Potential Effects of Wet Conditions on Signalized Intersection LOS

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ABSTRACT

Although rain and other precipitation is common, analyses of signalized intersections based on the Highway Capacity Manual require clear weather and dry pavement conditions. Three factors may be affected by wet weather: saturation flow, effective green time and progression. Saturation headway may lengthen, effective green may shrink and progression may worsen in wet conditions. As a result, signalized intersection operations become less efficient. This is demonstrated in the longer delays estimated for five sample intersections. A methodology was developed for the derivation of the probability of rainfall \( P_{\text{wet}} \) during the morning and evening peak hour for any intersection in the U.S. using readily available rainfall accumulation data from NOAA. Once delay and LOS are estimated for both dry and wet conditions, a weighted average is employed for estimating delays and LOS that represent the prevailing dry and wet peak period conditions at a signalized intersection.
INTRODUCTION

The Highway Capacity Manual (TRB 2000) states “there have been relatively few efforts to quantify the effects of adverse weather on capacity”. To this end, this paper summarizes the limited evidence on the effect of wet conditions on signalized intersection operations and presents a methodology for incorporating the effects of wet conditions into the HCM2000 procedure for the capacity and performance analysis of signalized intersections.

Usually worse congestion conditions are observed in real life under rainy conditions compared to dry conditions with the same amounts of traffic volumes. To wit, a small sample of over 60 travel times with a 4:30 PM departure was taken on the same 4-lane wide arterial street segment in Honolulu during normal work days in March 2004. However, only 16 runs were unaffected by known odd occurrences such as incidents, lane closures, etc. The mean travel time and standard deviation were 9.6 and 2.1 minutes, respectively, for dry conditions, and 18.2 and 6.6 minutes, respectively, for wet conditions. Given that the length examined is 2.4 miles long, the average speed in dry conditions was 15.0 mph, and 7.9 mph under wet conditions which indicate substantially worse conditions under rainy conditions.

Research by Zhang and Prevedouros (2005) based on an Internet survey with 2017 responses indicates that drivers drove 2.7 mph (4.9%) slower on wet roads and 6.1 mph (11.1%) slower when it was raining and that they reduced travel by about 3% if rain was forecast.

Most civil engineering designs typically consider the worst likely conditions and often apply a safety factor on the design specifications. Highway traffic analysis is conservative by focusing on the peak periods of demand and by applying the peak hour factor which typically inflates peak hour volumes.

The current HCM analyses is based on clear weather, dry pavement and daytime conditions whereas in most metropolitan areas, rain and other precipitation is common. As a result of the assumption of ideal environmental conditions, the assessment of the level-of-service (LOS) and traffic impacts of future traffic generators may be considerably inaccurate because long-term average conditions that include weather impedances are ignored.

Unlike impedance due to construction, crashes, incidents or other rare and stochastic events, impedance due to wet conditions may be frequent and can be incorporated reliably using long series of historical statistics from the National Oceanic and Atmospheric Administration (NOAA). Therefore, if the derivation of realistic peak period performance measures is the goal of the HCM, then the effects of wet conditions should be accounted for.
BACKGROUND

Rain affects roadways, vehicles and drivers. The main effects of rain on roadways is the reduction of friction between tire tread and road surface. The windscreen and windows of vehicles are covered by raindrops during rain which lead to poor visibility. Splash and spray from other vehicles worsen visibility problems by adding a film of dirt. Drivers may try to maintain longer distances between vehicles and drive at slower speeds to account for the longer perception times, reduced cornering ability (e.g., while making turns at an intersection) and longer stopping distances during rain (Jones et al. 1970, OECD 1984, Pisano and Goodwin 2003.)

Martin et al. (2000) and Perrin et al. (2001) reported about arterial street operations in inclement weather. They reviewed seven past studies, but none provided estimates of potential capacity losses due to rain and wet conditions. Most of the studies they reviewed were focused on signal timing settings and strategies that are appropriate for ice and snow conditions. Traffic data was collected from two intersections. Saturation flows were obtained with automated traffic data collectors. Speeds were collected using radar guns. The saturation flow and speed data were obtained on dry weather days and 14 different inclement weather days during the winter of 1999–2000. The data collection procedure implied that the observers manually recorded weather data while collecting traffic data. The weather conditions were categorized into seven conditions: normal/clear, rain, wet and snowing, wet and slushy, slushy in wheel paths, snowy and sticking, and snow packed surface. Average speed decreased about 10% in rain. Rain caused a reduction in saturation flow of about 6%. The average start-up lost time increased from 2.0 sec to 2.1 sec. Longer headway, slower speed, and decreased acceleration rate were reported to be the main reasons for the reduction in saturation flow.

FHWA’s Weather Management web site (Internet reference) contains comprehensive summaries of the effect of weather on traffic systems but sources for the information are not cited: Rain reduces speed by 10% and capacity by 6% on arterial streets, which coincide with the reports of Martin and Perrin cited above.

Our analysis of 127 four-hour video tapes from freeway and arterial surveillance cameras in Honolulu recorded between 1996 and 2000 focused on measurements from traffic platoons ranging in size between 6 and 61 vehicles with an average platoon size of 12 vehicles. Data were collected during busy but fluid conditions and headways were measured at identical locations under dry conditions (680 platoons), wet pavement but no rain (436
platoons) and light-to-moderate rain conditions (388 platoons). Out of a total of 1,504 platoons observed, 323 where on 6-lane class I arterials.

The overall results indicate that under both wet and light rain conditions freeway capacity is reduced by 8.3% and arterial street capacity is reduced by 4.7%, on the average. For arterial streets, the mean headway \( h \) for dry conditions was 1.69 sec. The mean \( h \) for rain and wet conditions were 1.76 sec. and 1.77 sec., respectively. The difference in \( h \) between dry and rain was significant at the 95% level and the difference in \( h \) between dry and wet was significant at the 85% level (based on a t-test). The difference in \( h \) between rain and wet was not significant. A linear regression model was developed for arterial streets (all parameters are significant at the 95% level):

\[
\begin{align*}
  h &= 1.411 + 0.052 G + 0.056 R + 0.448 W \\
  (R^2=0.30)
\end{align*}
\]  

where,

- \( h \) = headway in sec.
- \( G \) = grade in %
- \( R = \) rainy or wet conditions, 1=rain/wet, 0=dry
- \( W = \) weekend day, 1=weekend or holiday, 0=normal work day

The model indicates that weekday peak period headways are much shorter (1.47 sec.) than headways during weekends and holidays (1.86 sec.) and about 4% longer in wet or rainy conditions.

**METHODOLOGY**

The proposed methodology consists of three parts:

a) Assessment of the effect of wet conditions on signalized intersection LOS.

b) Modification of the HCM procedure for capacity analysis of signalized intersections.

c) Estimation of the probability of rainfall for any location.

The detailed components of parts (b) and (c) are shown in Figure 1.
**Effect of Wet Conditions on LOS**

Three components of signalized intersection operations are likely to be affected by inclement weather: saturation headway, lost times and progression. The limited studies presented above on saturation headways under light rain and wet pavement conditions suggest a headway increase (or saturation flow reduction) of about 5%. Lost times are likely longer under inclement weather because start-up times become longer and clearance interval (Y+AR) utilization becomes smaller as drivers become more cautious. Progression is also likely to worsen due to the reduction in speeds on approach links and the elongation of queues at stop lines which make offsets derived under dry conditions suboptimal. The effects of progression are largely limited to the through movements only.

These changes in driver behavior could be compensated for by traffic-adaptive signal control, but common pretimed and actuated signals with stop line detection cannot make adjustments unless inclement weather plans are available. (Typically no special plans are developed for rain). As a result, the three behavioral changes of drivers have important impacts on intersection delay and LOS, as demonstrated later herein.

**Modification of HCM Procedure for Capacity Analysis of Signalized Intersections**

Modifications to the HCM analysis and models are not required. However, the capacity analysis procedure needs to be executed twice. One time with the user’s inputs for prevailing saturation flow, effective green and progression factors, all based on dry conditions, which produce the $D_{dry}$ delays. A second time with saturation flow decreased by $\alpha\%$, effective greens decreased by $\beta$ sec. and progression factors worsened by $\gamma\%$, which produce the $D_{wet}$ delays.

Currently, only a little is known about parameter $\alpha$ and practically nothing is known about parameters $\beta$ and $\gamma$. Conservative assumptions were made to demonstrate the effect of wet conditions: $\alpha=5\%$, $\beta=1.5$ and 2 sec., and $\gamma=10\%$. Li and Prevedouros (2002) observed that start up lost time is 0.5 sec. shorter for protected left turn movements, which explains the two values for $\beta$.

Prevailing delays are derived as probability-weighted averages for morning and afternoon peak periods based on the probability for wet conditions ($P_{wet}$):

\[ D_{AM} = (1 - P_{wet,AM}) D_{dry,AM} + P_{wet,AM} D_{wet,AM} \]  

(2a)
\[ D_{PM} = (1 - P_{wet,PM}) D_{dry,PM} + P_{wet,PM} D_{wet,PM} \] (2b)

The same formulae can be used to derive weighted averages for lane group and approach delays. The derivation of the probability for wet conditions \( P_{wet} \) is given below.

**Probability of Rainfall at Any Location**

This part of the methodology develops the estimation of the probability of wet \( P_{wet} \) conditions at any location. Approximate probabilities may be derived from aggregate rainfall statistics. The World Climate Internet site (www.worldclimate.com) offers a wealth of monthly rainfall accumulation statistics for each station available by city. NOAA (2003) offers rainfall data in 15-minute and hourly intervals for all states in the U.S. For example, the National Climatic Data Center has data for the state of California from 293 stations in a 15-minute format and from 510 stations in a hourly format.

Developing estimates for \( P_{wet} \) requires a considerable effort in order to screen and summarize rainfall data during peak traffic periods. If this work is done for a sample of years, then a comprehensive representation of the prevailing wet conditions in a state becomes available. The methodology used to derive \( P_{wet} \) is shown on the left side in Figure 1.

The process starts by gathering data for a state or metropolitan area and for selected years and months. The NOAA data represent cumulative monthly rainfall readings, so if consecutive values are different, then some rainfall occurred and its magnitude was recorded, thus, rainfall occurrence is established and rainfall intensity can be estimated. The proportion of periods with rainfall in the total number periods is \( P_{wet} \). The monthly averages per station are exported to a GIS application for mapping. On these digital maps the user selects the desired morning or afternoon peak period, zooms into the geographical area of interest, locates the subject intersection and receives the rainfall probability from the GIS tool.

A manual that details this process has been developed by Prevedouros and Chang (2003). The \( P_{wet} \) contour maps, such as the one for the City and County of Honolulu shown in Figure 2, may be revised in long cycles that perhaps coincide with major updates of the HCM. Such maps would be useful not only in traffic engineering applications but also in hydraulic design, geotechnical investigations and construction scheduling.

National or local policies for \( P_{wet} \) may be determined based on:
1. The average rainfall (all month average).

2. The average *work year rainfall* which excludes the summer months of June, July and August as atypical traffic months in the US.

3. The average summer month rainfall (average rainfall for June, July and August) – this determination is appropriate for routes with heavy recreational traffic in the summer months.

4. The month with the highest rainfall.

5. A typical month of normal traffic and moderate rainfall.

On a national basis, option (2) from the list above may be the most appropriate base for $P_{\text{wet}}$ determination – it also reduces the effort for $P_{\text{wet}}$ determination by 25% due to the exclusion of summer months.

**RESULTS FROM FIVE SIGNALIZED INTERSECTIONS**

The aforementioned potential effects of wet conditions on signalized intersections were investigated in a case study. Table 1 presents a summary of results from the analysis of five intersections. These intersections range in geometric configuration from a simple T-intersection with single lane approaches to a multi-lane, high design 4-approach intersection. Their phasing schemes range between three and six phases. All data were collected near the morning peak period under clear and dry conditions. These intersections experience moderate to heavy amounts of traffic.

The results are presented in Table 1 in four vertical sections. One assuming dry conditions and three with various scenarios of potential wet weather related impacts. The scenarios include reduced saturation flow (wet scenario 1), reduced saturation flow and reduced effective green (wet scenario 2) and reduced saturation flow, reduced effective green and worsened progression (wet scenario 3).

The impacts of weather in delay and LOS are shown to be quite large. For example, overall intersection delays increase from dry conditions to wet conditions (scenario 3) by 28%, 45%, 67%, 50% and 37% for intersections 1, through 5, respectively (Table 2). Under wet conditions the LOS worsens by one level for four out of the five intersections.

Delays tend to be larger for movements served by shorter phases (e.g., protected left turn movements), because of the disproportionally larger reduction of the effective green. Overall, the largest impact is due to the reduction of the effective green and the smallest impact is due to the lower quality of progression.
The results of Table 1 may change once reliable field estimates for parameters $\alpha$, $\beta$ and $\gamma$ have been established. Although our estimates for $\alpha$, $\beta$ and $\gamma$ are conservative approximations, smaller reductions in effective green and larger impacts to the progression factor and the saturation flow are possible due to the changes of motorist behavior in wet conditions. All three factors are likely to be affected by rainfall intensity and the type of precipitation.

The location of these intersections is in an area of Honolulu in which historical 15-minute rainfall data from NOAA indicate a probability of wet conditions in the morning peak (6-8 AM) of $P_{\text{wet}} = 21\%$. Accordingly, the delay at this intersection that accounts for both dry and wet conditions can be derived using a weighted average (Eq. 2a) to combine the delays with dry conditions and the delays with wet conditions from scenario 3. In this way, the prevailing intersection delays can be calculated as shown in Table 2. Prevailing delays are 6% to 14% higher than those occurring in dry conditions. Although intersection LOS did not worsen for any of the five intersections examined, all of them would be one level worse if volumes were higher by 5% to 10% (e.g., intersection 3 is only 0.9 sec. away from being one level worse.)

Accounting for wet conditions in the capacity analysis of signalized intersections also reveals operational deficiencies of lanes, lane groups or approaches which may lead to appropriate measures such as modifications to signal timings and reevaluation of the channelization layout.

SUMMARY AND DISCUSSION

Three components of signalized intersection operations are affected by inclement weather: saturation headway (thus saturation flow and capacity), lost times (thus effective green and capacity) and progression, all of which affect average control delays and the corresponding LOS. These factors may change significantly during rainy conditions due to changes in motorists’ driving behavior. As a result, signalized intersection operations are affected and this is manifested by longer delays and worse LOS. Although much worse congestion is observed in real life under rainy conditions, these normally and frequently occurring conditions are not reflected in HCM analyses of signalized intersections. This paper proposed a methodology for rectifying this shortcoming so that prevailing conditions can be assessed based on the probability of rain in the peak periods.

Research is required for establishing reliable values for the saturation headway, lost times and progression factors during inclement weather conditions. Research should account for rainfall intensity and provide pertinent
measures for the representation of wet conditions. A substantial effort would be required in order to overlay rainfall (or other precipitation) probability contours onto metropolitan or statewide street networks. This effort will benefit several civil engineering applications in construction, geotechnics, hydraulics as well as traffic engineering. All the required components for doing so are readily available – GIS applications, reliable street maps and rainfall data from NOAA.

This presentation is a first step in demonstrating the significance of accounting for the effects of rain to signalized intersection capacity. Much additional research is necessary from the perspectives of driving behavior and signalized intersection control, at various locales, and for different forms and intensities of precipitation. This in turn may provide the evidence required in order to make a convincing case to TRB’s Highway Capacity and Quality of Service committee that oversees the technical content of the HCM that the proposed additions and modifications outlined herein should become a routine part of traffic analyses.
REFERENCES

FHWA. Road Weather Management. (www.ops.fhwa.dot.gov/Weather/faqs.htm)


For example, use the Spot Elevation function in Maptitude.

Monthly NOAA data

Choose year and month (Files of all stations in one zipped file)

Import into a spreadsheet program name by station_month_year (e.g. Manoa_Jan_2002)

Insert date (columns) and time (rows)

Manually select AM peak period (7-9 AM)
PM peak period (4-6 PM)

Calculate rainfall in AM, PM peak periods

Introduce binary RAIN variable (0,1) for days with rainfall > 0.00

Sum up RAIN = 1 to find days with rainfall in each month and AM, PM period

Estimate probability for rainy conditions in AM, PM peaks

\[ P_{AM} = \frac{\text{SUM} (\text{RAIN})_{AM}}{\text{Days in Month}} \]

\[ P_{PM} = \frac{\text{SUM} (\text{RAIN})_{PM}}{\text{Days in Month}} \]

Repeat the process for another month of the year or another station

Generate AM, PM summaries with:
- station names, coordinates
- rainfall probability of each month/station
- average, max, min per station

Output file: P_RAIN_SUM_year (e.g. P_RAIN_SUM_2002.XLS)

Find Rainfall Probability at any Intersection with GIS Mapping

Import rainfall probability file into a GIS application

Add layer of AM or PM peak hours rainfall probability

Choose month

Generate P_RAIN_AM or P_RAIN_PM contour layer

Zoom into target location

Use GIS function to estimate P_RAIN at target location

Use derived probabilities in HCM 2000 intersection analysis

For example, use the Spot Elevation function in Maptitude.

Fig. 1 Methodology for incorporating the effects of wet conditions into the HCM2000 procedure for signalized intersection analysis
**Fig. 2** Sample morning peak period rainfall probability ($P_{\text{wet,AM}}$) contour generation for City and County of Honolulu with NOAA 15-minute interval data (February 2002)
### Table 1. Analysis of Five Intersections under Dry and Wet Conditions

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</tr>
</tbody>
</table>

### Table 2. Estimation of Prevailing Delays That Account for Dry and Wet Conditions

<table>
<thead>
<tr>
<th>Intersection</th>
<th>DRY ($p=0.79$)</th>
<th>WET (scenario 1)</th>
<th>WET (scenario 2)</th>
<th>WET (scenario 3)</th>
<th>Change in Delay</th>
<th>Prevailing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Delay (h)</td>
<td>LOS (a,c)</td>
<td>Delay (h)</td>
<td>LOS (a,c)</td>
<td>Delay (h)</td>
<td>LOS (a,c)</td>
</tr>
<tr>
<td>1</td>
<td>46.9</td>
<td>D</td>
<td>59.8</td>
<td>E</td>
<td>27.5</td>
<td>49.6</td>
</tr>
<tr>
<td>2</td>
<td>26.4</td>
<td>C</td>
<td>38.4</td>
<td>D</td>
<td>45.5</td>
<td>28.9</td>
</tr>
<tr>
<td>3</td>
<td>29.9</td>
<td>C</td>
<td>50.0</td>
<td>D</td>
<td>67.2</td>
<td>34.1</td>
</tr>
<tr>
<td>4</td>
<td>26.9</td>
<td>C</td>
<td>40.3</td>
<td>D</td>
<td>49.8</td>
<td>29.7</td>
</tr>
<tr>
<td>5</td>
<td>24.6</td>
<td>C</td>
<td>33.8</td>
<td>C</td>
<td>37.4</td>
<td>26.5</td>
</tr>
</tbody>
</table>