An Analysis of Effects of Rainfall on Travel Speed at Signalized Surface Road Network Based on Probe Vehicle Data

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ABSTRACT

The rainfall effect on the travel speed is investigated for a signalized urban surface road network by using probe vehicle data and rainfall data. The data sets were obtained from the central area of Nagoya City, Japan in May and June 2004. The results show that as the rainfall becomes heavier, the average travel speed becomes lower significantly. In the case of heavy rain, the average travel speed decreases 6.03 km/h when compared to the case of no rain. However, the size of the effects varies across the hierarchy of the road, the number of lanes, and the travel speed at no rain. We can now provide more accurate travel time forecasts at signalized urban surface road networks by considering these factors when the weather forecasts are obtained.

KEYWORDS: rainfall, probe vehicle data, travel time, travel speed, regression model.

INTRODUCTION

How to relieve traffic congestion and reduce the effects on the environment of the road traffic have become very important in Japan. The economic loss of 12 million Japanese yen is caused by the traffic congestion every year, and then the average time loss is about 42 hours per person per year. However, it is difficult to construct more roads to solve these problems. Therefore, more efficient use of the existing roads becomes the main direction for realization of the environment-friendly transportation

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systems in future. In this background, the demands for highly-detailed travel time information which is based on Dynamic Route Guidance System (DRGS) are increasing rapidly. Thanks to the IT evolution, the traffic surveillance system has made remarkable progress, and the real-time traffic condition can be now precisely observed. Forecasting future traffic condition is, however, still difficult task. The traffic condition is affected by many external factors. The weather condition is one of the important factors, which affects the traffic flows by influencing driver's sight, attention, braking performance and so on. The weather forecast is already in practice, so the traffic condition in the future can be more precisely forecasted by taking account of the weather in the future.

The purpose of this study is to analyze the rainfall effect on the travel speed and to model the relationship between travel speed and rainfall intensity using probe vehicle data and rainfall data. These data were collected from the central area of Nagoya City, Japan in May and June 2004.

In this paper, the data is divided into several groups according to the road category, number of the lanes and rainfall intensity. The rainfall intensity is defined as heavy rain (rainfall intensity is above 4.0mm/h), light rain (rainfall intensity is less than 4.0mm/h) and no rain by the amount of rain in ten minutes. The decrease in travel speed is analyzed with respect to time of day, rainfall intensity and several road characteristics. Also, the relationships between rainfall intensity in 10 minutes and travel speed of each probe vehicle are analyzed using regression models based on the road category and the number of lanes. Additionally, we propose a framework for estimating more appropriate travel time information based on the result of regression analysis.

LITERATURE REVIEW

The Highway Capacity Manual (HCM) (TRB, 2000) notes, "Conditions under which the full capacity of a basic freeway section is achieved are good weather, good visibility, and no incidents or accidents. When one or more of these conditions fail to exist, the speed, level of service, and capacity of the freeway section all tend to be reduced". HCM also suggests that free-flow speed on freeways is reduced by 9.7km/h in light rain, and by 19.3km/h in heavy rain. But HCM does not define the rainfall intensity ranges explicitly. FHWA's Road Weather Management Program (FHWA, 2004) reports that driving speed on freeways can be reduced by roughly 10% in light rain and approximately 16% in heavy rain. Kyte *et al*. (2001) finds that a wet surface reduces the free flow speed by 9.5 km/h. Smith *et al*. (2004) concludes that light rain (intensity of 0.01-0.25inches/hour) decreases freeway capacity by 4-10%; heavy rain (intensity of 0.25 inches/hour or greater) decreases freeway capacity by 25-30%; and the presence of rain, regardless of intensity, results in approximately a 3.0-5.0% average decrease in travel speeds. He also concludes that heavy rain does not impact operating speed any more (or less) than light rain. Ibrahim and Hall (1994) suggests that weather condition affects relationship of flow-occupancy and speed-flow; light rain decreases travel speed by 2km/h; and heavy rain decreases travel speed by 5-10km/h; the highway capacity can be decreased 10-20% under heavy rain.

The past researches on travel speed under rainfall shows that the rainfall impacts travel speed considerably, and a large amount of the studies suggests that rainfall could reduce the mean free-flow speed, but in different area or city the results are different. However, these studies are aimed at the highway; almost none of them are aimed at signalized surface road network in central city area. This research investigates the relationship between different rainfall intensity and travel speed on signalized urban surface road network in Nagoya City, and provides the results to ATIS for that the road users can get more accurate travel information. .

DATA COLLECTION AND CLEANING

In Nagoya City there had a probe vehicle system, which was one of the largest systems in the world, with total 1,570 taxis equipped with GPS receiver, and this system had been continued 18 months in 3 years[5]. The probe vehicle data used in this study was collected from 0:00 May 1st, 2004 to 23:59 June 30th, 2004 in the central area of Nagoya City (Figure 1). The probe vehicle data include information of location, shortstop, short trip, speed and so on; the detail of the data is shown in Table 1. These data were matched on the digital road map (DRM) of Japan Digital Road Map Association. The travel time information from the probe vehicle data was calculated from the result of map matching on DRM link. Please refer to Miwa *et al*. (2004) for details of map matching algorithm. The link travel time on the links with 100 meters and longer is used for this study, because if link length is less than 100m, even a small degree of map matching errors may bring a large effect on the result of calculating travel speed. Additionally, outlying observations such as travel speeds with over 100 km/h and less than 3.6 km/h are discarded from the data set. The link travel speed is defined as the average speed between the time entering the link and that going out of the link. The link travel speed of the resulting data set ranges from 3.6km/h to 100.8km/h with the link length longer than 100m.

The Japan Weather Association collects the rainfall data from Automated Meteorological Data Acquisition System (1 km mesh, total is 20 meshes) in the same time and same area as the probe vehicle data is collected (Figure 1). The interval of the rainfall data is 10 minutes and the unit of the data is mm/h. The rainfall intensity is classified into 3 groups in this study: heavy rain (rainfall intensity is above 4.5 mm/h), light rain (rainfall intensity is 0.5 to 4.0 mm/h) and no rain (0 mm/h) by the amount of rain in ten minutes. Furthermore, a day is divided into 144 time periods by 10 minutes.

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[5] The period of probe vehicle system operation is from January to March 2002, October to December 2002, January to March 2003, October 2003 to June 2004

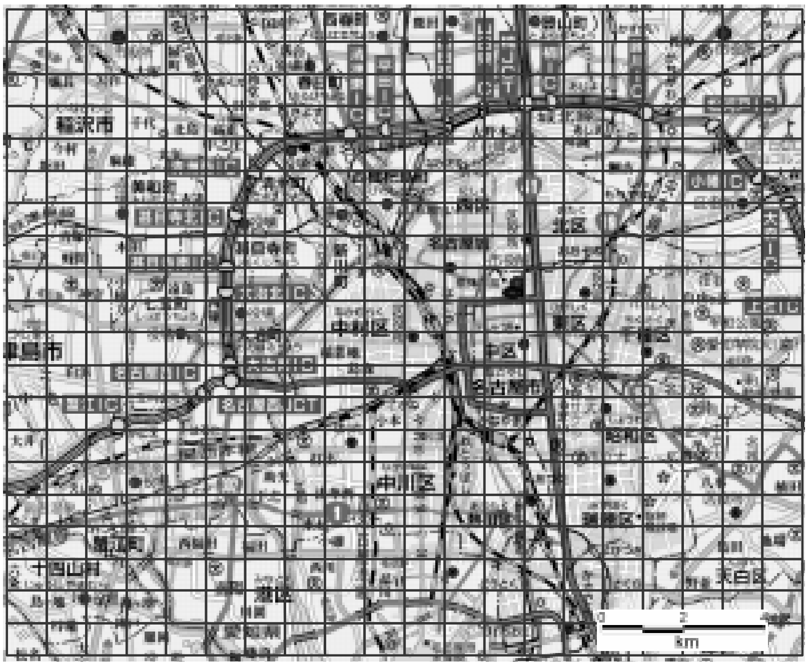

Figure 1. The data (probe vehicle and rainfall data) collection area

Table 1. Event of sending data and collected item of data

Event	Definition	Ratio
Separation	No other events occur in 300m	35.1%
SS	Short Stop: when vehicle start	31.3%
ST	Short Trip: when vehicle stopping	29.8%
Others	Time interval 550s, changing between in-service/out-service, engine stop/start, etc.	3.8%
Collected item of data	Time and date, longitude/latitude, speed, direction, acceleration, ST/SS flag, in-service/out-service flag, wiper flag, etc.	

THE ANALYSIS OF RELATIONSHIP BETWEEN TRAVEL SPEED AND RAINFALL INTENSITY

In order to take account of the rainfall effect on the driver's running speed, at first, the correlation between the rainfall and travel speed on the city road network should be confirmed. The study begins with checking the variance of travel speed among the different rainfall intensity with respect to time of day. The result is shown in Figure 2. Figure 2 shows a tendency that when rainfall becomes heavier, the average travel speed becomes lower. In addition, the difference of travel speed under different rainfall intensity shown in Figure 3 suggests that maximum difference is 4.46 km/h at

18:00, and the minimum difference is -0.54 km/h (this means travel speed in rain is faster than that in no rain at 15:00). The average difference of travel speed between light rain and no rain (1.46 km/h) is smaller than that between heavy rain and no rain (2.03 km/h). From Figure 2 and Figure 3, it is found that there are some exceptional cases where travel speed under heavy rain is faster than travel speed under no rain. These results are not obtained by chance because sample size is large enough: 8,895,387 for no rain, 1,139,807 for light rain, and 310,271 for heavy rain.

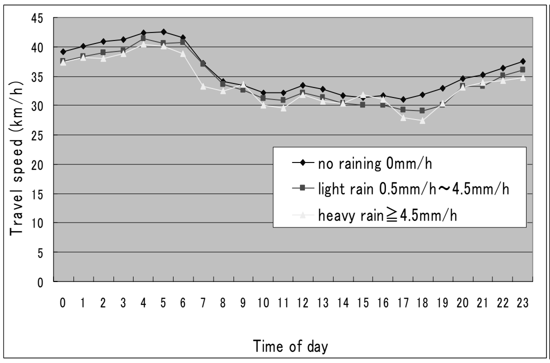

Figure 2. The variance of travel speed in different rainfall intensity with respect to time of day

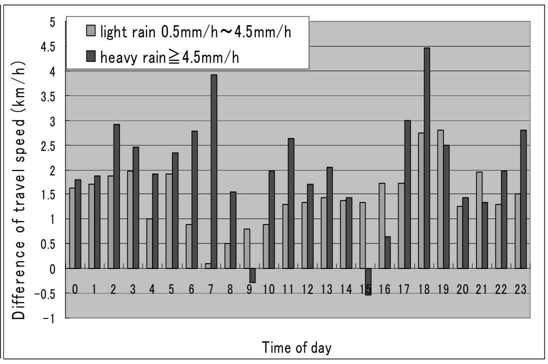

Figure 3. Difference of travel speed under different rainfall intensity

As the travel speed is affected by the road attributes, the factor of the road category and the number of lanes must be taken into account when the effect of the rainfall on the travel speed is examined. Therefore, the sample cases are divided into 6 types of the road hierarchy: highway, national road, main prefecture road, main city road, other prefecture road, and other city road. Also the number of lanes (except highway) is divided into 2 lanes, 4 lanes and 6 lanes. The highway is only divided into 2 lanes and 4 lanes. The total number of categories becomes 15. Enough sample cases are taken for each category, from 704 to 1,300,000 for each category. The highway has the smallest number of sample cases under heavy rain. The results of the analysis on the effect of rainfall considering road category and the number of lanes are:

- The same tendency of decrease in travel speed for different rainfall intensity is shown.
- The maximum difference in travel speed between no rain and heavy rain is 6.03 km/h for the highway; and 2.54 km/h for the 6 lanes of national road.
- The faster the travel speed under no rain is, the larger the travel speed decreases under rainfall.

Travel time ratio of heavy rain to no rain and that of light rain to no rain are an important index for providing travel time information under rainfall condition. So, we also calculate the ratio of travel time on different rainfall intensity to no rain. Figure 4 shows the ratios of travel time under different rainfall intensity. Here, we add one more category suggesting very heavy rain (rainfall intensity is above 10 mm/h). The results suggest that travel time has an unremarkable variance under light rain, heavy rain, and very heavy rain. The results show that travel time on city road network increases by at most 10% in light rain, 18% in very heavy rain, and the average increase is about 9%.

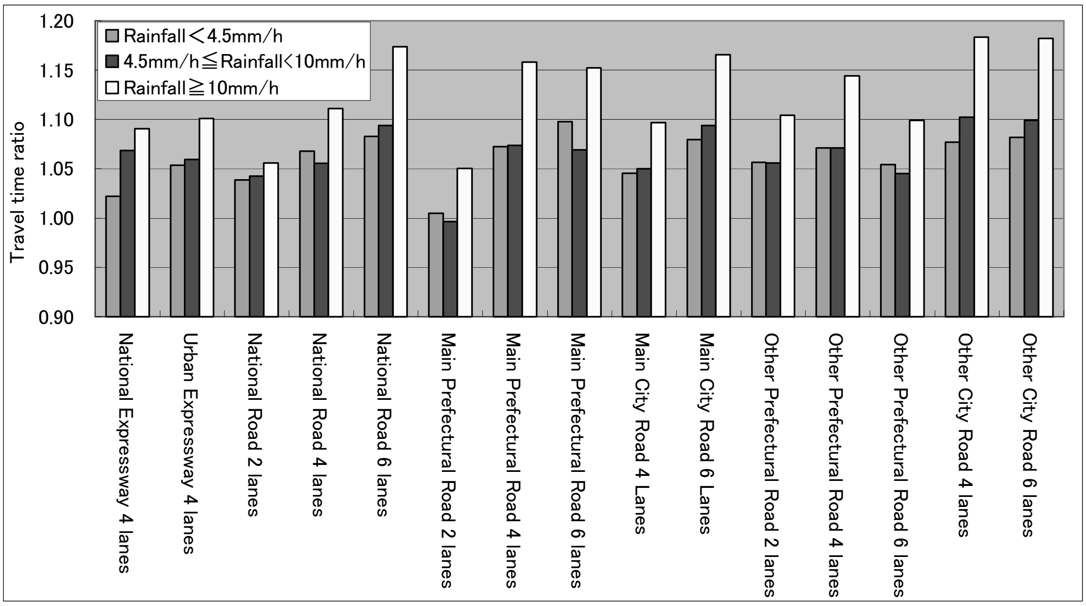

Figure 3. Average travel time ratio under different rainfall intensity

REGRESSION MODELS

In order to understand the relationships between rainfall intensity in 10 minutes and travel speed of each probe vehicle clearly, regression models are developed based on the road category and the number of lanes.

First, a regression model is developed that does not consider travel speed under no rain. The model takes account of rain intensity and dummy variables indicating time of day for each road category and the number of lanes (Model 1). Square and natural logarithm of rainfall intensity are included in the regression model as explanatory variable in order to find the best relationship between rainfall and travel speed. The regression models (Model 1) are given as

$$\ln y = \beta_1 x + \beta_2 \quad (1)$$
$$\ln y = \beta_1 x^2 + \beta_2 \quad (2)$$
$$\ln y = \beta_1 \ln(x+1) + \beta_2 \quad (3)$$

where y is travel speed, x is rainfall intensity, β_1 is unknown parameter, and β_2 is a dummy variable representing time of day.
The results of this regression analysis are shown in Table 2. Here, only the results for

national road are shown due to limitation of space.

Table 2. The result of regression model (Model 1) for National road

	National road 2 lanes			National road 4 lanes			National road 6 lanes		
	β_1		$\overline{R}^2$	β_1		$\overline{R}^2$	β_1		$\overline{R}^2$
	Coef.	t-stat.		Coef.	t-stat.		Coef.	t-stat.	
(1)	-0.0129	-1.81	0.053	-0.0387	-10.20	0.031	-0.0588	-31.48	0.034
(2)	-0.00254	-1.46	0.053	-0.0048	-4.80	0.031	-0.00739	-14.41	0.034
(3)	0.0302	-2.23	0.053	-0.0831	-12.10	0.031	-0.123	-36.70	0.034
Sample size	56416			306819			1267701		

The results show that as the number of lanes increases, the effect of rainfall intensity on travel speed becomes more significantly; suggesting that as the number of lanes increases, the effect of rainfall on the travel speed becomes larger. The results also show that the relationship between rainfall and travel speed becomes much stronger by taking natural logarithm for rainfall intensity and travel speed. Because only rainfall intensity is used as independent variable in the model, while in fact many factors affect the travel speed, for example the road capacity and the number of signals and so on, the $\overline{R}^2$ value is very small in every case of the model 1.

Obviously travel speed under no rain affects on the travel speed under rain, therefore, as the next step, the relationship between travel speed under no rain and the difference of travel speed under no rain and rain are considered simultaneously. Figure 4 shows this relationship under different rainfall intensity for National road with 2 lanes and 4 lanes.

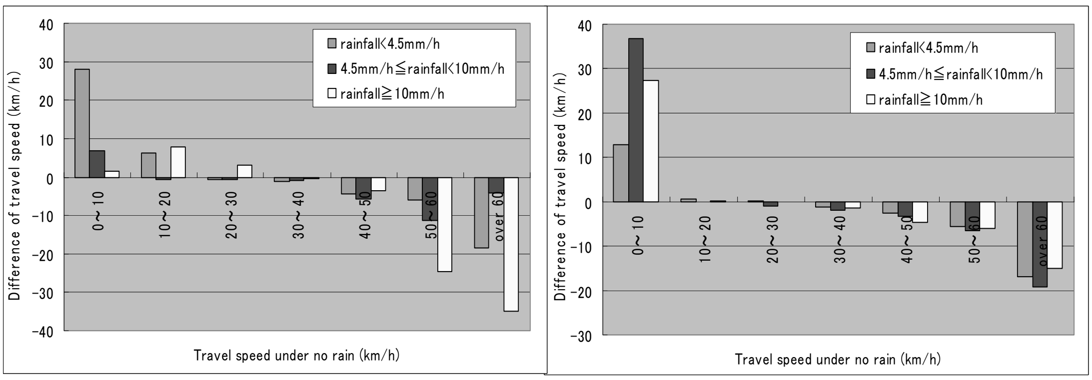

Figure 4. The relationship between travel speed under no rain and difference of travel speed between under no rain and rain for National road
(2 lanes on the left and 4 lanes on the right)

Figure 4 shows that as the travel speed under no rain increases, the decrease of travel speed under no rain and rain also becomes large. The decrease is very small when travel speed is from 0 to 10 km/h and from 10 to 20 km/h. Contrary, the travel speed becomes faster when rain at those roads where the travel speed is 0 to 10 km/h at no rain. As a result, the travel speed under no rain is an important factor for decrease of travel speed under rain.

The regression models considering travel speed under no rain are developed (Model 2); the difference between travel speed under no rain and rain is used as dependent variable in the model. The regression models (Model 2) are given as

$$y - \bar{y} = (\beta_3 \bar{y} + \beta_4) \ln(x+1) \quad (4)$$

$$y - \bar{y} = (\beta_2 \bar{y}^2 + \beta_3 \bar{y} + \beta_4) \ln(x+1) \quad (5)$$

$$y - \bar{y} = (\beta_1 \bar{y}^3 + \beta_2 \bar{y}^2 + \beta_3 \bar{y} + \beta_4) \ln(x+1) \quad (6)$$

where y is travel speed under rain, $\bar{y}$ is travel speed under no rain, x is rainfall intensity, and β_1, β_2, β_3 are parameters β_4 is a dummy variable indicating time of day.

The results are shown in Table 3. Only the results for 4-lanes National road are shown here due to limitation of space. The results suggest that the model fit does not improve significantly even if the cube or square of the travel speed under no rain is included in the model. The results also show that the travel speed variance isn't linear for rainfall intensity, though. The $\bar{R}^2$ value of cube is the largest among model 2, suggesting that if the travel speed is low under no rain, the travel speed becomes faster under rain, and if the travel speed is fast under no rain, the travel speed becomes lower under rain.

Table 3. The result of regression model (Model 2) for 4-lanes National road

National road 4 lanes									
	β_1		β_2		β_3		β_4		$\bar{R}^2$
	Coef.	t-stat.	Coef.	t-stat.	Coef.	t-stat.	Coef.	t-stat.	
(4)					-0.312	-17.72	2.08	11.97	0.0100
(5)			-0.0400	-8.34	0.458	4.88	-1.30	-2.95	0.0120
(6)	-0.00900	-8.97	0.227	7.53	-2.12	-7.02	6.27	6.59	0.0150
Sample size	28161								

CONCLUSION

This study analyzed the relationship between travel speed and rainfall for signalized urban road network by probe vehicle data and rainfall intensity data in the central area of Nagoya City, Japan. Through these analyses, the effect of rainfall on travel speed is confirmed in signalized urban surface road network. The hierarchy of road and the number of road lanes are divided into 15 categories in order to consider the heterogeneous relationship between travel speed and rainfall among categories. As a result, the size of the effects on travel speed is different among different rainfall intensity; the largest decrease in travel speed is 6.03 km/h on highway. Travel time ratio of heavy rain and light rain to no rain is also analyzed. The results show that the average increase in travel time is 9%. In ATIS, travel information provider must consider the various effects of rainfall.

The regression models of travel speed considering the effect of rainfall intensity were also developed. The effects of travel speed under no rain on the difference (decrease) in travel speed between under no rain and rain was also examined in this study; as the travel speed under no rain increases, the decrease in travel speed under rainfall becomes more significant, so it is necessary to consider the travel speed under no rain also to provide more precise travel time information at rain.

In this study, the road capacity was not considered. However, the road capacity also is affected by rainfall as Smith *et al*. (2004) suggested for the highway. The investigation on the effect of the rainfall at the signalized urban surface road network remains as a further research task.

ACKNOWLEDGEMENT

This study is part of Probe-based Dynamic Route Guidance System (P-DRGS) project. The authors are grateful to the consortium members for providing valuable suggestions. The authors also wish to thank the Internet ITS Project Group and Japan Weather Association for providing the probe data and rainfall data for use in this study.

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