Synthesis of the Effects of Wet Conditions on Highway Speed and Capacity

Panos D. Prevedouros, Ph.D.
Associate Professor of Civil Engineering
Department of Civil Engineering, University of Hawaii at Manoa
2540 Dole Street, 383, Honolulu, HI 96822
Telephone: (808) 956-9698
Fax: (808) 956-5014
E-mail: pdp@hawaii.edu

and

Piyalerg Kongsil, MSCE
Ph.D. Candidate

Honolulu, Hawaii
July 21, 2003
ABSTRACT

Wet and rainy conditions impact driver, vehicle, and roadway. These effects cause a reduction in speed or density (car-following headway) or both which, in turn, cause a reduction in highway capacity. This paper is a synthesis of 26 studies relating wet conditions to speed and capacity.

If the results from all reviewed studies after 1980 with original data from freeways are averaged assuming equal weights, then, the average speed reduction is 4.7 mph in light rain (11 studies) – HCM2000 suggests 6.0 mph which is similar to FHWA’s 10% reduction – and 19.6 mph in heavy rain (2 studies) – HCM2000 suggests 12.0 mph which is higher than FHWA’s 16% reduction. The average capacity reduction is 8.4% in light rain (7 studies) and 20.0% in heavy rain (1 study).

The impact of rainy conditions on highway capacity is important. Much additional research is needed for reducing the wide variance of observations in past studies. A methodology is needed for capacity and LOS analysis of freeways, intersections and arterials that accounts for wet conditions as part of typical conditions.
INTRODUCTION

Unlike most civil engineering designs that typically consider the worst possible conditions and often add a safety factor, highway traffic analysis is conservative by focusing on the peak periods and applying the peak hour factor which typically inflates hourly volumes, but the analysis is based on clear weather, dry pavements and daytime conditions. However, in most metropolitan areas, rain and other precipitation is common and darkness prevails during peak periods in northern cities in winter months. Furthermore, incidents, road works and the presence of police usually reduce capacity or speed or both. As a result, the assessment of both prevailing level-of-service (LOS) and traffic impacts of future traffic generators may be considerably inaccurate because long-term average conditions are ignored.

Incidents, road works and police presence may be infrequent and random, but the presence of rain and darkness is not. Kleitsch and Cleveland (1) emphasized that the significance of the 8% measured capacity reduction in rain on a Detroit freeway is “increased by the fact that at least one time in ten it will rain with enough intensity in Detroit to significantly reduce freeway capacity during one, or both of the peak periods.”

There is scant evidence on the effect of nightfall and darkness on highway capacity, but there is a modest amount of evidence from research on the effects of wet conditions on highway capacity. 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 (longer queues and travel times). Some of this maybe due to mode switching from fair weather modes such as bicycling and walking to motor vehicles, but the share of these modes for commuter trips in large metropolitan areas is minuscule.

The 2000 edition of the Highway Capacity Manual (2) states that “base conditions assume good weather, good pavement conditions, users familiar with the facility, and no impediments to traffic flow.” For freeways, HCM2000 specifies that “the base conditions under which the full capacity of a basic freeway segment is achieved are good weather, good visibility, and no incidents or accidents”. Only in Chapter 22 – Freeway Facilities there is a brief accounting for the effect of inclement weather in the form of speed-flow curves for different weather conditions. HCM2000 suggests that free-flow speed (FFS) is reduced by 10 km/h (6 mph) in light rain, and by 19 km/h (12 mph) in heavy rain. The capacity reduction in wet and rainy conditions is not mentioned.

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. This paper presents a comprehensive synthesis of findings relating to the effects of wet and rainy conditions on highway capacity, including preliminary results of an on-going study by the authors of this paper. The paper concludes with a summary of findings recommendations for improvement.

EXPECTED EFFECTS OF RAIN ON PREVAILING CONDITIONS

Light intensity, rain, fog, ice, and snow are significant for highway capacity (3). The main impedance factors due to rain are (4,5,6):

- The presence of a water film on the surface of the pavement.
- Reduced visibility and light scattering.
- Rain drops, spray and road grime on vehicle windscreens.
Rain affects roadways, vehicles and drivers. The main effects of rain on roadways are the reduction of friction between tire tread and road surface, and the reduction of pavement skid resistance. Water film thickness can vary from damp or visibly wet to a depth of several millimeters. Reduction of pavement skid resistance is a combined result of factors such as the thickness of water film on the surface, pavement texture, tire tread depth and composition, and vehicle speed. When a critical thickness of water film is exceeded, aquaplaning may occur and tire-road friction is lost. In general, rain decreases vehicle stability and maneuverability (6).

The windscreen and windows of vehicles during rain are covered by raindrops which lead to poor visibility. Moreover, splash and spray from other vehicles worsen visibility problems by adding a film of dirt. Rain drop diameter and concentration correlate with rainfall intensity. Visibility is reduced with increasing rain drop diameter, and intensity of precipitation which may be expressed in terms of volume of water per unit area per unit time, e.g., in cm³/sec (7). Visibility reduction is mostly attributable to (4):

- The combined effect of a screen of rain and light causes bright and scattering light affecting the visual perception of drivers.
- The drops and windscreen glass create unbalanced lenses reflecting light into driver eyes. The surface of drops also scatters light.

The problem of visibility reduction is more severe when rain occurs at night (4). The overall effect of rain on drivers is poor visibility and object recognition. Drivers may try to maintain longer distances between vehicles and drive at slower speeds to account for the longer perception/reaction time and stopping distance during rain.

The result of the aforementioned effects of rain on roadway, vehicle and driver performance is a change of the fundamental speed–flow–density relationship as shown in Figure 1: Drivers may decrease their speed to ensure that they can stop safely if needed and/or lengthen their car-following headway because stopping distances on wet pavement are longer due to reduced friction.

**CHRONOLOGICAL REVIEW OF RELEVANT STUDIES**

This section presents a chronological summary of previous studies on the effects of wet pavement and rainy conditions on capacity. The basic characteristics of the studies reviewed herein are summarized in Table 1.

Stohner (8) conducted a study for the New York State Department of Public Works on speeds of passenger cars on wet and dry pavements in New York, in the spring of 1954. Five locations in rural highways free of intersections and with minimum interference from roadside development were selected. There were four sites on two-lane roads and one site on a four-lane divided road. Two of the two-lane sites had blacktop pavements and the other three sites had whitetop pavements. To minimize the effect of grades on speed, each selected location had a horizontal curve with reasonably long and approximately level grade tangents. The degree of the curves varied from 2.5 to 9 degrees.

The study focused on passenger cars, only. The data collection time depended on the presence of wet and rainy conditions. The free flow speeds (FFS) of passenger cars were measured. To prevent the effects of interaction between vehicles in the traffic stream, vehicles following at a 9-second headway or shorter were excluded from the data. Rainfall intensity varied from 2.8 to 67.3 mm (0.11 to 2.65 in) of rain during data collection periods that varied
from 1½ to 4 hours. Rainfall intensity is mentioned to cause no visibility difficulties to the drivers.

The average speed of passenger cars on wet and dry conditions were not significantly different (8). The maximum drop of the average speed in wet conditions at tangent and curve locations were 4.44 km/h (2.76 mph) and 2.96 km/h (1.84 mph), respectively. In two of the five sites the average speed during wet condition was higher than in dry conditions.

Jones et al. (3) conducted a study for the Texas Highway Department published in 1970 to evaluate the effect of rain on freeway capacity. The study was conducted on a three-lane section of Gulf Freeway (I-45) near central Houston. The selected freeway section had a fully operational freeway control system and automatic detection system connected to a computer for data acquisition. Two subsections with bottlenecks which had historical maximum flows that exceed capacity were selected. Morning and afternoon peak period traffic flow data were collected from detectors and converted into 5-minute traffic flow and density measurements.

Rainfall records were obtained from two stations. Rainfall intensity was not collected because the rainfall rate could vary throughout the length of the 6.6 km (3.5 miles) portion of freeway and throughout the 2-hour peaks. Instead, each day was classified as either “dry” or “rain.” Most of the recorded rainfall was about 0.02 in. (0.51 mm) or more during wet conditions. Flow and speed models were developed:

\[
q = 89.02 \times k \times (1 - (k/319.96)^{0.7}) \quad (1)
\]

\[
u = 89.02 \times (1 - (k/319.96)^{0.7}) \quad (2)
\]

where,

- \( q \) = flow in vph
- \( u \) = speed in mph
- \( k \) = density in vpm

The mean capacities during dry conditions for this three-lane freeway section varied between 5,570 and 5,845 vph. The results showed that rain reduced freeway capacity by 14% to 19%, with 95% statistical confidence.

Kleitsch and Cleveland (1) reported in 1971 a capacity decrease of 8% during rain and observed that the degree of impact was directly related to rainfall intensity. They asserted that the pioneer ramp metering application on the Lodge Freeway had an effect because a nearly contemporaneous study in Houston (3) had observed almost twice as high a capacity reduction.

Maeki’s article in *Tielehti* (in Finnish, 1972 – cited in Edwards 1999) presents results from a speed study in inclement weather in Finland. About 30% of the total of 11,500 speed data were obtained by radar guns (spot speed) and the rest were collected by license plate surveys (average travel speeds). Observations included weather conditions, pavement conditions and type of pavement including unfinished oil gravel and gravel roads which were common in Finland. Speeds on wet pavements dropped by about 4% in light volume traffic and 2% in heavy volume traffic on hard-surface roadways.

A 1977 FHWA report (10) presents the economic impacts of inclement weather on each type of facility. Recommended speed reductions were as follows: dry 0%, wet 0%, wet and snowing 13%, wet and slushy 22%, slushy in wheel paths 30%, snowy and sticking 35%, snowing and packed 42%.
Reis’ 1981 report to the Minnesota DOT (cited in HCM1985 (11)) presents a study on a three-lane section with bottlenecks on I-35W freeway in Minneapolis. Peak demand on the studied section usually exceeds capacity. Rainfall intensity was accounted for. Rain significantly reduced freeway capacity and the impact of rain on capacity depended on the degree of rainfall intensity. A trace amount of precipitation reduced capacity by 8% and capacity was decreased by 0.6% for each additional 0.25 mm/hr (0.01 in) per hour of rain. Under snow conditions, capacity decreased by 8% in trace conditions, and 2.8% for each additional 0.01 inches per hour (0.25 mm/hr).

Galin (12) investigated several factors in the late 1970s that could affect speeds on Australian two-lane rural roads by multiple regression analysis. Analysis of speeds was performed by considering two weather conditions: dry and wet pavement. Wet conditions caused a drop on the average travel speeds of about 7 km/h (4.35 mph). However, Edwards (9) argued that this result may be of limited significance because base conditions were not clearly defined and the number of observed data was small (27 to 72 vehicles.)

Olson’s et al. (13) study published in 1984 investigated the differences between speed distributions on wet and dry pavements in daytime. The study locations were a set of 26 permanent speed-monitoring stations, which included 7 interstate highways, 15 rural arterials, and 4 rural collectors in Illinois. Speed data in days with rain and adjacent dry days were analyzed. The analysis accounted for time-of-day effects. Although several dates with high probability of rain over a large portion of Illinois were collected, information about rainfall intensity was not quantified. Days were classified as “dry” or “rain.” The mean speed, speed at various percentiles, and standard deviation were estimated. The Kolmogorov-Smirnov test was used to investigate differences between wet and dry day speed distributions. No differences among the daily speed distribution on dry and rainy days that were significant at a 95% confidence level were found.

Hall and Barrow (14) reported in 1988 about relationships between flow rates and roadway occupancies in inclement weather for use in automatic incident detection. The study was conducted on a 10 km section of the Queen Elizabeth Way near Hamilton, Ontario. To control for the effect of grades, traffic data were collected from two data collection stations on relatively level sections. Days with a rainfall duration of 8 hours or longer were selected for analysis. Weather data was obtained from the Hamilton Airport weather station, but rainfall intensity was not modeled. Days were classified as either “adverse weather day” or “clear weather day.” Adverse weather days included days with prolonged periods of rain. Data from congested conditions were removed from the analysis. Regression models were estimated:

\[
\ln(\text{flow}) = 5.385 + 0.8137\times \ln(\text{occ}) \quad \text{“clear weather day”} \quad (3)
\]

\[
\ln(\text{flow}) = 5.352 + 0.7969\times \ln(\text{occ}) \quad \text{“adverse weather day”} \quad (4)
\]

where,
\[
\text{flow} = \text{flow rate in vph}
\text{occ} = \text{occupancy in %}
\]

The models indicate that in heavy flow conditions and for an occupancy of 27%, maximum flow dropped by about 270 vph or 8.5% below the clear weather day maximum.
Hawkins (15) reported in 1988 about the relationship of vehicle speeds and weather conditions on UK’s M1 motorway in Nottinghamshire. Weather conditions were classified into nine conditions with clear visibility and dry pavement as the base. Speed began to drop when visibility was reduced to about 300 m (984 ft), with all lanes showing a reduction of between 25% and 30% as visibility reached 100 m (328 ft). Both light and steady or heavy rain were reported to cause a speed reduction of about 4 km/h (2.5 mph) on the slow and center lanes and about 6 km/h (3.7 mph) on the fast lane. Greater impacts on speeds were reported as a result of strong head wind – speed reduction up to 13 km/h (8.1 mph) – and, snow or slush – speed reduction of 30 km/h to 40 km/h (18.6 mph to 24.9 mph).

Lamm et al. (16) reported in 1990 about the effects of design parameters, traffic volume, and wet pavements on free flow speeds of passenger cars on curved sections of two-lane rural highways. The selected sites were 24 curved roadway sections of two-lane rural highways in New York state, which were free of intersections and with minimal interference from roadside development. To minimize the effect of grades on operating speeds of cars, each curved site had approximate horizontal curve of 0 to 27 degrees with reasonably long tangents. Other site selection requirements included segments that have paved shoulders, no changes in pavement and shoulder widths, protected by guardrails when the height of the embankment exceeded 1.5, grade $\leq 5\%$, $400 \leq \text{ADDT} \leq 5,000$ veh/day and no potentially hazardous physical features such as narrow bridges.

The speed of isolated vehicles with minimum time spacing between them of about 6 seconds, or those heading a platoon of vehicles, was measured. Rainfall intensity varied from a sprinkle to moderately heavy rain. Observed rainfall was never intense enough to affect driver visibility. The degree of curve was found to affect speed as follows (16):

$$V_{85} = 58.656 - 1.135 \times \text{DC} \quad (5)$$

where,

- $V_{85}$ = 85th percentile of sampled speeds in mph
- DC = degree of curve (range $0^\circ$–$27^\circ$)

Kolmogorov-Smirnov tests showed that the operating speeds of cars on dry and wet pavements were not statistically different. Also, drivers did not significantly decrease their speed to account for curvatures in wet conditions.

Ibrahim and Hall (17) reported in 1994 about freeway operations under adverse weather conditions on a section of the Queen Elizabeth Way in Mississauga, Ontario. Three capacity parameters, volume, occupancy and speed, were collected continuously at 30-sec. intervals. Two sites with measured speeds and flow data, and unrestrained from ramp or weaving sections, were selected for analysis. Uncongested traffic data from 10 AM to 4 PM were used. The type and intensity of precipitation were accounted for. Weather conditions were categorized into six types: clear, light rain, heavy rain, light snow, heavy snow, and snowstorms. The intensity of rainfall was indicated by accumulation on rain gauges. The intensity of snow was measured based on visibility criteria.

Both flow-occupancy and speed-flow relationship were affected by weather conditions. The degree of the effect corresponded to the severity of weather conditions. Light rain caused minimal effects on both relationships. Light rain caused a drop in speed of less than 2 km/h (1.2 mph). Heavy rain caused serious such as a speed reduction varying from 5 to 10 km/h (3.1 mph.
Maximum flows were estimated to decrease by about 10% to 20% during heavy rain conditions.

Brilon and Ponzlet (18) reported in 1996 on a study of fluctuations of average speeds from 15 stations on German autobahns. Ten 4-lane (two lane per direction) sections and five 6-lane sections were monitored continuously between 1991 and 1993. Weather data were obtained from meteorological stations located about 5 to 50 km (3 to 31 miles) away from each observed area. Although, there were not perfect sources of weather data, they provided sufficient information to classify the weather conditions into five categories: dry, wet, dry or wet, somewhat snowy, and snow and ice.

The influence of several independent factors was examined with ANOVA and several comprehensive models were developed that accounted for year, month, type of day (weekday, Saturday, day before holiday, and holiday), location, daylight and darkness, traffic density, percentage of heavy vehicles, and weather in five categories as defined above.

Wet roadway conditions caused a speed reduction of about 9.5 km/h (5.9 mph) on 2-lane freeways, and about 12 km/h (7.46 mph) on 3-lane freeways (18). It was estimated that freeway capacity dropped by about 350 vph on 2-lane freeways, and more than 500 vph on 3-lane freeways. Speed reduction was greater in darkness. Average speed dropped by about 5 km/h (3.1 mph) in darkness. Capacity reduction due to darkness on 2- and 3-lane freeways was estimated at 200 and 375 vph, respectively.

Hogema (19) reported in 1996 that rain caused a mean speed reduction of about 11 km/h (6.8 mph) on Dutch freeways, with the greatest impact observed on the fast lane which was the lane with the lowest traffic volume. Edwards (9) pointed out that weather data were obtained considerably far from the study site, the observed vehicles were not separated according to type, and lighting conditions was not a factor in the analysis.

Kockelman (20) reported in 1998 about her investigation that weather conditions, driver, and vehicle population characteristics affect the flow-density relationship of a homogeneous roadway segment. Data were obtained from the Freeway Service Patrol Project from paired loop detectors on a 5-lane section of I-880 in Hayward, California. Lane 2 (second from the median) was selected to avoid merging effects from upstream and downstream ramps (lane 1 is an HOV lane). Lane 2 was the most heavily used with high speeds; 50% of speeds were over 100 km/h (62 mph). Weather data was obtained from a variety of sources such as newspaper reports and NOAA reports. Rainfall intensity was not considered; days were either “rainy” or “dry”. Kockelman concluded that rain could have a statistically significant influence on the flow-density relationship. Factors such as roadway users and type of vehicles could also be important.

Holdener (21) reported in 1998 about the effect of rainfall on freeway speed and capacity using data from U.S. 290 freeway in Houston, Texas. Rainfall had a significant impact on speeds. Wet conditions caused a drop in speed from 0.2 to 37.9 km/h (0.12 to 23.6 mph) with an average speed drop of 13.9 km/h (8.6 mph) when traffic volume was at or near capacity during the afternoon peak period. A speed drop of 10.7 to 16.3 km/h (6.7 to 10.1 mph) with an average speed drop of 13.1 km/h (8.1 mph) occurred when the volume was low, during midday. Wet conditions were estimated to cause a capacity reduction of about 8% to 24%.

In 1998, May (cited in 25,27) synthesized the effects of adverse weather conditions on freeway capacity based on previous work in (17) and (18). May’s FFS recommendations for HCM2000 were as follows:
<table>
<thead>
<tr>
<th>Condition</th>
<th>FFS (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear and dry</td>
<td>120</td>
</tr>
<tr>
<td>Light rain and light snow</td>
<td>110</td>
</tr>
<tr>
<td>Heavy rain</td>
<td>100</td>
</tr>
<tr>
<td>Heavy snow</td>
<td>70</td>
</tr>
</tbody>
</table>

Edwards (9) reported in 1981 about her investigations of driver behavior in three weather conditions: dry, rainy and foggy. Traffic data were collected from a 2-lane section on motorway M4 in Cardiff, UK. Data were recorded by an automated traffic counter at the site. To decrease the visual discouragement effect, spot speed data were obtained by a mobile radar speed gun from an overhead survey spot. Weather data were manually recorded by the observer who collected the speed data. Weather conditions were categorized into sunny (clear), dull (overcast, cloudy), steady/heavy rain, drizzle (road surface spray), and misty (fog). Both mean and 85th percentile speeds were investigated. The results suggest that drivers decreased their speeds during rain. This finding was statistically significant but speed reduction was small at about 4.8 km/h (3 mph). Speed variation in rain was lower than in dry conditions, that is, drivers maintained more stable and lower vehicle speeds in rainy conditions.

Martin et al. (22,23) reported in 2000 about arterial street operations inclement weather 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 over winter 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 are the main reasons for the reduction in saturation flow.

In 2000, Zuylen (24) quoted “a recent Dutch capacity manual for motorways” in which capacity is reduced by 5% in darkness, by 9% in rainy conditions on regular porosity pavements and by 6% on porous pavements that offer better water drainage.

Kyte et al. (25) measured prevailing free flow speed during good conditions and in rain, snow, fog, low visibility, and high wind conditions. Data were collected between 1996 and 2000 from a level grade 4-lane section of I-84. Volumes were usually below 500 vphpl. Count and speed by lane, time, and length of vehicle data were obtained. Weather and visibility sensors were located in the same area to measure wind speed, direction, air temperature, relative humidity, roadway surface condition, the type and amount of precipitation, and visibility. The developed speed model includes several weather factors (25):

\[
\text{speed} = 100.2 - 16.4 \times \text{snow} - 9.5 \times \text{wet} + 77.3 \times \text{vis} - 11.7 \times \text{wind}
\]

where,

\[
\begin{align*}
\text{speed} &= \text{passenger-car speed in km/h} \\
\text{snow} &= \text{variable indicating presence of snow on roadway} \\
\text{wet} &= \text{variable indicating that pavement is wet}
\end{align*}
\]
vis = visibility, equal to 0.28 km (919 ft) when visibility ≥ 0.28 km
and actual value of visibility when visibility < 0.28 km
wind = variable indicating that wind speed exceeds 24 km/h (15 mph)

Speed decreased by 9.5 km/h (5.9 mph) when the pavement was wet. Speed decreased by 11.7 km/h (7.3 mph) when wind speed exceeded 24 km/h (15 mph). Speed decreased by 0.77 km/h (0.48 mph) for every 0.01 km (33 ft) below the critical visibility of 0.28 km.

Venugopal and Tarko (26) reported in 2001 about potential capacity reduction factors such as rain and wind, heavy vehicles, type of lane drop, police presence, and presence of a novel traffic control system called Indiana Lane Merge System (ILMS) for work zones on rural freeways where some lanes were temporarily closed. Traffic data were collected from work zones on two-lane rural sections of I-65 near Lafayette, Indiana. Data included traffic volume, percentage of heavy vehicles, presence of ILMS, presence of rain, wind speed, type of lane drop, and presence of police. The average volume at the studied location was about 1320 vphln. The source of weather data of rain and wind were from the Earth and Atmospheric Sciences Department at Purdue University. The weather station was about 5 miles away from the study location. Rainfall intensity was not an observed factor. Analysis of covariance indicated that only four factors, ILMS, rain, police, and heavy vehicles were important. The estimated capacity model shown below revealed a capacity reduction of about 140 vph (or 10%):

\[ C = 1433 - 76M - 140R - 196P - 4.04H \]  
(7)

where,
- \( C \) = capacity of the work zone expressed in vph
- \( M \) = indicator variable for ILMS
- \( R \) = indicator variable for rain
- \( P \) = indicator variable for police presence
- \( H \) = percentage of heavy vehicles in the traffic stream

Kyte, et al. (27) reported in 2001 on the effects of weather-related factors such as visibility, road surface condition, precipitation, and wind speed on free-flow speeds. Data were collected during two winter periods, 1997-1998 and 1998-1999, as part of an ITS field operation test of a storm warning system, located on an isolated section on I-84 in southeastern Idaho. Sensors were installed to obtain traffic, visibility, roadway, and weather data. Normal conditions included no precipitation, dry roadway, visibility greater than 0.37 km (0.23 mile), and wind speed of less than 16 km/h (9.94 mph). The average speed for passenger cars was 117.1 km/h (72.8 mph) and average truck speed was 98.8 km/h (61.4 mph). The mean speed for all vehicles was 109.0 km/h (67.7 mph). The average 5-minute flow rate at the observed site was 269 vph with 52% truck volume.

Light rain caused a drop in speed between 14.1 and 19.5 km/h (8.8 to 12.1 mph). Heavy rain caused a drop in speed of about 31.6 km/h (19.6 mph). The best-fit model included three variables: wind speed, precipitation intensity, and pavement conditions (27):

\[ \text{speed} = 126.53 - 9.03 \times \text{WS} - 5.43 \times \text{PC} - 8.74 \times \text{R} \]  
(8)

where,
speed = prevailing average vehicle speed in km/h
WS = wind speed in two levels, WS ≤ 48 km/h, WS ≥ 48 km/h
PC = pavement condition with three levels, 1=dry, 2=wet, 3=snow/ice
R = rain intensity with 4 levels, 1=none, 2=light, 3=medium, 4=heavy

FHWA’s Weather Management web site (28) contains comprehensive summaries of the effect of weather on traffic systems but sources for the information are not cited. The site reports that 22% of injury crashes and 18% of fatal crashes between 1995 and 1999 occurred in adverse weather. In addition it reports the following impacts:

a) Freeways: Light rain reduces speed by roughly 10%, decreasing capacity by approximately 4%.

b) Freeways: Heavy rain decreases speed by about 16%, lowering capacity by roughly 8%.

c) Arterials: Rain reduces speed by 10% and capacity by 6%.

Chin et al. (29) reported in 2002 on an assessment of the aggregate effects of various non-recurrent capacity losses. They found that inclement weather accounted for 23.5% of total delay and 23.3% of delay per driver due to capacity losses from crashes, breakdowns, work zones, adverse weather and suboptimal signalization. Only icy, fog and snow conditions were considered because based on their review of (16,17,18) rain does not impede traffic flows substantially. This conclusion is incompatible with most of the conclusions of studies reviewed herein.

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 exhibits major congestion issues during peak periods. Average headways were measured for traffic platoons ranging in size between 6 and 61 vehicles (average platoon size is 12). 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 where on 6-lane class I arterials and 1,181 where 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. The results from pair-wise t-tests are as follows:

<table>
<thead>
<tr>
<th>All observations</th>
<th>Freeway</th>
<th>Arterial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h</td>
<td>sig.</td>
</tr>
<tr>
<td>Dry</td>
<td>1.50</td>
<td>95%</td>
</tr>
<tr>
<td>Rain</td>
<td>1.62</td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>1.50</td>
<td>95%</td>
</tr>
<tr>
<td>Wet</td>
<td>1.68</td>
<td></td>
</tr>
</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. Although these reductions are modest, they may cause a substantial deterioration in the level of service in peak periods.
Separate models were estimated for freeways and arterials, as follows (all parameters are significant at the 95% level):

\[
h = 1.411 + 0.052 \, G + 0.056 \, R + 0.448 \, W \quad \text{(arterials, } R^2=0.30) \tag{9}
\]
\[
h = 1.504 + 0.062 \, R - 0.034 \, LT \quad \text{(freeway, } R^2=0.10) \tag{10}
\]

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
- \( LT \) = freeway left lane

**SUMMARY AND DISCUSSION**

A total of 26 studies relating to impacts of rain and wet conditions on highway capacity and operations were reviewed. Table 2 summarizes the results of speed reduction due to inclement weather. If the results from all primary studies after 1980 that are focused on freeways are averaged assuming equal weights, then, the results of speed reduction are as follows:

- **7.6 km/h or 4.7 mph in light rain (\( N=11 \))** – HCM2000 suggests 6.0 mph which is similar to FHWA’s 10% reduction (6 mph is 10% of a 60 mph average freeway speed in dry conditions).
- **31.6 km/h or 19.6 mph in heavy rain (\( N=2 \))** – HCM2000 suggests 12.0 mph which is higher than FHWA’s 16% reduction.

\( N \) is the number of primary studies, that is, studies with original data.

Similarly, Table 3 summarizes the results of capacity reduction due to inclement weather. If the results from all primary studies after 1980 that are focused on freeways are averaged assuming equal weights, then the results of capacity reduction are as follows:

- **8.4% in light rain (\( N=7 \))**.
- **20.0% in heavy rain (\( N=1 \))**.

It can be concluded, therefore, that Exhibit 22-7 in HCM2000 roughly approximates averages from several studies in terms of speed reduction under free flow conditions. However, capacity reduction averages from seven studies indicate that 5% to 10% of capacity may be lost under light rain and wet conditions, which can cause a major reduction in the level-of-service under congested conditions. A methodology for addressing effects of wet and rainy weather on signalized intersection capacity analysis is presented in a separate paper (30). The proposed procedure is a waited average of conditions with and without rainfall based on probabilities derived from readily available meteorological data for most counties in the U.S. The same methodology can be applied to the analysis of freeways.

The impact of rainy conditions on highway capacity is important. Additional research is needed for reducing the wide variance of observations in past studies and for developing accurate
adjustment factors and modifications to the HCM procedure for accounting for the presence of wet conditions as part of typical conditions. Specifically,

- HCM2000, Chapter 22 on Freeways: treatment of inclement weather is based on an adjustment of fundamental relationships based on limited empirical evidence gathered under free flow conditions. This needs to be upgraded by researching the entire q-u-k relationship along a wide range of prevailing values for various facilities, primarily in U.S. urban areas.
- In general, information on the effects of rain on arterials and signalized intersections is limited.
- A methodology is needed for capacity and LOS analysis of freeways, intersections and arterials that accounts for wet conditions as part of typical conditions (e.g., long term probability of rainfall in peak periods.)

REFERENCES


FIGURE 1 Conceptual reduction in flow, speed and density due to wet conditions. (Data shown are for illustration purposes only.)
<table>
<thead>
<tr>
<th>Authors</th>
<th>Year of Publication</th>
<th>Location</th>
<th>Type of Facility</th>
<th>Measured Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stohner</td>
<td>1956</td>
<td>New York, U.S.</td>
<td>Two and Four-Lane Rural Highway</td>
<td>✓</td>
</tr>
<tr>
<td>Jones, Goolsby, and Brewer</td>
<td>1970</td>
<td>Texas, U.S.</td>
<td>Freeway</td>
<td>-</td>
</tr>
<tr>
<td>Kleitsch and Cleveland</td>
<td>1971</td>
<td>U.S.</td>
<td>not known</td>
<td>-</td>
</tr>
<tr>
<td>Maeki</td>
<td>1972</td>
<td>Finland</td>
<td>not known</td>
<td>✓</td>
</tr>
<tr>
<td>FHWA</td>
<td>1977</td>
<td>U.S.</td>
<td>not known</td>
<td>✓</td>
</tr>
<tr>
<td>Reis</td>
<td>1981</td>
<td>U.S.</td>
<td>Freeway</td>
<td>-</td>
</tr>
<tr>
<td>Galin</td>
<td>1981</td>
<td>Australia</td>
<td>Two-lane rural highway</td>
<td>✓</td>
</tr>
<tr>
<td>Olson, Cleveland, Fancher and Kostyniuk</td>
<td>1984</td>
<td>Illinois, U.S.</td>
<td>Interstate highway, Arterial, Collector</td>
<td>✓</td>
</tr>
<tr>
<td>Hall and Barrow</td>
<td>1988</td>
<td>Ontario, Canada</td>
<td>Freeway</td>
<td>-</td>
</tr>
<tr>
<td>Hawkins</td>
<td>1988</td>
<td>U.K.</td>
<td>Freeway</td>
<td>✓</td>
</tr>
<tr>
<td>Lamm, Choueiri, and Mailaender</td>
<td>1990</td>
<td>New York, U.S.</td>
<td>Two-lane rural highway</td>
<td>✓</td>
</tr>
<tr>
<td>Ibrahim and Hall</td>
<td>1994</td>
<td>Ontario, Canada</td>
<td>Freeway</td>
<td>✓</td>
</tr>
<tr>
<td>Brilon and Ponzlet</td>
<td>1996</td>
<td>Germany</td>
<td>Freeway</td>
<td>✓</td>
</tr>
<tr>
<td>Hogema</td>
<td>1996</td>
<td>The Netherlands</td>
<td>Freeway</td>
<td>✓</td>
</tr>
<tr>
<td>Kockelman</td>
<td>1998</td>
<td>California, U.S.</td>
<td>Interstate highway</td>
<td>✓</td>
</tr>
<tr>
<td>Holdener</td>
<td>1998</td>
<td>Texas, U.S.</td>
<td>Freeway</td>
<td>✓</td>
</tr>
<tr>
<td>May</td>
<td>1998</td>
<td>U.S.</td>
<td>not known</td>
<td>✓</td>
</tr>
<tr>
<td>Edwards</td>
<td>1999</td>
<td>Great Britain</td>
<td>Freeway</td>
<td>✓</td>
</tr>
<tr>
<td>Martin, Perrin, Hansen, and Quintana</td>
<td>2000</td>
<td>Utah, U.S.</td>
<td>Corridors w/ 2 intersections</td>
<td>✓</td>
</tr>
<tr>
<td>Zuylen</td>
<td>2000</td>
<td>The Netherlands</td>
<td>Motorways</td>
<td>✓</td>
</tr>
<tr>
<td>HCM 2000</td>
<td>2000</td>
<td>U.S.</td>
<td>Freeway</td>
<td>✓</td>
</tr>
<tr>
<td>Kyte, Khatib, Shanon, and Kitchener</td>
<td>2001</td>
<td>Idaho, U.S.</td>
<td>Freeway</td>
<td>✓</td>
</tr>
<tr>
<td>Venugopal and Tarko</td>
<td>2001</td>
<td>Indiana, U.S.</td>
<td>Two-lane rural highway work zone</td>
<td>✓</td>
</tr>
<tr>
<td>Kyte, Khatib, Shanon, and Kitchener</td>
<td>2001</td>
<td>Idaho, U.S.</td>
<td>Freeway</td>
<td>✓</td>
</tr>
<tr>
<td>Prevedouros</td>
<td>2003</td>
<td>Hawaii, U.S.</td>
<td>Freeways and Class I Arterials</td>
<td>✓</td>
</tr>
</tbody>
</table>
### TABLE 2. SPEED REDUCTION DUE TO INCLEMENT WEATHER

<table>
<thead>
<tr>
<th>Authors, Year of Publication</th>
<th>Location</th>
<th>Type of Facility</th>
<th>Speed Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stohner 1956</td>
<td>New York, U.S.</td>
<td>Two and Four-Lane Rural Highway</td>
<td>none in wet and light to moderate rain</td>
</tr>
<tr>
<td>Maeki 1972</td>
<td>Finland</td>
<td>not known</td>
<td>4% for low traffic volume, and 2% for high traffic volume</td>
</tr>
<tr>
<td>FHWA 1977</td>
<td>U.S.</td>
<td>not known</td>
<td>none with wet pavement conditions</td>
</tr>
<tr>
<td>Galin 1981</td>
<td>Australia</td>
<td>Two-lane rural highway</td>
<td>7 km/h (4.4 mph)</td>
</tr>
<tr>
<td>Olson, Cleveland, Fancher, and Kostyniuk 1984</td>
<td>Illinois, U.S.</td>
<td>Interstate highway, Arterial, Collector</td>
<td>none in wet and light rain</td>
</tr>
<tr>
<td>Hawkins 1988</td>
<td>U.K.</td>
<td>Freeway</td>
<td>from 4 km/h (2.5 mph) on slow lane to 6 km/h on fast lane</td>
</tr>
<tr>
<td>Lamm, Choueiri, and Mailaender 1990</td>
<td>New York, U.S.</td>
<td>Two-lane rural highway</td>
<td>none in light rain</td>
</tr>
<tr>
<td>Ibrahim and Hall 1994</td>
<td>Ontario, Canada</td>
<td>Freeway</td>
<td>varied from 13 km/h (8.1 mph) in light rain to 6-21 km/h (9.9 - 19.6 mph) in heavy rain</td>
</tr>
<tr>
<td>Brilon and Ponzlet 1996</td>
<td>Germany</td>
<td>Freeway</td>
<td>varied from 9.5 km/h (5.9 mph) on 2-lane freeway to 11 km/h (6.8 mph) on 3-lane freeway</td>
</tr>
<tr>
<td>Hogema 1996</td>
<td>The Netherlands</td>
<td>Freeway</td>
<td>11 km/h (6.8 mph)</td>
</tr>
<tr>
<td>Kockelman 1998</td>
<td>California, U.S.</td>
<td>Interstate highway</td>
<td>not known</td>
</tr>
<tr>
<td>Holdener 1998</td>
<td>Texas, U.S.</td>
<td>Freeway</td>
<td>varied from 4.8 km/h (3 mph) in light traffic to 13.9 km/h (8.6 mph) at capacity</td>
</tr>
<tr>
<td>May 1998</td>
<td>U.S.</td>
<td>not known</td>
<td>varied from 10 km/h (6.2 mph) in light rain to 20 km/h (12.4 mph) in heavy rain</td>
</tr>
<tr>
<td>Edwards 1999</td>
<td>U.K.</td>
<td>Freeway</td>
<td>3 km/h (1.9 mph)</td>
</tr>
<tr>
<td>Martin, Perrin, Hansen, and Quintana 2000</td>
<td>Utah, U.S.</td>
<td>Corridors w/ 2 intersections</td>
<td>10%</td>
</tr>
<tr>
<td>HCM 2000</td>
<td>U.S.</td>
<td>Freeway</td>
<td>varied from 10 km/h (6.2 mph) in light rain to 20 km/h (12.4 mph) in heavy rain</td>
</tr>
<tr>
<td>Kyte, Khatib, Shanon, and Kitchener 2001</td>
<td>Idaho, U.S.</td>
<td>Freeway</td>
<td>9.5 km/h (5.9 mph), and 11.7 km/h (7.3 mph) with strong wind; larger reduction under poor visibility conditions</td>
</tr>
<tr>
<td>Perrin, Martin, and Hansen 2001</td>
<td>Utah, U.S.</td>
<td>Corridors w/ 2 intersections</td>
<td>10%</td>
</tr>
<tr>
<td>Kyte, Khatib, Shanon, and Kitchener 2001</td>
<td>Idaho, U.S.</td>
<td>Freeway</td>
<td>varied from 14.1 km/h (8.8 mph) in light rain to 31.6 km/h (19.6 mph) in heavy rain</td>
</tr>
</tbody>
</table>
### TABLE 3. CAPACITY REDUCTION DUE TO INCLEMENT WEATHER

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year of Publication</th>
<th>Location</th>
<th>Type of Facility</th>
<th>Capacity Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jones, Goolsby, and Brewer</td>
<td>1970</td>
<td>Texas, U.S.</td>
<td>Freeway</td>
<td>14%-19% on more than 0.02 in (0.51 mm) of rain</td>
</tr>
<tr>
<td>Kleitsch and Cleveland</td>
<td>1971</td>
<td>U.S.</td>
<td>not known</td>
<td>8% and strongly dependent on rainfall intensity</td>
</tr>
<tr>
<td>Reis</td>
<td>1981</td>
<td>Minnesota, U.S.</td>
<td>Freeway</td>
<td>8% and increasing by 0.6% for each 0.01 inch/hr (0.25 mm/hr) of rain</td>
</tr>
<tr>
<td>Hall and Barrow</td>
<td>1988</td>
<td>Ontario, Canada</td>
<td>Freeway</td>
<td>8.5% at 27% occupancy</td>
</tr>
<tr>
<td>Ibrahim and Hall</td>
<td>1994</td>
<td>Ontario, Canada</td>
<td>Freeway</td>
<td>10-20%</td>
</tr>
<tr>
<td>Brilon and Ponzlet</td>
<td>1996</td>
<td>Germany</td>
<td>Freeway</td>
<td>varied from 9.6% on 2-lane section to 9.1% on 3-lane section</td>
</tr>
<tr>
<td>Martin, Perrin, Hansen, and Quintana</td>
<td>2000</td>
<td>Utah, U.S.</td>
<td>Corridors with intersections</td>
<td>6%</td>
</tr>
<tr>
<td>Zuylen</td>
<td>2000</td>
<td>The Netherlands</td>
<td>not known</td>
<td>varied from 6% to 9%, depending on pavement type, and lighting condition</td>
</tr>
<tr>
<td>Venugopal and Tarko</td>
<td>2001</td>
<td>Indiana, U.S.</td>
<td>Two-lane rural highway work zone</td>
<td>10%</td>
</tr>
<tr>
<td>Prevedouros</td>
<td>2002</td>
<td>Hawaii, U.S.</td>
<td>6-lane freeways and class I arterials</td>
<td>4%</td>
</tr>
</tbody>
</table>