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Investigating the Impact of Rainfall on Travel Speed

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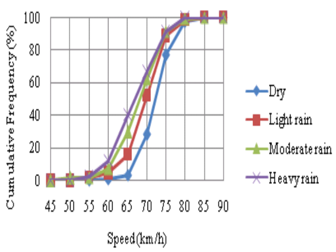
Graphical abstract



Abstract

The road network is particularly susceptible to adverse weather with a range of impacts when different weather conditions are experienced. Adverse weather often leads to decreases in traffic speed and subsequently affects the service levels. The paper is aimed at investigating the impact of rainfall on travel speed and quantifying the extent to which travel speed reduction occurs. Empirical studies were conducted on principle road in Terengganu and Johor, respectively for three months. Traffic data were collected by way of automatic traffic counter and rainfall data from the nearest raingauge station were supplied by the Department of Irrigation and Drainage supplemented by local survey data. These data were filtered to obtain traffic flow information for both dry and wet operating conditions and then were analyzed to see the effect of rainfall on percentile speeds. The results indicated that travel speed at 15th, 50th and 85th percentiles decrease with increasing rainfall intensities. It was observed that all percentile speeds decreased from a minimum of 1% during light rain to a maximum of 14% during heavy rain. Based on the hypothesis that travel speed differ significantly between dry and rainfall condition; the study found substantial changes in percentile speeds and concluded that rainfalls irrespective of their intensities have significant impact on the travel speed.

Keywords: speed; rainfall; principle road; percentile speed; adverse weather

1.0 INTRODUCTION

The presence of rain, fog or snow makes the driver's task more difficult [1]. These weather conditions reduce driver perception in several ways and is especially debilitating at night. It both directly affects perception but also produces visibility changes through its action on headlamps, windshields, the road itself and road markings [2]. The impacts of adverse weather conditions on the road network operation have been recognized since the middle of the twentieth century due to the various driver behaviours. These include increased risk of accidents, delays, more hazardous driving conditions and general flow disruptions [3].

In Malaysia, rainfall is a natural phenomenon that occurs nearly every month per year with average recorded rainfall of 2409 mm in a year and 200 mm in a month. The copious rain is influenced by seasonal wind flow patterns coupled with the local topographic features. Rainfall events may begin or end at any time of the day, occurring for a few minutes, hours or at interval for several days. The pouring intensity varies with time and space. The variability gives different impact to the drivers' visibility, driving comfort, pavement friction, and vehicle performance which contribute the speed reduction. Speed reduction caused by rainfall would affect the quality of road service.

Currently, there is a less of research work about the influence of rainfall on travel speed available in the literature, than there is in normal weather condition. This is probably due to the difficulty in understanding how motorists respond to a rainfall i.e., whether a reduction in speed is due to a reduction in pavement friction or reduction in visibility [4], difficulty in collecting speed data [5], or lack of disaggregate weather information [6]. Since speed is one of the components that show drivers behaviour on the road, this paper aims to estimate variable travel speed at 15th, 50th and 85th percentiles caused by rainfall condition on two-lane highway in Malaysia and to quantify the extent to which travel speed reduction occurs. The rest of the paper deals with background of the subject, followed by the method adopted for this study. Finally, results, discussion and conclusions are presented.

2.0 PERCENTILE SPEED

Speed is one of the three macroscopic traffic flow measures, the others being volume and occupancy. It expresses the rate at which traffic is moving and, therefore, is a natural measure of the quality of the flow. Speed is an essential parameter for traffic engineers and road providers in determining traffic safety and effectiveness of highway service. In most cases, the tools used are speed percentiles, or also known as quantiles. The most important speed percentiles are 85th and 15th percentiles. The 85th percentile is defined as the speed at or below which 85 percent of vehicles moving and it is the primary guide in determining what speeds the majority of safe and reasonable drivers are travelling. In other words, this percentile is normally used in evaluating or recommending posted speed limits as it is assumed to be the highest safe speed for a roadway section. For example, in the Manual on Uniform Traffic Control Devices (MUTCD) for streets and highway when a speed limit is to be posted, the 85th percentile speed of free-flowing traffic, rounded up to the nearest 10 km/h increment is used [7]. The 15th percentile is the speed at or below which 15 percent of vehicles are travelling. This value is useful in determining the allowable speed limit because the vehicles travelling below this speed tend to obstruct the flow of traffic, thus would increase the potential of accident. While, the 50th percentile represents the speed at which half of the observed vehicles are below and half of the observed vehicles are above. Thus, it is useful in determining the average speed of the traffic stream.

The comparison of two or more sample populations is very common in analytical works for engineers and scientists. Several methods have been used for comparing percentiles such as nonparametric double bootstrapping [8,9], quantile regression, binomial test [10], and averaging percentiles [11-13]. Even though these statistical methods were applied in many studies, the most recent study found that there are some problems associated with existing methods [14]. A nonparametric double bootstrapping and the quantile regression are fairly complex methods and not easy to apply. The use of binomial test and averaging percentiles for analyzing percentile values is questionable and could be argued because it is perhaps not the most appropriate fit. Since there is a lack of a statistical test for comparing percentiles that can be easily applied and is theoretically sound, some studies have not pursued statistical analysis.

Therefore, Hou *et al.* proposed statistical test for the 85th and 15th percentiles based on Crammer's theory of asymptotic distribution of sample quantile [14]. This theory has been in existence for many years as derived by Crammer [15]. Normality of data is required for accuracy of the quantile test. This statistical test is fully developed for 85th percentiles speed with the assumption that 15th percentile speed has the same form because of the symmetry of the normal distribution. The difference can be compared using the test statistic below when the sample size reached approximately 200.

$$\frac{X_{([n0.85]+1)} - Y_{([n0.85]+1)} - 0}{1.53\sqrt{S_x^2/n_x + S_y^2/n_y}} \quad (1)$$

Where $X_{([n0.85]+1)}$ and $Y_{([n0.85]+1)}$ are the 85th sample quantile from independent normal distributions, X_n and Y_n are sample sizes, and S_x and S_y are the sample variances. The accuracy of this test is compromised if the data is not normally distributed.

3.0 SPEED STUDIES IN RAINFALL CONDITION

The impacts of adverse weather conditions on transportation are now widely acknowledged [3]. However, several studies have examined the impact of rainfall condition on speed specifically. Ibrahim and Hall analysed the traffic flow data collected from a freeway in Ontario, Canada during off-peak weekday duration and the analysis showed that light rain caused a drop of 1.9 km/h and 6.4 to 12.9 km/h in operating speeds can be expected during free-flow conditions and at a flow of 2,400 vehicles per hour, respectively. Whereas heavy rain caused a drop of 4.8 to 6.4 km/h and 12.9 to 16.0 km/h in speed can be expected[16]. Results obtained by Kyte *et al.* showed that light rain caused a 14.1 to 19.5 km/h reduction in speed and heavy rain caused 31.6 km/h reduction in speed [17].

Smith *et al.* conducted a research on two freeway links in Hampton Roads, Virginia and the results showed that both light and heavy rains decreased operating speeds by 5 to 6.5 percent [18]. In Agarwal *et al.* studies on urban freeway traffic flow for the metro freeway region around the Twin Cities, the analysed data showed that the operating speed decreased from 1 to 2%, 2 to 4 % and 4 to 7% during trace, light and heavy rains, respectively [19]. Rakha *et al.* investigated and quantified the impacts of various weather events on traffic flow at three major metropolitan areas in the U.S. using 2 years data and the study reported that the free flow speed during light rain and rain decreased from 2% to 3.6% and from 6% to 9%, respectively. For speed at capacity, light rain cause reduction between 8% and 10%, and rain cause reduction between 8% and 14% [20]. While, Chin *et al.* studies showed that the speed for urban freeway and rural freeway reduced from 10 to 16%, and 10 to 25% under light and heavy rain categories, respectively. At urban arterial and rural arterial, both light and heavy rain categories reduced the speeds by 10% [21].

Some studies conducted in Japan also show the speed reduction due to rainfall. For instance, Chung *et al.* reported that the free flow speed on the Tokyo Metropolitan Expressway (MEX) decreased from 4.5% during light rain to 8.2% during heavy rain [22]. Other reseachers, Hong and Oguchi studied on multilane expressways found that even 1 mm of rainfall increment reduced the 85th percentile speed and the change of rainfall from 0 to 1 mm resulted in the greatest reduction in the 85th percentile speed [5]. The study in Vaud canton, Switzerland by Pham *et al.* on Swiss National Highways A1 and A9 recognised that the median free flow speed at 500-600 veh/h fell by 0.91%, from 87.9 km/h in fine weather condition to 87.1 km/h in rain condition [23].

In conclusion, studies on the impact of rainfall in different locations and different road networks are inadequate, and even less research has been focus on percentile speed and principle road. Thus, the current study was initiated in response to this need.

4.0 METHODOLOGY

The traffic flow data used in this study were collected from automatic traffic counters which are installed on the principle roads in Terengganu and Johor as shown in Fig. 1 and 2. The principle road plays a significant role in road network operation since it connects all cities in Malaysia. The time period of data collection was during the monsoon season for about three months. The rainfall data obtained from nearest rain gauge station belongs to Department of Irrigation and Drainage supplemented by local survey data were used for the purpose of analysis.

The fields of traffic flow data including travel speed, traffic volume, headway and manymore were recorded in the database. While, rainfall data consisted of rain intensity, time and date during the period. Traffic data during off-peak daylight condition was organised to correspond with rain intensities to obtain traffic data under dry and rainfall conditions. The categories of rain intensity were identified in accordance World Meteorological Organisation standard as follows: dry; light rain ($i < 2.5$ mm/h); moderate rain ($2.5 \leq i < 10.0$ mm/h); heavy rain ($10.0 \leq i < 50.0$ mm/h) and very heavy rain ($i \geq 50.0$ mm/h). The traffic data under dry and each rain intensity were analysed separately and compared.

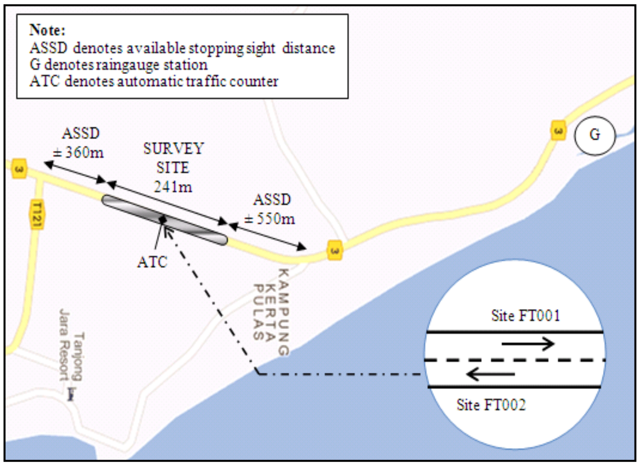


Figure 1 Sites FT001 and FT002 at Kuala Abang, Terengganu

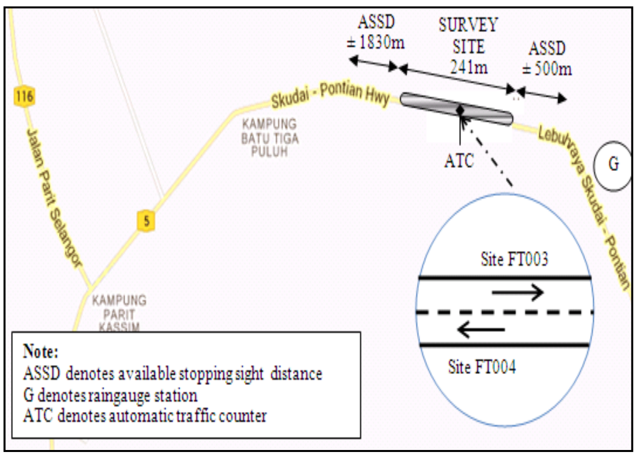
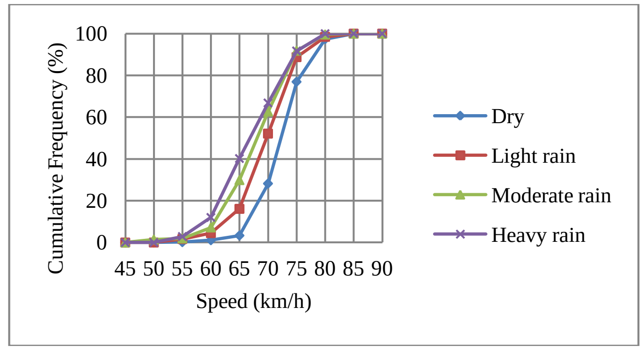


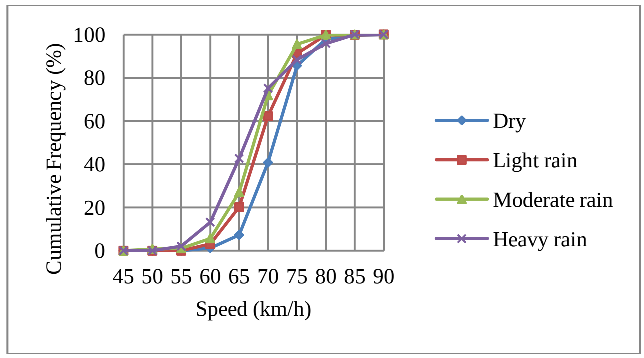
Figure 2 Sites FT003 and FT004 at Pengkalan Raja, Johor

5.0 RESULTS AND DISCUSSION

Fig. 3 and 4 below illustrate the cumulative speed distribution curves under dry, light rain, moderate rain and heavy rain conditions at four study sites. Very heavy rain condition is not included in this study because lack of data recorded during this condition. The cumulative speed distribution curves demonstrated that the speed distributions in all cases have normal-like curves and the curve shifts from right to left, which clearly indicating speed reduction due to prevailing conditions. More importantly, it showed the difference between travel speeds during dry and various rainfall conditions.

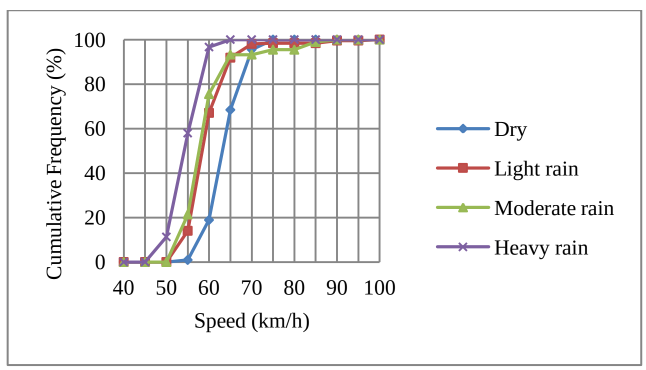


(a) Site FT001

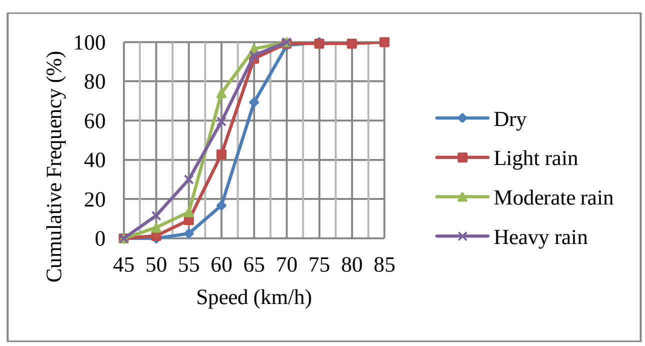


(b) Site FT002

Figure 3 Cumulative speed distribution for dry and rainfall conditions in Terengganu



(a) Site FT003



(b) Site FT004

Figure 4 Cumulative speed distribution for dry and rainfall conditions in Johor

The 15th, 50th and 85th percentile speeds show speed distribution relative to driver population. Tables 1 to 3 show computed speed percentiles for dry and various rainfall conditions for all survey sites including the extent of speed reduction. In general, the results of speed percentile showed that 15th, 50th and 85th reduced with the increase of rainfall intensities, thus suggesting that drivers were constrained by rainfall condition.

Table 1 15th percentile speed for dry and rainfall conditions

Site	Condition	15th percentile (km/h)	Change (%)
FT001	Dry	67.3	-
	Light Rain	64.5	-4.2
	Moderate Rain	61.7	-8.3
	Heavy Rain	60.5	-10.1
FT002	Dry	66.1	-
	Light Rain	63.4	-4.1
	Moderate Rain	62.1	-6.1
	Heavy Rain	60.3	-8.8
FT003	Dry	58.9	-
	Light Rain	55.0	-6.6
	Moderate Rain	50.7	-13.9
	Heavy Rain	50.3	-14.6
FT004	Dry	59.3	-
	Light Rain	55.8	-5.9
	Moderate Rain	55.1	-7.1
	Heavy Rain	50.9	-14.2

Table 2 50th percentile speed for dry and rainfall conditions

Site	Condition	50th percentile (km/h)	Change (%)
FT001	Dry	72.2	-
	Light Rain	69.7	-3.5
	Moderate Rain	68.0	-5.8
	Heavy Rain	66.8	-7.5
FT002	Dry	71.0	-
	Light Rain	68.5	-3.5
	Moderate Rain	67.5	-4.9
	Heavy Rain	66.1	-6.9
FT003	Dry	63.1	-
	Light Rain	58.3	-7.6
	Moderate Rain	55.5	-12.0
	Heavy Rain	54.1	-14.3
FT004	Dry	63.1	-
	Light Rain	60.7	-3.8
	Moderate Rain	58.0	-8.1
	Heavy Rain	58.3	-7.6

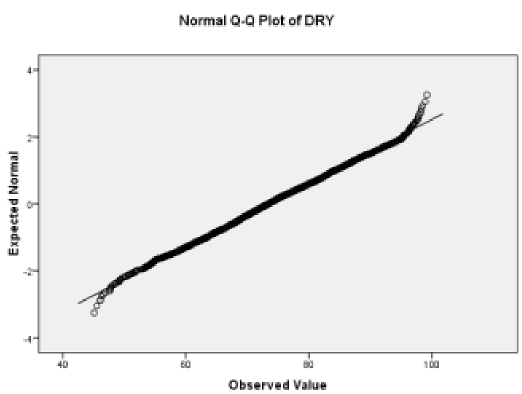
Table 3 85th percentile speed for dry and rainfall conditions

Site	Condition	85th percentile (km/h)	Change (%)
FT001	Dry	76.9	-
	Light Rain	74.4	-3.3
	Moderate Rain	73.8	-4.0
	Heavy Rain	73.6	-4.3
FT002	Dry	74.9	-
	Light Rain	73.9	-1.3
	Moderate Rain	72.7	-2.9
	Heavy Rain	73.7	-1.6
FT003	Dry	68.0	-
	Light Rain	63.6	-6.5
	Moderate Rain	62.6	-7.9
	Heavy Rain	58.5	-14.0
FT004	Dry	67.7	-
	Light Rain	64.3	-5.0
	Moderate Rain	62.4	-7.8
	Heavy Rain	63.7	-5.9

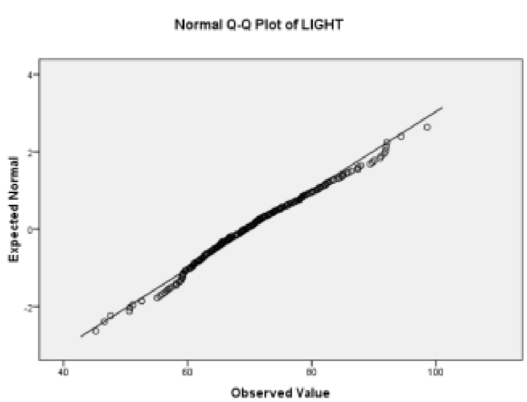
The speed percentile at all sites also showed similar trend in reduction although not by the same percentage. For 15th percentile speed, the range of reduction is 4.1 to 14.6%. The reduction range for 50th percentile speed is between 3.5 and 14.3%. While for 85th percentile speed, the reduction range is 1.3 to 14.0%. The dramatically change of all percentile speeds are found at site FT003.

In order to perform statistical test based on Crammer's theory of asymptotic distribution of sample quantiles, it is required to check the normality of the data. Fig. 5 shows the typical normal Quartile-Quartile (Q-Q) plots for dry and rainfall conditions. The x-axis in a Q-Q plot is for the observed data point. The y-axis is the expected data point if the population distribution of the variable is normal with the population mean and the population standard deviation. The normality of the data was assessed using Kolmogorov-Smirnov Test. With the null hypothesis that there is no difference between observed values and expected normally distributed values at 95% confidence level, the results indicated that the is no significance difference for all cases.

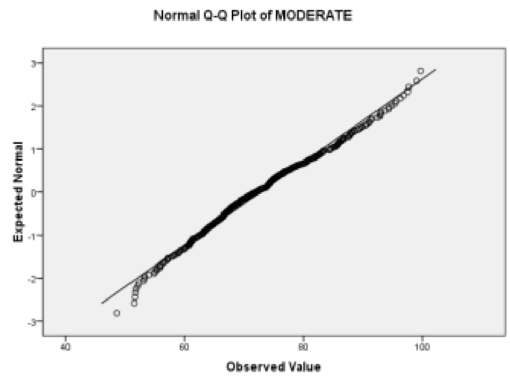
Since the test above signify the normality of the data, statistical test based on Crammer's theory of asymptotic distribution of sample quantiles was performed to assess the statistical significance of the difference in 15th, 50th and 85th percentile speeds between dry and rainfall conditions, respectively. Based on null hypothesis that there is no difference in percentile speed between two sample populations at 95% confidence level, the results of quantile test indicated that all percentile speeds were statistically significant difference for all cases. Therefore, it is clear that all speed percentiles under dry condition are statistically higher than speed under rainfall condition.



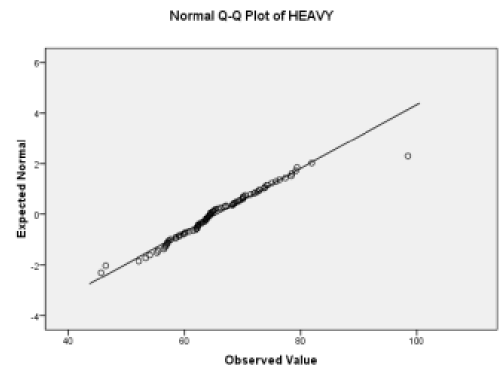
(a) Dry



(b) Light rain



(c) Moderate rain



(c) Heavy rain

Figure 5 Q-Q plots for dry and rainfall conditions for site FT001

■6.0 CONCLUSION

In this paper, the impact of rainfall on travel speed and the extents of speed reduction under rainfall conditions have been estimated using three months data collected during rainy season in Malaysia. Based on the synthesis of evidences obtained from the relationship between travel speed and rainfall, it is correct to conclude that:

- travel speed at 15th, 50th and 85th percentiles decrease with increasing rainfall intensities,
- all percentile speeds decreased from a minimum of 1 percent during light rain to a maximum of 14 percent during heavy rain, and
- there is a significant change in travel speed resulting from rainfall condition especially during heavy rainfall.

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