DOES WEATHER AFFECT HIGHWAY CAPACITY?

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ABSTRACT
Various studies on negative effects of rainfall on travel demand and accidents are well documented. However, there are fewer studies on the effect of weather on capacity. As capacity can only be measured on a short section with high traffic flow and it demands more localised weather information which are not easy to collect. The aim of this paper is to determine the effects of rain on capacity and speed and the effects of daylight on capacity. Traffic data from the Tokyo Metropolitan Expressway (MEX) and weather data from the Tokyo Sewerage Bureau's radar rain gauge system (AMESH) are used. From the analysis of 5 highly congested sections of MEX, the effects of rain on capacity and speed are demonstrated. Further analysis of the capacity during the morning peak of the winter and summer months show a reduction in capacity due to effects of daylight.

1. INTRODUCTION

Researches into the effects of weather and travel demand were carried out as early as the 50s by Tanner (1952) and later by Codling (1974), Changnon (1996), Hogema's (1996), Keay and Simmonds (2005) and Chung et al. (2005a, b). It is not easy to compare the results as the type of traffic counts and weather information used are different (e.g. hourly, daily) and also the periods and sites of the analysis. Nevertheless, it can be said that bad weather decreases travel demand with lower level of reduction during weekdays than during weekends. The mode of transport could also be a factor as people may favour transport with more protection against rain. Hence, countries with high percentage of cyclists or motorbikes may abandon their two wheelers for drier mode of transport such as private car. Various studies show that rainfall also increases accident rate (Codling 1974; Chung et al. 2005b; and Keay and Simmonds 2005). A more detail comparison of results from various studies are presented in the next section.

Whilst the effect of weather on travel demand and accidents are well documented, there are fewer studies that directly measure the effect of weather on capacity. As capacity can only be measured on a short section with high traffic flow, it demands more localised weather information. This paper's aim is to study the effect of rain on motorway capacity and speed using satellite weather information and also the effect of daylight on capacity. Sections 3 to 6 describe results the rainfall information system, study area and effects of the weather and daylight on capacity.

2. LITERATURE REVIEW

Using census data collected at 21 selected points over Great Britain during a fine week in August 1949 and a wet week in August 1950, Tanner (1952) observed a marked reduction in the flow for 1950. He showed the negative correlation between rainfall and traffic flow; and calculated the percentage decrease in traffic flow per mm of rain for cars and taxis during weekdays and Sunday to be 1.3 and 3.1 percent respectively. Interestingly Hogema's (1996) study on the Dutch highway found that there is no statistically significant difference in traffic volume observed during rain and dry period and apparently no major modality shift towards road traffic. Changnon (1996) studied summer precipitation on urban transportation and concluded that rain had negligible influence on weekday traffic volume on busy highways but there was a 9% decrease in traffic volume on weekends.

Chung et al. (2005b) using the toll collected on the Tokyo Metropolitan Expressway over a 6 year period, found that on average weekdays daily traffic demand decreased by 2.9% and on Saturday and Sunday, daily traffic demand decreased by 7.9% and 5.2% respectively. As the Tokyo Metropolitan covers a large area and not all meteorological stations in the area observed rainfall for small daily rainfall, Chung et al. used 13 mm of rain per day as the threshold to define rainy day. Keay and Simmonds (2005) investigated the effect of weather variables on road traffic volume collected for the period 1989-1996 at a site in Melbourne, Australia. They found statistically significant decreases of 1.35 and 2.11% in traffic volume on wet days in winter and spring, respectively. The reduction increases as rainfall increases, with largest for 2-5 mm rain in spring.

Hogema (1996) observed that the headway distribution changes during rain and dry condition. His results showed that percentage of headways < 1 second was smaller in rain conditions (5.0%) than in dry conditions (10.8%). Similar results but smaller effect for headways < 3 seconds, changing from 44.8% to 46.4% in rain and dry conditions, respectively. No main effect of weather was recorded for headways >5 seconds. In Hogema's study, the highest traffic volume 1500 veh/h/lane which is still well below the road capacity of the order of 2200 veh/h/lane. Therefore, the results of Hogema's study did not lead to a conclusion about the effect of rain on road capacity.

Codling (1974) concluded that in terms of numbers of accidents, the greatest weather problems are associated with rain and wet roads. From the data collected in Great Britain in 1970, Codling's analysis showed that 31% of all injury accidents occurred on wet roads, nearly half of them when rain was falling. Keay and Simmonds (2005) found the rain effect to increase daytime and night time accident count by 1.9 and 5.2% over dry mean accident count.

The literatures reviewed have shown that the negative effects of rain on traffic demand and accident. The effect of rain on traffic flow is greater on weekends than on weekdays and greater in spring than in winter. The magnitude of the decrease probably varies depending on the function of the roads where the data are collected. Although drivers' behaviour changed during rain such as decrease in speed and increase in headway, the increase in accident clearly shows that drivers are not compensating for poorer visibility (i.e. longer reaction time) and longer braking distance, sufficiently.

3. TOKYO AMESH

An accurate rainfall information system named *Tokyo Amesh* was introduced in 1988 by the Tokyo Sewerage Bureau to ensure the proper operation of sewerage facilities (Bureau of Sewerage website). The radar rain gauge system consists of two radar base stations (Minato Radar and Inagi Radar) is capable of isolating electromagnetic waves that are reflected off falling rain. The radar can observe an area within 50 km radius (see Figure 1) and precipitation is observed using a 250 meter mesh. This system is able to monitor changing rainfall conditions every minute.

Figure 1: Rainfall observation area covered by the Minato and Inagi radars.

4. STUDY AREA

The area chosen for this study is the Tokyo Metropolitan Expressway (MEX). MEX serves as the major arteries of the Tokyo Metropolitan Area, carrying a daily average volume of 1.14 million vehicles over a total length of 283 km. MEX carries approximately 28% of all arterial vehicle traffic in the Tokyo Metropolitan Area and approximately 35% of its cargo volume. All the routes of Tokyo Metropolitan Expressway are equipped with ultrasonic detectors which are approximately 300m apart. Traffic data such as speed, flow and occupancy are collected by the detectors.

5. EFFECT OF RAIN

Traffic detector data of 1 minute resolution is used and aggregated over 5 minutes. The traffic data was collected over a 2 year period from 1 July 2002 to 30 June 2004. Five sections covering merging, weaving and curve were selected and shown in Figure 2. Description of the 5 sites and their lane width are listed on Table I

Since the flow aggregation is 5 minutes, it would not be sensible to use hourly rainfall, for example. Given that Tokyo Amesh can detect rain at 1 minute cycle and 250 metre grid, Amesh data was used for this study.

The rainfall is divided into the following groups

- No rainfall
- 1 mm/h
- 2 mm/h
- 3 mm/h
- 4 mm/h,
- 5-10 mm/h
- 10-20 mm/h
- >20 mm/h

The last 2 categories of extreme rainfall are observed during the typhoon seasons only i.e. small number of data points and therefore bigger range of rainfall grouping is necessary.

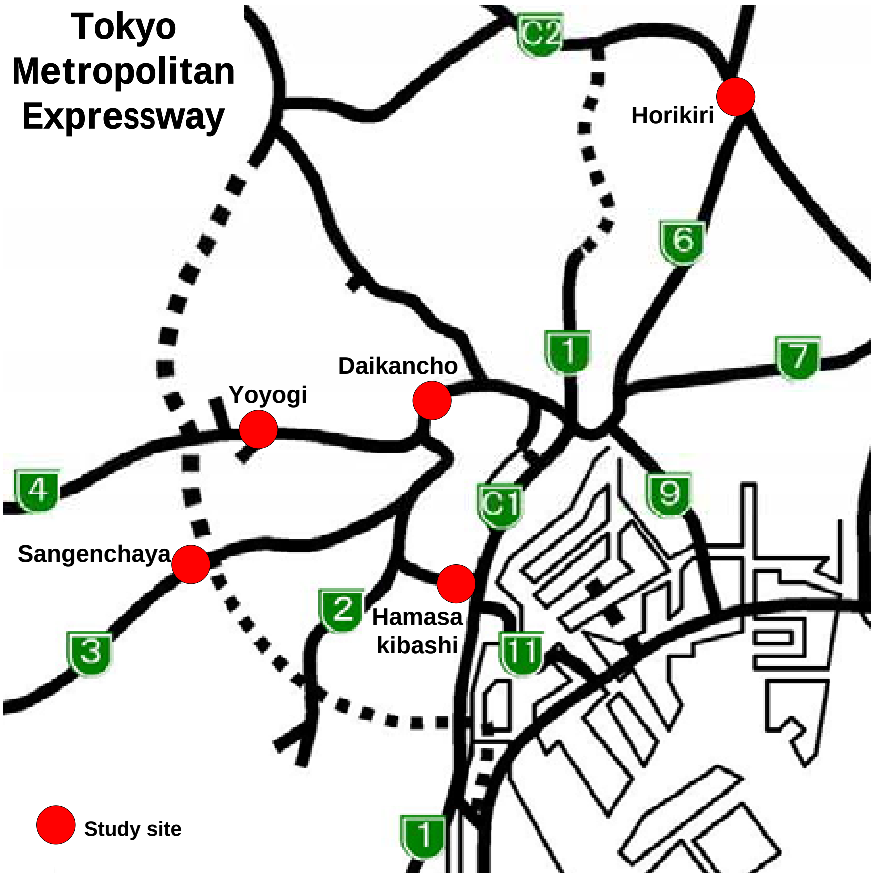

Figure 2: Study sites on the Tokyo Metropolitan Expressway

Table I: Sites used in the capacity analysis

Site	Description	Lane width
Sangenchaya	Located between the Ikejiri on-ramp and Sangenchaya off-ramp on Shibuya route 3 in the outbound direction. This section has a weaving section.	3.25 m
Daikancho	Located at the merging section between on-ramp and mainline (Inner circular route - inner circle). This section is also on a positive gradient.	3.25 m
Hamasakibashi junction	This site is on merging section of outer circle of the Inner circular route. Vehicles traveling on the 2 lane (in one direction) circular route would continue in a clockwise direction but merge with a 2 lane section from Route 1 inbound direction.	3.25 m
Horikiri junction	This site is meeting of mainline and mainline (inner circle of middle circular route and Route 6 outbound). Vehicles weave to change route and some vehicles have to perform more than one lane changing maneuvers.	3.5 m
Yoyogi	Located on a curve section of Route 4 in the outbound direction. There is no merging or weaving	3.25 m

Figure 3 shows the speed flow curve measured at Hamasakibashi junction for different level of rainfall over 2 year period. The flow is aggregated over 5 minutes. The figure clearly shows the decrease in free flow speed and in capacity with increasing amount of rainfall.

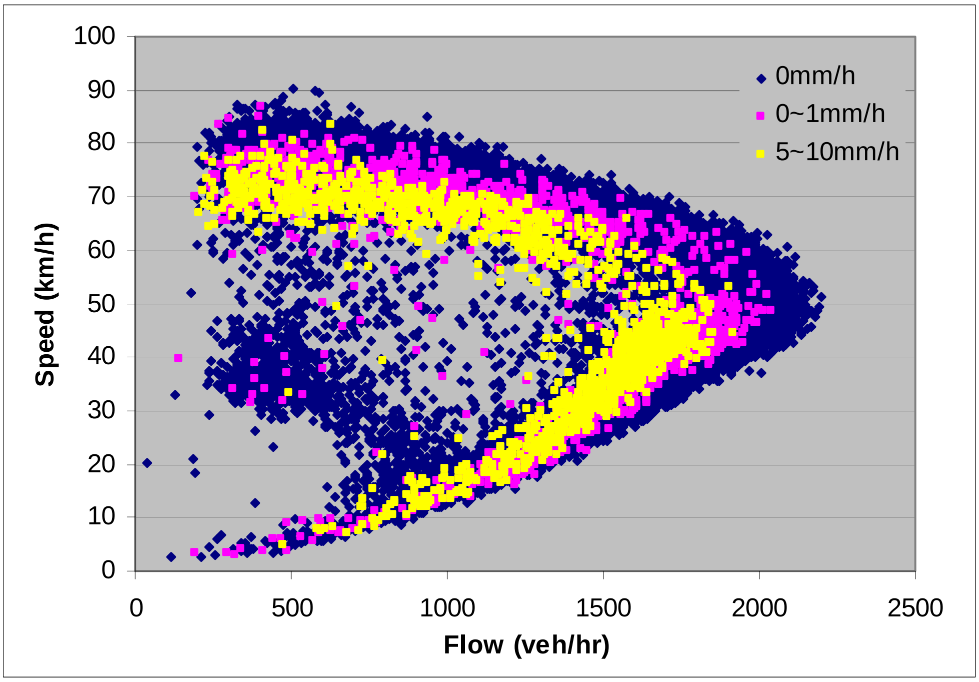

Figure 3: Speed flow curve at Hamasakibashi Junction for different rainfall

There are lots of scatter in the data and the 99th percentile flow rate is used to represent the capacity for each level of rainfall. Table II shows the capacity for all sites at different rainfall.

Table II: Capacity at 5 sites against rainfall

Rainfall (mm/h)	Capacity (veh/h)				
	Sangenchaya	Daikancho	Hamasakibashi	Horikiri	Yoyogi
0	1674	1902	2064	1888	2022
1	1584	1826	1933	1812	1878
2	1560	1770	1892	1824	1842
3	1572	1770	1880	1804	1854
4	1572	1764	1860	1800	1844
5	1542	1745	1846	1751	1809
5-10	1524	1722	1818	1733	1784
10-20	1536	1666	1764	1717	1749
>20	1475	1788	1706	1791	1719

The capacity amongst the five sites during fine weather ranges between 1674-2064 veh/hr. Although all sites have 2 lanes except Horikiri with 3 lanes and wider lane width of 3.5m, the geometries are different. For example, Yoyogi is on a curve section. When the decrease in capacity due to rain for all the sites are plotted (see Figure 4), there is a clear trend of decreasing capacity against rainfall. Figure 4 shows a decrease of 4-7% in capacity when light rain of 1mm/h is observed. Capacity can decrease up to 14% for heavy rain condition.

Capacity at Horikiri decreases least compared to other sites and could be due to the fact that the section is on the lower deck of a multi-tier expressway. It means that the subject section did not get the full impact of rain. Another factor to note is that vehicle counts were used and therefore did not take into account of the different percentage of heavy vehicles.

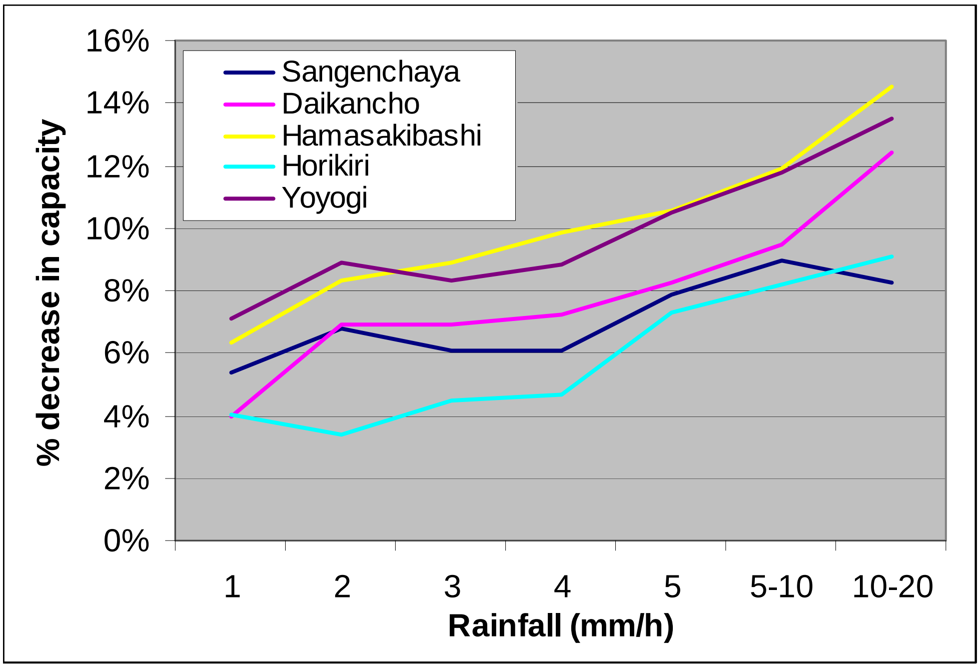

Figure 4: Decrease in capacity due to rain

Noticeable reduction in speed is observed during rain (see Figure 3). When the median free flow speed is calculated (see Table III) i.e. flow rate of ≤500 veh/h/lane, speed reduced between 4.5% and 8.2% when rain. This shows that drivers are changing their behaviour when driving in the rain. This observation is also reported by Hogema (1996) and Edwards (1999). Edwards' study found a small but significant reduction in mean speeds on the M4 motorways (south Wales, UK) in both wet weather and misty conditions. The dry mean speed of 64.3 km/h dropped to 61.5 and 62.1 in wet and misty conditions, respectively.

Despite the speed reduction of drivers, the accident rates on MEX is still higher (Chung et al. 2005b) which suggests that drivers may underestimate their braking distance or time to collision. In the French motorways for example, speed limit is reduced from 130 km/h to 110 km/h during rain. This would compensate for the increase in breaking distance on wet roads. For example, with a deceleration rate of 6 m/s^2 on wet road; breaking distance shortened by 31 m when speed is reduced from 130 km/h to 110 km/h.

Table III: Median Free Flow Speed

Rainfall (mm/h)	Median free flow speed (km/h)	Percentage reduction in speed (%)
0	77.7	
0-1	74.2	4.5
1-2	74.2	4.6
2-3	73.4	5.6
3-4	72.7	6.4
5-10	71.4	8.2

6. EFFECT OF DAYLIGHT

Rain affects driving both in terms of vehicle handling (as wet roads reduce tyre pavement friction) and in visibility. Daylight may also affect the way people drive. This section investigates the capacity at a bottleneck during the summer and winter months. Data was collected at the Funaboribashi entrance (middle circular route, clockwise direction) for June 2003 and December 2003. Only fine weather during the morning period between 5 and 7 AM was used in the analysis. Drivers were not facing the sun when driving in the morning.

The meteorological data shows that sunrise around 4:30AM in June and 6:30AM in December. However, detector data shows that vehicles speed start reducing at 6 AM indicating the onset of the morning peak period. This means that for the month of June, the morning peak occurs well after sunrise. On the other hand, for the winter month of December, the morning peak occurs around sunrise. This shows that drivers arrive at the bottleneck in summer when it is bright but in winter it is still fairly dark.

The capacity is measured as maximum 5 minute flow and Figure 5 shows the median capacity in June and December are 1968 and 1716 veh/h respectively. It shows that capacity during daylight is higher than capacity during daybreak by 12.8%. Interestingly the effect of daylight on capacity is greater than rainy condition. The reason could be better visibility during summer. As this result is only from 1 site, it is not possible to draw firm conclusion on this finding. Note that congestion started at 6 AM which is relatively early for AM peak and therefore it was possible to capture the seasonal (daylight) effect. Attempts were made to use data from other sites for comparing AM capacity with PM capacity. Unfortunately congested sites during the AM peak were not congested during the PM peak; and vice versa. Further effort to collect data from other sites is necessary.

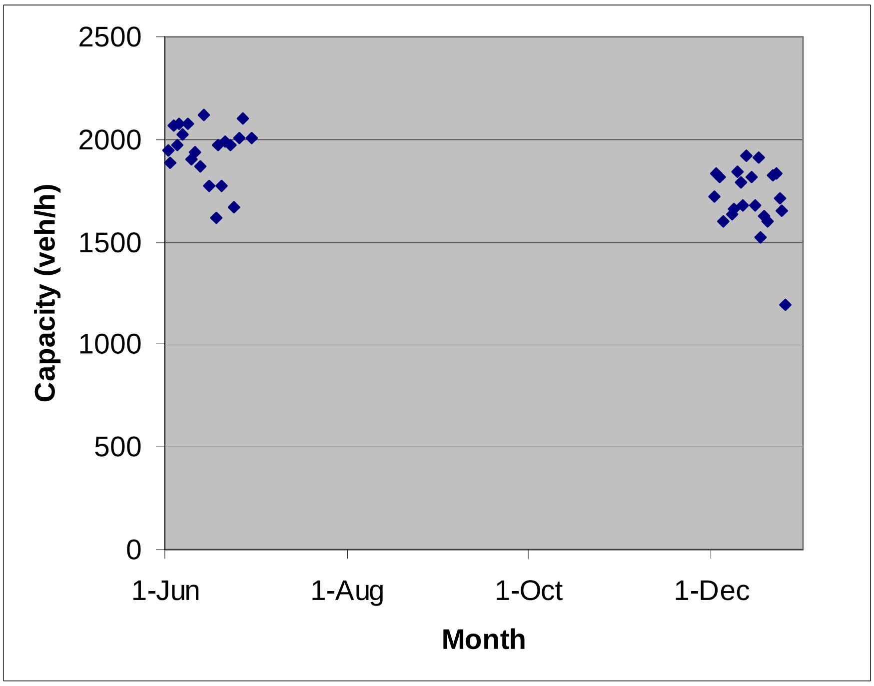

Figure 5: Capacity measured during summer and winter month of June and December respectively

7. CONCLUSION

This study combined the precise rainfall data from Tokyo AMESH with detector data at 5 highly congested sections of the Tokyo Metropolitan Expressway. The results clearly show that rain decreases capacity ranging from 4-7% in light rain to a maximum of 14% during heavy rain. Free flow speed is also affected by rain because drivers have to adapt to the slippery road and poorer visibility driving condition. Reductions of free flow speed between 4.5% in light rain to 8.2% in heavy rain are observed. The effect of daylight on capacity i.e. when congestion occurs at poor natural lighting condition i.e. near time of sunrise in winter versus bright summer lighting condition is also analysed. The results show capacity in winter decreased by 12.8% over summer lighting condition.

REFERENCES

Bureau of Sewerage Tokyo Metropolitan Government http://tokyo-ame.jwa.or.jp/en/amesh.html

CHANGNON, S.A. (1996). Effects of summer precipitation on urban transportation. *Climatic Change* **32** pp 481-494.

CHUNG, E., OHTANI, O. and KUWAHARA, M. (2005a). Effect of rainfall on travel time and travel demand. *5th ITS European Congress,* Hannover, Germany.

CHUNG, E., OHTANI, O., WARITA, H., KUWAHARA, M. and MORITA, H. (2005b). Effect of rain on travel demand and traffic accident. *8th IEEE Intelligent Transportation Systems Conference,* Vienna, Austria.

CODLING, P.J. (1974). Weather and Road Accidents. In: ed. Taylor, J.A. *Climatic resources and economic activity: a symposium*, pp 205-222, Newton Abbot, UK.

EDWARDS, J.B. (1999). Speed adjustment of motorway commuter traffic to inclement weather. *Transportation Research Part F,* **2(1)** pp 1-14.

HOGEMA, J.H. (1996) *Effects of rain on daily traffic volume and on driving behaviour*. TNO-report TM-96-B019, TNO Human Factors Research Institute, Soesterberg, the Netherlands.

KEAY, K. and SIMMONDS, I. (2005) The association of rainfall and other weather variables with road traffic volume in Melbourne, Australia. *Accident Analysis and Prevention,* **37** pp 109-124.

Levine, N., Kim, K. E. and Nitz, L. H. (1995) Daily fluctuations in Honolulu motor vehicle accidents. *Accident Analysis & Prevention,* 27(6), December 1995, pp 785-796.

OHTANI, O. A study on the traffic phenomenon influenced by weather conditions. Masters Thesis, Nihon University, 2004. (in Japanese)

TANNER, J.C. (1952) Effect of Weather on Traffic Flow. *Nature,* **4290** pp 107.