amount of green time necessary for phase splits. Sufficient phasing must be provided to allow a pedestrian to safely cross the intersection. This pedestrian crossing time may be longer than the optimal green time needed by the vehicles thereby causing the pedestrian crossing time to become the limiting factor. Amber and all-red time are necessary in clearing an intersection between phases. If insufficient amber time is provide for a vehicle to either stop prior to the intersection or pass through the intersection, then a dilemma zone is created. The all-red time is used to clear the intersection of any vehicles prior to the start of the next phase and is most important for permitted left turning vehicles that may be caught in the intersection during the amber phase.

Pedestrian Crossing Time

Knoblaugh et al. (9) identified that all pedestrians increase their walking speed during inclement weather. Younger pedestrians (under 65 years old) increased by 9% from 1.46 meters per second (mps) (4.82 fps) to 1.60 mps (5.24 fps) while older pedestrians (over 65 years old) increased by 8% from 1.22 to 1.33 mps (4.03 to 4.37 fps). Based on these findings, the minimum crossing time to pedestrians should not change and therefore there is no impact to minimum signal timing restrictions.

Dilemma Zone, Amber and Red Time

Longer stopping distances are needed during the inclement weather because of changes in traction, whether real or perceived. Typically this relates to drivers being more aware and cautious in their driving patterns. For a signalized intersection, the amount of amber time provided under dry conditions may not be sufficient to eliminate a potential dilemma zone during inclement conditions. There are two factors that contradict each other in determining the appropriate amber time: the decrease in speed which reduces the needed amber time, and the reduction in deceleration rates which requires longer amber time. The following equation is the means of determining the appropriate amber time to eliminate dilemma zones.

$$\tau_{min} = \delta + \frac{W + L}{u_o} + \frac{u_o}{2a} \qquad (10)$$

where:

τ_{min} = minimum amber time (s)

δ = perception-reaction time (s)

a = constant rate of braking deceleration (ft/s^2)

W = width of the intersection (ft)

L = length of the vehicle (ft)

u_o = approach speed (ft/s)

Garber and Hoel (10) assert that the deceleration rate under normal conditions is 27% the gravitational acceleration (2.65 m/sec^2). With decreased traction in snowy conditions, drivers tend to be more comfortable with 20% the gravitational constant (1.95 m/sec^2). It is expected that for Condition 7, snow packed roads, this deceleration rate may be further reduced.

The observed 30% reduction in speed during inclement weather is not sufficient to account for the reduced deceleration and there is a resulting need for a 10% to 15% increase in amber time. For large intersections, more time is needed since the second term in the equation (clearing the intersection) is much greater with a wider intersection and yet slower speed with inclement weather. The needed increase is between 0.5 and 1.0 seconds and is therefore likely to have little effect on signal efficiency operations. It does, however, affect the dilemma zone and may have a substantial positive effect on reducing accidents. In addition to a reduced capacity for permitted left turn, the two sneakers are slower in clearing the intersection. Based on 136 observations during weather conditions 4 through 6, the sneakers took an average of 0.75 seconds longer to clear the intersection. Based on these findings, a one second increase in all-red time is recommended.

DISCUSSION

The saturation flows measured in Salt Lake City were compared to similar field values found in three prior studies, not to validate the results of the other three findings, but rather as a means to check their authenticity. The speed and saturation flow largest decrease was between severity categories 3 and 4. Category 3 is defined as “wet and snowing”, and category 4 is defined as “Wet and Slushy”. The addition of slush to the roadway seemed to be the boundary where vehicles begin to see their largest decrease in performance. This is defined as the beginning point of “inclement weather”, or the point at which a modified signal timing plan may become appropriate. The values for speeds and saturation flows that should be used in developing the inclement weather signal timing plan should be based on those reductions found for the average reduction among severity categories 4-6.

The question of when to implement the signal timing plan is much more subjective and difficult to answer. This decision could be triggered by an automatic process whereby the saturation flow or speed is monitored and when thresholds are met, the inclement timing plans are implemented. Although there are ways to automate the decision process, more research is needed prior to implementation as recent attempts have been unsuccessful. Instead, it is recommend that a trained Transportation Operation Center operator or engineer decide to implement based on a judgment as to the value of implementing the inclement plan.

In theory, changing cycle lengths would not benefit inclement weather conditions if traffic demand remained constant. Although the reality is there will likely be a different optimum cycle length, this is most likely due to changes in traffic volume and turning movement flows during inclement weather periods. This assumption is based on the observed volume reduction during the Minnesota research (2). There is insufficient SLC data to provide a confident statement recommending a general reduced volume during inclement weather since there are many other external factors that control volume trends other than inclement weather. Therefore, unless specific inclement weather traffic flows are collected on each corridor, the cycle length will remain constant. Instead, the offsets, splits, and clearance intervals should be changed for the inclement weather plans. The splits are affected because side-street may need to be subjected to longer delays to allow more green time for the main corridors, thereby reducing overall average delay and congestion.

While the discussion of start-up lost time indicates that intersection efficiency is decreased, other factors also reduce intersection performance. Larger gaps are required to accommodate permitted left turn movements, primarily because of reduced traction, which reduces the available unprotected left turn capacity. The updated 1997 HCM (6) identifies the critical gap for left turns as being 4.1 seconds. While a gap acceptance study was outside the scope of this study, it was observed to increase for severity levels 4 through 6. It is the opinion of the authors that there is a probable increase of 25% to 30% in critical gap time. There is, however, no substantial data to support this opinion.

The inclement weather signal timing plan should be activated based on engineering judgment. Four general areas should be considered when making this judgment to ensure that the plan provides sufficient benefit to the network. These areas are: severity, duration, area of influence, and traffic flows.

1. Severity. There should at least be slush on the road. Another measure of the severity might be to check on the current speeds. If the speeds fall below about 70% of normal (due to weather conditions), this could be used as a consideration for implementing a plan.

2. Duration. The predicted duration of the storm must be sufficient to warrant the plan. Translating from one plan to another causes the network to be unable to recover quickly enough to benefit from a plan (11). It is therefore recommended that the storm be projected to continue to cause poor road conditions for a minimum of 20 to 30 minutes in order to allow the network to recover from the transition.

3. Area of Influence. The storm must influence a large enough area. If the plan can be implemented by corridor, then the storm must be affecting a sufficient length of the corridor to be effective. This length will depend on engineering judgment at the time.

4. Traffic Flows. Traffic conditions should be sufficient to warrant a new timing plan. These signal timing plans are probably most useful on a corridor basis, rather than a network-wide application. AM and PM peak plans are the most appropriate. Mid-day plans could also be developed, depending on the demand and the estimated benefit the network or corridor might receive. Night or weekend plans would not receive as much benefit because of the decreased demand.

CONCLUSION AND RECOMMENDATIONS

Snow and ice conditions contribute to congestion. The use of standard dry condition signal timing plans is sub-optimal during inclement weather conditions. Specific signal timings plans should be developed to reduce inclement weather congestion in urban areas. Identifying when those plans should be implemented is described under a four-step process of severity, duration, area of influence, and measured traffic flows. Saturation flow, speed, and start-up lost times were measured during various weather severity levels in Salt Lake City with the following conclusions for modifying the traffic parameters in developing new inclement weather timing plans.

1. Increase amber time by 10% to 15% (1/2 to 1 second) depending on intersection size, with half-second increases for intersections under 15.2 meters (50 feet) wide increasing to a one second increase for intersections 30.5 meters (100-feet) wide.
2. Increase all red time by one second to account for the slower clearing of the intersection by “sneakers” at permitted/protected intersections (taking 0.75 seconds longer than during dry conditions).
3. Decrease the measured or calculated “dry” saturation flows by 20%.
4. Decrease the average “dry” speeds by 30%.

5. Start-up lost time should increase by 23% from 2.0 to 2.5 seconds.
6. No change in pedestrian crossing timing needs is necessary.
7. Clearance intervals may be increased even further at intersections that have high speed or steep grade approaches.

Ongoing research will verify the findings through modeling, simulation, and evaluation of field implementation. The Synchro/Simtraffic software package will provide the modeled effectiveness of the inclement weather plans. Field evaluations will also be performed as the Utah Department of Transportation implements inclement weather plans on its major corridors. In addition, a SCOOT (10) evaluation using the CORSIM-SCOOT connection developed by the University of Utah (12) will determine how an adaptive signal control system accommodates inclement weather. The modeling results will provide a comparison of the estimated benefits of using some form of an inclement weather signal timing plan.

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