Methodology for Accounting for Wet Conditions in Signalized Intersection Capacity Analysis

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ABSTRACT

This paper summarizes the limited evidence on the effect of wet and rainy conditions on signalized intersection capacity. Preliminary evidence suggests that wet conditions reduce saturation flow by 5% to 6%. This small reduction in capacity may become critical under congested conditions. Based on this experience, a factor $f_{\text{wet}} = 0.95$ is proposed to be added to the saturation flow formula in the HCM2000 formula for assessing delay and LOS in wet conditions. A methodology was developed for the derivation of the probability of rainfall ($P_{\text{wet}}$) at any intersection in a state or metropolitan area 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 proportion of prevailing dry and wet conditions at any given intersection. The methodology is illustrated with a case study. Substantial future research is needed for establishing national and local $f_{\text{wet}}$ and $P_{\text{wet}}$ factors.
INTRODUCTION

The Highway Capacity Manual (1) states “there have been relatively few efforts to quantify the effects of adverse weather on capacity”. Our objective was to summarize the limited evidence on the effect of wet and rainy conditions on signalized intersection capacity and develop a methodology for incorporating the effects of wet and rainy conditions into the HCM2000 procedure for the capacity and performance analysis of signalized intersections.

Most civil engineering designs typically consider the worst possible conditions and often apply a safety factor on the design specifications. In this regard, highway traffic analysis is conservative by focusing on the peak periods of demand and by applying the peak hour factor which typically inflates peak hourly volumes. The analysis, however, is based on clear weather, dry pavements and daytime conditions whereas in most metropolitan areas, rain and other precipitation is common, and darkness prevails during peak periods in northern cities during winter months. As a result of the assumption of ideal environmental conditions, the assessment of both prevailing level-of-service (LOS) and traffic impacts of future traffic generators may be considerably inaccurate because long-term average prevailing conditions that include weather and lighting impedances are ignored.

Most research results suggest a reduction in both capacity and speed in wet and rainy conditions. This agrees with the casual observation that traffic conditions in urban areas are worse under rainy and wet conditions (i.e., longer queues and travel times). There have been at least 15 studies on the effect of inclement weather on highway speed and capacity published after the latest reference cited in HCM2000. A separate paper presents a comprehensive synthesis of findings of 26 studies relating to the effects of wet and rainy conditions on highway capacity (2). Most of the studies summarized in (2) concentrate on research of free flow speed on freeways and highways.

This paper first summarizes the limited evidence on the effect of wet and rainy conditions on intersection capacity. Then, a methodology is proposed that (i) utilizes a capacity reduction, (ii) includes the derivation of the probability of rainfall at any intersection in a state or metropolitan area in the U.S. and, (iii) employs a weighted average for estimating delays and LOS in dry and wet conditions. The methodology is illustrated with a case study with field data. A summary and directions for future research conclude this paper.

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 during rain are covered by raindrops which lead to poor visibility (3,4,5,6). Moreover, splash and spray from other vehicles worsen visibility problems by adding a film of dirt. The problem of visibility reduction is more severe when rain occurs at night (3,4,5,6). The overall effect of rain on drivers is poor visibility and object recognition which tends to lengthen the perception time. Drivers may try to maintain longer distances between vehicles and drive at slower speeds to account for the longer perception times and stopping distances during rain.

Martin et al. (7,8) reported in 2000 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 studies were focused on signal timing settings and strategies that
are appropriate for ice and snow conditions. Traffic data was collected from two intersections (7,8). 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 (9) contains comprehensive summaries of the effect of weather on traffic systems but sources for the information are not cited. It reports that rain reduces speed by 10% and capacity by 6% on arterial streets.

The authors of this paper are involved in on-going analysis of 127 four-hour video tapes recorded between 1996 and 2000 from freeway and arterial surveillance cameras in Honolulu, which is the 11th largest metropolitan area in the U.S. and has major congestion problems during peak periods. Average headways were measured for 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 three conditions: 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 were on 6-lane class I arterials and 1,181 were on 6-lane freeway segments. The distribution of measurements per lane was fairly even with 399 observed platoons on the right (shoulder) lane, 454 on the middle lane and 651 on the left lane. Headways on arterial streets were measured at midblock locations. The results from pair-wise t-tests are as follows:

<table>
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<th>Arterial</th>
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<tr>
<td></td>
<td>h</td>
<td>sig.</td>
<td>h</td>
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<td><strong>Dry</strong></td>
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<tr>
<td><strong>Dry</strong></td>
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<td>95%</td>
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</tr>
<tr>
<td><strong>Wet</strong></td>
<td>1.68</td>
<td></td>
<td>1.56</td>
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</tbody>
</table>

These results indicate that under both wet and light rain conditions, freeway capacity was reduced by 8.3% and arterial street capacity was reduced by 4.7%, on the average. A linear regression model was developed for arterial streets, as follows (all parameters are significant at the 95% level):

\[
h = 1.411 + 0.052 G + 0.056 R + 0.448 W \quad (R^2=0.30)
\]  

(1)

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 limited information on the effect of wet conditions on capacity indicates that under light rain and wet pavement conditions, a capacity reduction in the order of 5% to 6% should be expected. Although this is a modest reduction, it may cause a substantial deterioration in the level of service in peak periods, as illustrated in Figure 1 where a 5% capacity reduction caused a substantial increase in delay (from 52.1 sec/veh to 56.4 sec/veh for X=0.90) and a subsequent deterioration of the level of service from D to E.

METHODOLOGY

The methodology consists of three parts:

a) Assessment of the effect of wet conditions on saturation flow.

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

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

Effect of Wet Conditions on Saturation Flow

This part of the methodology was summarized in the previous section. Although much more research is needed on this subject, it may be preliminarily assumed that a capacity reduction of about 5% occurs in wet conditions. This reduction applies to the saturation flow which implicitly accounts for the discharging behavior of vehicles under a set of prevailing conditions.

Modification of HCM Procedure for Capacity Analysis of Signalized Intersections

According to HCM2000, the saturation flow rate for each lane group is calculated as follows (explanation of terms can be found in HCM2000):

\[ s = s_o \cdot N \cdot f_{HV} \cdot f_g \cdot f_p \cdot f_{bb} \cdot f_a \cdot f_{LU} \cdot f_{LT} \cdot f_{RT} \cdot f_{Lpb} \cdot f_{Rpb} \]  

(2)

For part (b) of the methodology, a factor to account for light rain and wet conditions \( f_{wet} \) is proposed to be added to this equation, as follows:

\[ s = s_o \cdot N \cdot f_w \cdot f_{HV} \cdot f_g \cdot f_p \cdot f_{bb} \cdot f_a \cdot f_{LU} \cdot f_{LT} \cdot f_{RT} \cdot f_{Lpb} \cdot f_{Rpb} \cdot f_{wet} \]  

(3)

The \( f_{wet} \) factor may be expressed either as a constant or as a function. Given the limited amount of empirical information available, \( f_{wet} \) was treated as a constant herein. The constant value of \( f_{wet} = 0.95 \) was used based on the aforementioned findings. In the future, different levels of \( f_{wet} \) may be developed according to rainfall intensity. Rainfall intensity can be derived with ease from readily available data, as discussed later herein and allows for a more descriptive classification of rainfall conditions, such as light, medium and heavy rain as well as major storm. Parameters for \( f_{wet} \) under major storm (e.g., hurricane) are not advocated for regular use in
capacity analyses, but they can be useful in estimating the capacity of evacuation routes under conditions of unusually heavy rainfall and wind.

If extensive research is conducted in this area, then, it is possible to produce a generalized form of $f_{\text{wet}}$ which may be called $f_{\text{envir}}$, the environmental conditions adjustment factor. The factor $f_{\text{envir}}$ may be developed in the form of a linear or non-linear function with several independent variables. A number of models have been developed for freeways and highways with average free flow speed as the dependent variable and independent variables such as rainfall intensity, rainfall duration, day of week, time of day (peak or off-peak period), wind speed, wind direction (parallel or perpendicular to roadway), pavement status (wet or dry), other forms of precipitation, and the presence of fog or nightfall (2).

The second part of part (b) of the methodology consists of a brief extension of the HCM2000 procedure so that wet conditions are accounted for as part of a more comprehensive representation of prevailing conditions. For a given intersection location, the probabilities of wet conditions during the morning and afternoon peak conditions are denoted as $P_{\text{wet,AM}}$ and $P_{\text{wet,PM}}$, respectively. (These probabilities are derived below; see eq. 5)

First, we apply the HCM2000 procedure, without any modification, e.g., by using eq. 2. This intersection delay is $D_{\text{dry}}$. Then, we apply the HCM2000 procedure, with the modified saturation flow equation, e.g., by using eq. 3. This intersection delay is $D_{\text{wet}}$. The overall delay at this intersection that is representative of long-term average prevailing conditions is derived as a probability-weighted average, as follows:

$$D_{\text{AM}} = (1 - P_{\text{wet,AM}}) D_{\text{dry,AM}} + P_{\text{wet,AM}} D_{\text{wet,AM}}$$  \hspace{1cm} (4a)

$$D_{\text{PM}} = (1 - P_{\text{wet,PM}}) D_{\text{dry,PM}} + P_{\text{wet,PM}} D_{\text{wet,PM}}$$  \hspace{1cm} (4b)

The same formulae can be used to derive weighted averages for lane group and approach delays.

**Probability of Rainfall at Any Location**

This part of the methodology develops the estimation of the probability of wet ($P_{\text{wet}}$) conditions at any location. Approximate probabilities may be derived from aggregate rainfall statistics. For example, the World Climate web site (10) offers a wealth of monthly rainfall accumulation statistics for each station available in a given city – the site is city searchable. Interesting rainfall contour maps can be derived as the one illustrated in Figure 2. However, monthly or annual rainfall accumulation may correlate poorly with rainfall in the peak periods of traffic. A correlation between rainfall and wet conditions during peak periods is not readily available and it was not pursued further in our research because there are more appropriate rainfall data available for our purposes. Specifically, NOAA (11) offers rainfall data in 15-minute and hourly intervals for all states in the U.S. (Figure 3). The National Climatic Data Center has data for the state of California, for example, from 293 stations in a 15-minute format and from 510 stations in a hourly format. The sizes of the text-delimited files is 3.3 MB and 4.8 MB, respectively. Regardless of size, all data are available for each state for $60 (as of July 2003) for private users, but they are available at no

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1 Please note that Figure 3 is included so that the reviewers are shown the wealth of data available without visiting the NOAA web site. It is our intent to remove Figure 3 if the paper is approved for publication.
charge for qualified uses and users. The national NOAA database provides data sets which are limited due to missing information and the provision of a sample of dates (e.g., some stations may have data from as little as one day in a year). On the other hand, locally procured rainfall information tends to be comprehensive, at least for several recent years.

The information for Hawaii includes 15-minute interval rainfall data for all stations (with station longitude, latitude and altitude) and months from 1998 to 2002. The only limitation noted in the data used so far is that some monthly files contain information in hourly intervals.

Getting estimates for $P_{\text{wet}}$ requires a considerable effort in order to screen and summarize peak period rainfall data. (In this context, peak period refers to peak periods in traffic such as 7-9 AM and 4-6 PM.) However, once this work is done for a sample of years, it provides a comprehensive representation of prevailing wet conditions in a state. This summary of wet conditions may not need updating for several years. The data from NOAA provide the opportunity to analyze not only the prevailing wet and dry conditions but also to estimate rainfall intensity.

The methodology is summarized in flowchart form in Figure 4. The process starts by choosing data for a state or metropolitan area for selected year(s) and month(s). The selected data are downloaded, entered to a spreadsheet program and dates (columns) and 15-minute time intervals (rows) are added to them. A manual or automated procedure (i.e., Excel macro) can be used to identify 15-minute periods in the morning (e.g., 7 to 9 AM) and afternoon (e.g., 4 to 6 PM) peak periods and develop a binary variable $\text{RAIN}$ which takes the value of ‘0’ when no rain is detected and ‘1’ when rain is detected. The NOAA data represent cumulative monthly rainfall readings, so if consecutive values are identical, then, no rainfall was measured. If there is a difference in rainfall values between consecutive cells, then, some rainfall occurred and its magnitude was recorded, thus, rainfall occurrence is noted and rainfall intensity can also be estimated.

At this stage of our investigation, a simple definition of probability is used to derive the average probability of rainfall in each month: If a peak period had at least one 15-minute period with rainfall, that peak period was characterized as “wet”. The average $P_{\text{wet}}$ for a month, was estimated using the following ratios:

$$
P_{\text{RAIN}}^{\text{AM}} = \frac{\text{SUM}(\text{RAIN})_{\text{AM}}}{\text{Days in Month}} \quad \quad P_{\text{RAIN}}^{\text{PM}} = \frac{\text{SUM}(\text{RAIN})_{\text{PM}}}{\text{Days in Month}}
$$

(5)

In future developments, fractional days as well as rainfall intensity are planned to be accounted for. However, the ratios in eq. (5) are a reasonable starting point for separating peak periods according to wet and dry conditions.

This processing of NOAA data may be repeated for several months and years in order to derive reliable averages. The monthly averages per station are then copied to a summary spreadsheet file and exported to a GIS application for mapping. In our case, Caliper’s Maptitude (13) was used to develop rainfall probability contours for Oahu County (Figure 5). This process is detailed in a brief manual (14). Once this process is completed for a state or region, the user may simply select the desired period (morning or afternoon peak), month and year as the active layer, zoom into the geographical area of interest, locate the subject intersection and receive the rainfall probability from the Surface Analysis Toolbar in Maptitude. For example, a displayed value of 10 denotes that there is a 10% probability of wet conditions at the selected location to be used with eq. (4a) or (4b).
This procedure allows for defining a national or local policy for $P_{\text{wet}}$ which may be determined based on:

1. The average rainfall (all month average).
2. The average “work year” rainfall (all month average excluding the summer months of June, July and August as atypical traffic months in the U.S.)
3. The average summer month rainfall (average rainfall for June, July and August) – this determination is appropriate for routes with seasonal or recreational traffic.
4. The month with the highest rainfall which, for example, is January or February in most sun-belt states in the U.S.
5. A typical month of normal traffic and moderate rainfall, such as October or April.

On a national basis, option (2) from the list above would seem as 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.

An advantage of the procedure outlined herein is that states or metropolitan areas need to do this process once with a number of representative years and months and then publish $P_{\text{wet}}$ contours on street maps for use by the engineering community for traffic analyses. The $P_{\text{wet}}$ contour maps, such as the one for Oahu County shown in Figure 5, may be revised in long cycles that perhaps coincide with major updates of the HCM.

**CASE STUDY**

This case study illustrates the basic method of incorporating both $f_{\text{wet}}$ and $P_{\text{wet}}$ into the HCM procedure for signalized intersection capacity analysis. The chosen location is an intersection of a collector street with two lanes per direction and an arterial street with three lanes per direction and exclusive left lanes. The intersection has a moderately heavy traffic in the morning peak period examined herein. The field data include traffic volume on each lane group at 15-minute intervals (turning movements), percentage of heavy vehicles, lane width, grade, and number of pedestrians in each crossing, as summarized in the top part of Table 1. These data were collected in sunny and dry conditions.

Based on Figure 5, the rainfall probability at this location is 21% (e.g., 6 out of 28 days in February 2002 had some rainfall accumulation in the morning peak). It is also assumed that $f_{\text{wet}} = 0.95$. Separate capacity and performance analysis were performed without $f_{\text{wet}}$ (dry conditions shown in the bottom-left part in Table 1) and $f_{\text{wet}} = 0.95$ (wet conditions shown in the bottom-right part in Table 1).

The results in Table 1 show that for this intersection, wet conditions lower the LOS of certain lane groups and approaches by one letter grade. The overall intersection LOS remains at level D but overall control delay increases by 4 seconds.

For $P_{\text{wet}} = 21\%$, the overall delay at this intersection that accounts for both dry and wet conditions is derived using the weighted average in eq. (4a):

$$D_{\text{AM}} = (1 - P_{\text{wet,AM}}) D_{\text{dry,AM}} + P_{\text{wet,AM}} D_{\text{wet,AM}}$$

$$D_{\text{AM}} = (1 - 21\%) \times 48.9 + 21\% \times 52.9 = 49.7 \text{ sec.} \Rightarrow \text{LOS} = D$$

In this example, if wet conditions are ignored, then, prevailing delays are underestimated by about 2%. This small error, however, masks the fact that for this example intersection the
LOS of two lane groups and two approaches deteriorated from D which is usually deemed acceptable to E which is usually deemed unacceptable. Thus, the accounting of wet conditions in capacity analysis of signalized intersections may also reveal operational deficiencies of lanes, lane groups or approaches leading to appropriate measures such as modifications to signal timings, re-evaluation of the channelization layout and so forth.

**SUMMARY AND DISCUSSION**

This paper summarized the limited evidence on the effect of wet and rainy conditions on signalized intersection capacity which suggests that wet conditions reduce saturation flow by 5% to 6%. This small reduction in capacity may become critical under congested conditions.

Based on this evidence, a saturation flow reduction factor, $f_{wet} = 0.95$, was added to the HCM2000 formula for the estimation of wet conditions. A methodology was presented for the derivation of the probability of rainfall ($P_{wet}$) at any intersection in a state or metropolitan area 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 proportion of prevailing dry and wet conditions at any given intersection.

Much additional research is required for establishing reliable national or regional values for the $f_{wet}$ factor prior to a potential future inclusion into the HCM procedure for analysis of signalized intersections. Notably, the HCM already includes some accommodation for inclement weather conditions by explicitly lowering free flow speeds used in LOS determination for freeways – Chapter 22.

A more comprehensive factor, $f_{envir}$, the environmental conditions adjustment factor, may be contemplated. This factor may account for a number of environment-related impedances to the discharging process of vehicular traffic including pavement status (wet or dry), rainfall intensity, rainfall duration, day of week (i.e., regular work day, weekend day, holiday), wind speed, wind direction (parallel or perpendicular to roadway), other forms of precipitation, and the presence of fog or nightfall, for a comprehensive assessment of non-ideal conditions.

A substantial effort would be required in order to overlay rainfall (or other precipitation) probability contours onto statewide street networks. All the required components for doing so are available (i.e., GIS applications, reliable street maps and rainfall data from NOAA.) Some difficulties due to missing or inadequate geographic or weather-related data are likely for some areas, but such difficulties are less likely for the country’s large metropolitan areas where a weather-related correction (and its concomitant capacity loss) is more critical in traffic operations assessments.

**REFERENCES**


FIGURE 1  A 5% capacity loss due to wet conditions has a major effect on delay and LOS when volume approaches capacity.
FIGURE 2  Sample rainfall contour generation for Oahu County with WorldClimate.com data (February 2002) – contours shown is monthly rainfall in inches $\times 10$. 
FIGURE 3  Rainfall accumulation data in 15-minute (top) and hourly intervals (bottom) are available from NOAA for all states for several years.
FIGURE 4  Methodology for incorporating the effect of wet conditions into the HCM2000 procedure for signalized intersection analysis.
FIGURE 5  Sample morning peak period rainfall probability ($P_{\text{we,AM}}$) contour generation for Oahu County with NOAA 15-minute interval data (February 2002).
### TABLE 1 Sample capacity analysis without and with $f_{\text{WET}}$

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<th>Approach</th>
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<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
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<th>%Slope</th>
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<tr>
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<tr>
<td>8</td>
<td>TH+RT+LT</td>
<td>1473</td>
<td>60.5</td>
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<td>64.9</td>
<td>E</td>
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</tbody>
</table>

**Note:** Delay and LOS values are indicated by letters (A, B, C, D, E) with associated colors for clearer distinction.