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Effect of Night-Time Rain on Travel Speed at Two-Lane Highway without Lights

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Abstract

Speed is one of the parameters used for performance measure of traffic. It is affected by weather changes. This paper investigates the effect of night-time rainfall on travel speed on two-lane highway without lights. Traffic and rainfall data were collected at four different sites in Nigeria for a period of eight weeks. The data were sorted into dry and rainy night-time, filtered and analysed. The use of flow-density relationship gives a better understanding of travel speed within traffic stream operation. The result of the study shows significant change in travel speed between the dry and rainy night-time conditions. The average travel speed reduction was observed to be 3.4%, 6.8% and 10.2% for light, moderate and heavy rain at night-time respectively. This confirms that travel speed reduces under night-time rainfall irrespective of its intensity.

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Keywords: Travel speed; free-flow speed; night-time rain; percentile

1. Introduction

Weather conditions and its impacts have been of primary concern to highway and traffic engineers in achieving a smooth, safe and reliable traffic operation. Changes in weather condition has been known to disrupt smooth traffic operations. The disruptions could result in delay, accident, safety implications, speed reduction, congestion and other hazardous driving conditions (FHWA, 2008 and Cools et al. 2010). Over the years, studies have recognised various

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weather conditions such as snow, rain, ice, darkness and fog and its effect on traffic flow. The traffic characteristics often affected include speed, flow, density, travel time, capacity amongst others. Due to various weather-related effects, traffic engineers now incorporate weather-based information into traffic operations (Tsapakis, et al. and Lam et al., 2013). Rain, a spatiotemporal weather condition affects traffic performance on road. Poor visibility, aquaplaning and reduction in tyre friction on pavement are some of rain effect on traffic. Rain disturbances depending on rainfall intensity may lead to travel speed reduction, increase in travel time, capacity loss and delay because of impaired visibility (Alhassan and Ben-Edigbe, 2014).

Traffic engineering guide and methods mostly assumed clear and normal weather (Agarwal et al 2005). Effect of rainfall intensities on traffic characteristics differs from road to road (Zhang et al., 2017). Rain affects driving in terms of tyre-pavement friction and visibility (Chung et al., 2006). Driving under rainy condition, drivers may reduce their travel speed because of poor visibility. Travel speed is important for assessing traffic operation on a roadway, however, little work had been done on night-time rainfall on a two-lane highway. It is on this opinion that this research is been carried out to investigate the effect of night-time rainfall on travel speed on a two-lane highway. The rest of this paper is divided as follows: Section 2 reviewed past literature on the subject. Section 3 is the materials and methodology used in the study. Results and findings are discussed in section 4 followed by conclusions in section 5.

2. Hypothetical Speed Shift caused by Night-Time Rainfall

Driving in the rain is generally harder than driving in fair weather, driving in the rain at night on a roadway without street lights, can cause dramatic declines in visibility. Standard vehicle headlights improve driver visibility at night by illuminating the roadway. Most vehicles use halogen lights with 700-2000 lumens. Lumens is the amount of light emitted from a source. Higher lumens generate brighter light with an estimated 100m illumined distance. Rain lessens the performance of headlamps and other light sources by filtering part of their luminous power, thus reducing the illuminance on the roadway ahead of the vehicle. This paper is not concerned with the effect of rainfall at night on headlights, rather it focuses on vehicle speed reduction at night on roads without street lights. Three types of speed were considered; free-flow speed, speed at capacity and travel speed under prevailing conditions. According to Angel et al (2014) rainfall at night would cause speed reductions of 1.6mph (light rainfall) 1.1mph (moderate rainfall) and 7.5mph (heavy rainfall). However, the study was carried out at night on roadways without street lights.

Speed is the rate at which a vehicle moves over a distance and is used qualitatively to describe vehicular movement on road. It is one of the basic macroscopic parameters of traffic flow. Highway and traffic engineers use speed for design purposes. Travel speed is the average speed of a traffic stream over an average time of vehicles moving in the stream. It is used to measure traffic performance in terms of service delivery of a roadway. Speed is affected by rain. Many studies have tried to quantify speed reduction under different rainfall conditions. HCM 2000 reported 2km/hr speed reduction in free-flow speed for light rain and 5-7km/hr speed reduction for heavy rain though the rainfall intensity ranges were not specified. Ibrahim and Hall (1994) observed a free-flow speed reduction of 2km/hr for light rain and 5-10km/hr for heavy rain on freeway operation in Canada. Free-flow speed reduction of 2km/hr and 10km/hr for light and heavy rainfall respectively was reported by May (1998). Likewise, Kyte et al. (2000) reported 5km/hr speed drop due to darkness for Brilon and Ponzlet (1996) study while Liang et al. (1998) observed 1.6km/hr speed reduction at night-time periods.

Chung et al. (2006) conducted a study on weather-induced impacts in Japan. They discovered a free-flow speed reduction of 4.5% and 8.2% in light and heavy rain respectively. In a related study, Hranac et al. (2007) reported free-flow speed reduces in the range of 2-3% for light rain. Wang and Luo (2016) reported free flow speed reduction of 4.4%, 7.3% and 10.6% for light, moderate and heavy rain respectively. Similarly, a study in Beijing, China shows speed reduction due to rain. Three classes of road (expressway, major arterial and collector) were studied by Zhang et al. (2017) for different time periods. Their study revealed travel speed reduction of 7.5, 5.0 and 9.4% for the expressway, arterial and collector roads respectively under heavy rain at night-time period.

This study is aimed at investigating the effect of rainfall on travel speed at a two-lane highway at night. Hypothetically, on a two-lane highway, travel speed reduces under night-time rain irrespective of its intensity as shown in figure 1. Note that U_D denotes speed under dry weather and U_R denotes speed under rainfall conditions.

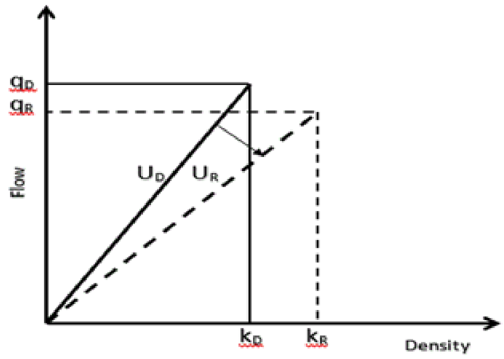

Fig 1: Hypothetical Shift in Travel Speed Caused by Rainfall at Night

Past studies analysed travel speed using the speed-density relationship (Lam et al. 2013, Wang and Luo 2016, Li et al. 2016 and Zhang et al. 2017). The drawback of the speed-density relationship is that individual speed characteristics of vehicles were considered without considering traffic flow in its totality. Consequently, the speed obtained from the speed-density relationship is best describes as spot speed. An alternative approach is the use of flow-density relationship. The flow-density relationship using fundamental diagram is assumed to reflect the proper travel speed within a traffic stream. It allows travel speed to operate within the boundary created in the flow density curve as shown below in figure 2. Note that the slope of the flow-density relationship represents travel speed and that:

Flow, $q = -ak^2 + bk - c$ (1)

Where; q = flow (pce/hr); k = density (pce/h); a, b and c are coefficients from the model equation.

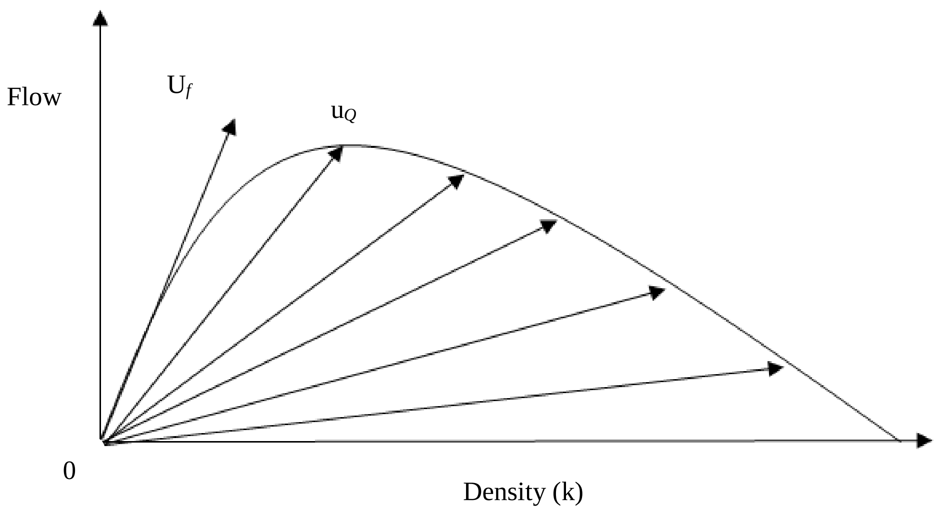

Fig 2: Flow, density and speed relationship

2.1. Percentile Speed

Since speed is a performance measurement tool, its percentiles are therefore important for design and safety purposes. The two percentiles often used are 85th and 15th percentiles though consideration could be given to the 50th percentile occasionally. 85th-percentile speed is the speed value less than 15% of a measured field speed (HCM 2000). Mashros et al. (2014) opined 85th percentile speed as the speed at or below which 85% of vehicle moved, 50th percentile speed represents half of the observed speeds while 15th percentile speed as the speed at which 15% of vehicles are moving. They further stated that 85th percentile is used in determining the safe speed of majority drivers on road while 15th percentile speed determines the allowable speed limit on a roadway. 50th percentile gives the average speed of the traffic stream observed. Furthermore, Hou et al. (2011) reported that 85th percentile speed is used in establishing speed limit while 15th percentile speed is for setting walking speed for signal timing. The critical volume to capacity ration known as degree of saturation (v/q) is important in traffic analysis. It is used in determining the traffic state of a roadway. If $v/q = 1$, it is possible to determine the 0.15, 0.5 and 0.85 percentiles of v/q.

As it is important to compare samples in a population, statistical tests are used to assess the statistical significance of different samples. Some of the statistical tests include nonparametric double bootstrapping, quantile regression, averaging percentiles and binomial test though their use is complex and questionable (Nordiana et al. 2014 and Hou et al. 2011). However, Hou et al. (2011) proposed using Cramer's theory of asymptotic distribution of sample quantile for testing 85th and 15th percentile of a sample. It is used to establish the normality of the data. The Cramer's theory is expressed mathematically as equation 2

$$\frac{(X_{([n0.85])+1} - Y_{([n0.85])+1}) - 0}{1.530\sqrt{\frac{S_x^2}{n_x} + \frac{S_y^2}{n_y}}} \tag{2}$$

Where $X_{([n0.85])+1}$ and $Y_{([n0.85])+1}$ are the 85th sample percentiles from independent normal distribution, and S_x^2 and S_y^2 are sample variances.

3. Methodology

Traffic and rain data were collected simultaneously for eight weeks on four selected two-lane highways in Nigeria. Rain data were obtained using rain-gauge with data-logger. The data-logger recorded rainfall data under a minute interval. This gives room for precision in rain data. Collected data were converted into intensity (i) and separated into light, moderate, heavy and very heavy rainfall using to World Meteorological Organisation (WMO) classification of light (i < 2.5mm/hr), moderate (2.5 ≤ i < 10 mm/hr) and heavy (10 ≤ i < 50 mm/hr) and very heavy (i > 50mm/hr). Only light, moderate and heavy rainfall intensity were considered. Very heavy rainfall was not considered due to aquaplaning and drag force effects capable of causing anxiety and aggression in driver's reaction. Rainfall intensity data were separated into daytime and night-time periods.

4. Traffic data were obtained with the use of Automatic traffic counter (ATC). The ATC collected traffic data continuously for the period of eight weeks. The continuity in traffic data collection allows for capturing of data under different weather and traffic conditions. This makes the use of ATC more reliable and safe to use in collecting traffic data under both daytime and night-time with or without rain. The traffic data collected include speed, vehicle type, headway, traffic volume, date and time of tyre hit on the pneumatic tubes. Traffic data collected were separated into daytime and night-time periods. Both traffic and rain data collected were separated into daytime and night-time using 6 am to 6 pm for daytime and from 7 pm to 11 pm for night-time. Night-time traffic data under dry and varying rain intensity were analysed and compared.

4. Analysis and Discussion

The stepwise method of analysis adopted because of its simplicity and clarity. Site 1 data for dry night-time is used as the sample for the analysis.

Step 1: Determine the speed percentile differentials caused by rainfall at night on a roadway without street lights.

Speed-cumulative frequency graph of site 1 under dry and rainy night-time periods is shown in figure 3. It is observed that speed is normally distributed. Moving from right to left, the first curve represents dry night-time condition while other curves represent the rainy night-time conditions. The curves show a shift from the right to the left which confirms speed reduction. The extent of speed reduction varies with rain intensity. A similar shift was observed at the other three study sites.

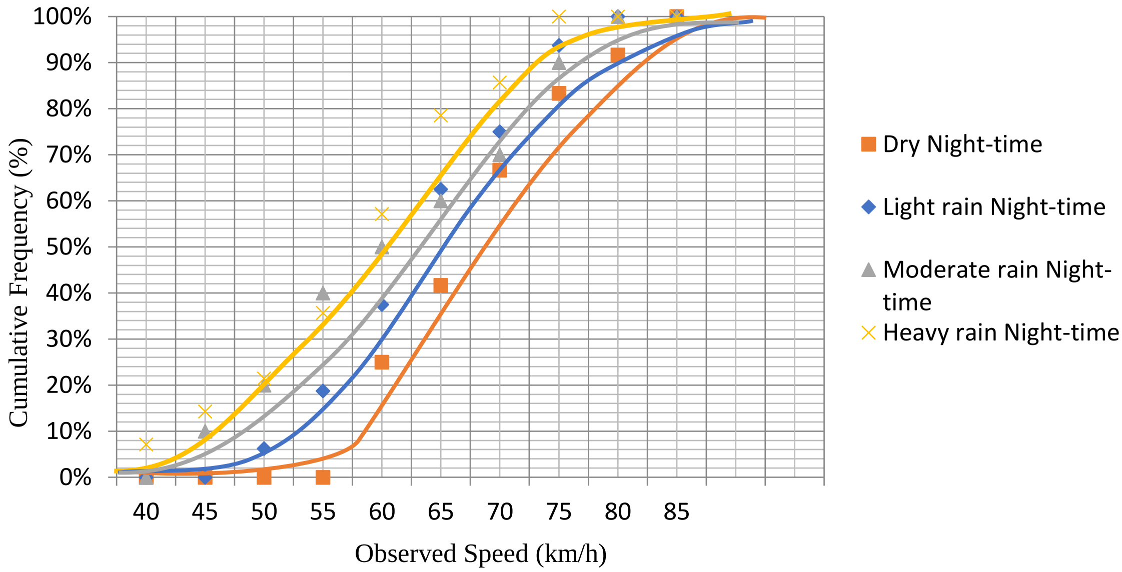

Fig 3: Speed-cumulative graph for dry and rainy night-time

The 85th, 50th and 15th percentile speeds were obtained from the cumulative distribution graph. Considering 85th percentile at site 1, speed reduced by 2.6% for light rain, 3.9% for moderate and 10.5% for heavy rain, 6.0%, 9.8% and 12.8% for light, moderate and heavy rain respectively for 50th percentile; and 8.6% for light, 17.2% for moderate and 20.7% for heavy rain at 15th percentile. The percentile summary for the entire four study sites is presented in table 1. It is evident in table 1 that speed reduces as rainfall intensity increases for all the study sites. The percentage of speed reduction varies from sites to site.

Cramer's theory of asymptotic distribution (Quantile-Quantile plot) was used in checking the normality of the data, use of. Fig 4 represents the Quantile-Quantile plot for both dry and rainy night-time of site 1. The x-x axis represents the expected normal distribution while y-y is the observed speed values. Furthermore, Kolmogorov-Smirnov test was used to test the normality of the data at 95% confidence level. The K-S value of 0.1206 obtained is lesser than 0.3754 critical values, d_{alpha} of the K-S table. Therefore, accept the null hypothesis that the data is normally distributed.

Table 1. Summary of speed percentile

Site	Weather condition	85%	Δ	50%	Δ	15%	Δ
1	Dry Night-time	76	-	67	-	58	-
	Light rain (Night-time)	74	2.6	63	6.0	53	8.6
	Moderate rain (Night-time)	73	3.9	60	9.8	48	17.2
	Heavy rain (Night-time)	68	10.5	58	12.8	46	20.7
2	Dry Night-time	73	-	62	-	53	-
	Light rain (Night-time)	72	1.4	61	1.6	50	5.7
	Moderate rain (Night-time)	67	8.2	60	3.2	48	9.4
	Heavy rain (Night-time)	65	11.0	58	7.3	45	15.1
3	Dry Night-time	81	-	69	-	57	-
	Light rain (Night-time)	76	6.2	67	2.9	56	1.8
	Moderate rain (Night-time)	74	8.6	66	4.3	55	3.5
	Heavy rain (Night-time)	70	13.6	60	13.0	50	12.3
4	Dry Night-time	83	-	66	-	50	-
	Light rain (Night-time)	80	3.6	63	5.3	49	2.0
	Moderate rain (Night-time)	69	16.9	60	9.1	48	4.0
	Heavy rain (Night-time)	68	18.7	58	12.9	45	10.0

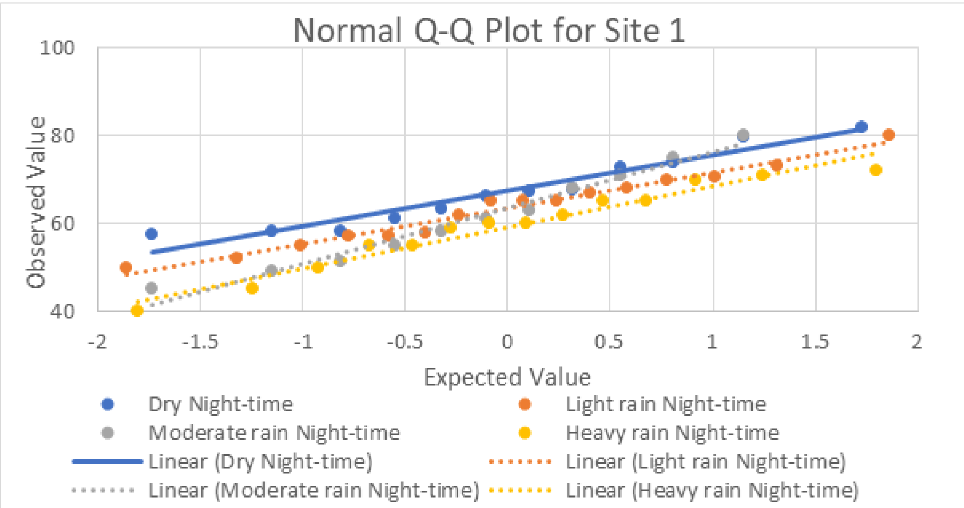

Fig 4: Normal Q-Q plot for site 1

Based on the effectiveness of the speed percentile in describing a reduction in speed due to rainfall, a further analysis of travel speed is carried

Step 2: Traffic volumes were converted to flow using modified passenger car equivalent (PCE) values, then speed and flow data were used to estimate densities. For example, when flow = 660pce/h and speed = 70km/h, therefore density (k) = q/u = 660/72 = 9pce/km

Step 3: Densities were plotted against flow to establish the quadratic model in equation 3. However, a statistical test for fitness was carried out on the model equation. The coefficient of determination (R^2) is greater than 0.5 signifying that the model is good for prediction. The F-observed at 5% significance is greater than F-critical (4.94) suggesting that the relationship did not occur by chance. The t-test is more than 2 which shows that the variables are important. All the models obtained for different weather conditions were statistically good.

$$q = -1.0123k^2 + 69.764k - 0.9499 \qquad R^2 = 0.9427 \tag{3}$$

$$\frac{dq}{dk} = -2.0246k + 69.764 = 0$$

$$k_c = 35pce/km$$

$$q_{0.85} = -1.0123 * (35)^2 + 69.764 * (35) - 0.9499$$

$$q_{0.85} = 1208 \text{ Pce/hr}$$

Step 4: Estimate speed at capacity

$$u = \frac{q}{k} = \frac{1209}{35} = 35pce/km$$

Same procedure was used in estimating the speed under dry and rainy conditions at night time for all the selected sites. The summary of the result is presented in Table 2. Where Uf denotes free-flow speed, ΔU denotes speed change, UQ denotes speed at capacity, U_f denotes travel speed, LR is light rain, MR is moderate rain and HR is heavy rain.

Table 2 shows that there is clear evidence that rain at night-time irrespective of its intensity has effect on travel speed. At site 1, free flow speed reduced from 70km/h to 67km/h with reduction of 3km/h (4.3%) for light rain and 66km/h (5.7%) for moderate and heavy rain. The speed at capacity reduce from 35km/h to 34km/h for light rain and 33km/h for both moderate and heavy rain. The travel speed changed from under dry night-time condition reduced from 58km/h to 57km/hr for light rain, 56km/hr and 55km/hr for moderate and heavy rain respectively. The percentage reduction for light rain is 1.7%, 3.4% for moderate and 5.2% for heavy rain. The reduction in speed occur due to changes in driver's behaviour. As it is a known fact, visibility is impaired under rain, drivers become more cautious of the vehicle ahead of them for safety and accident prevention. The cautiousness displayed because of impaired visibility forces drivers to reduce their speed. So as rain intensity increases, visibility is impaired more, and speed becomes more reduced.

Similarly, with increase in rainfall intensity, it was observed that speed reduced at sites 2, 3 and 4 anomalously i.e trend of speed reduction varies. This confirms the spatiotemporal nature of rainfall. At sites 1, 2 and 4, the free-flow speed, speed at capacity and travel speed for moderate and heavy rainfall are close with a difference in the travel speed at site 2. The closeness may be attributed to the fluctuation nature of rain in which the borderline for rainfall intensity classification cannot be taken as fixed. Rain might start initially as light and suddenly change into heavy within its period of occurrence or vice-versa, this therefore influences the intensity classification. Site 3 has the most significant reduction in speed. The free-flow speed reduction is 5.3% for light rain, 6.7% for moderate and 14.7% for heavy. Speed at capacity reduce from 38km/h to 35km/hr for light and moderate rain, and 32km/hr for heavy rain. The travel speed shows a significant reduction from 6.3% for light rain, to 7.9% and 26.9% for moderate and heavy rain respectively.

Taking the average free-flow speed, table 3 shows light rain reduces by 2.9%, moderate night and heavy rain at night-time reduce at 5.7% and 7.1% respectively. The average travel speed reduces by 3.4% for light rain, 6.8% for moderate rain and 10.2 for heavy rain. Considering speed as normally distributed with a ±5% standard deviation using the dry night-time speed, the change in speed is significant with moderate and heavy rain while light rain has no significant effect on speed.

Table 2. Summary of travel speed at dry and rainy night-time

Site	Condition	Model Equation	U_f (km/h)	ΔU_f (%)	U_Q (km/h)	ΔU_Q (%)	U_t (km/h)	ΔU_t	ΔU_t (%)
1	Dry	$-1.012k^2 + 69.76k - 0.949$	70		35		58		
	LR	$-0.992k^2 + 67.53k - 4.404$	67	-4.3	34	-2.9	57	-1	-1.7
	MR	$-1.031k^2 + 66.35k - 1.226$	66	-5.7	33	-5.7	56	-2	-3.4
	HR	$-1.032k^2 + 65.92k - 1.877$	66	-5.7	33	-5.7	55	-3	-5.2
2	Dry	$-0.975k^2 + 66.17k - 2.666$	66		33		55		
	LR	$-0.989k^2 + 63.38k - 1.177$	63	-4.5	32	-3.0	53	-2	-3.6
	MR	$-0.919k^2 + 60.62k - 0.333$	61	-7.6	30	-9.0	50	-5	-9.1
	HR	$-1.033k^2 + 62.09k - 1.736$	62	-6.1	31	-6.1	54	-1	-1.8
3	Dry	$-1.024k^2 + 75.17k - 1.009$	75		38		63		
	LR	$-1.099k^2 + 70.58k - 6.886$	71	-5.3	35	-7.9	59	-4	-6.3
	MR	$-1.088k^2 + 69.61k - 1.176$	70	-6.7	35	-7.9	58	-5	-7.9
	HR	$-0.969k^2 + 63.65k - 0.269$	64	-14.7	32	-16	46	-17	-27
4	Dry	$-0.942k^2 + 69.92k - 0.579$	70		35		58		
	LR	$-0.996k^2 + 69.76k - 2.341$	70	0	35	0	58	0	0
	MR	$-1.029k^2 + 66.54k - 4.645$	66	-5.7	33	-5.7	56	-2	-3.4
	HR	$-1.097k^2 + 67.54k - 6.488$	67	-4.3	34	-2.9	56	-2	-3.4

Table 3. Average speed summary for all sites

	$\bar{U}_f$ (km/h)	$\Delta\bar{U}_f$ (%)	$\bar{U}_Q$ (km/h)	$\Delta\bar{U}_Q$ (%)	$\bar{U}_t$(km/h)	$\Delta\bar{U}_t$ (%)
Dry night-time	70		35		59	
Light rain (night-time)	68	-2.9	34	-2.9	57	-3.4
Moderate rain (night-time)	66	-5.7	33	-5.7	55	-6.8
Heavy rain (night-time)	65	-7.1	33	-5.7	53	-10.2

5. Conclusion

This paper examined the effect of night-time rainfall on travel speed on a two-lane highway in Nigeria. The results of the study show that a significant effect of rainfall on travel speed. Travel speed decreases with increase in rainfall intensity at night-time and the reduction is more significant with heavy rain intensity. Therefore, the hypothesis that on a two-lane highway, travel speed reduces under night-time rain irrespective of its intensity is valid. Furthermore, spot speed reduces with increase in night-time rainfall intensity. The use of flow-density relationship over speed-density relationship gives a proper understanding of travel speed.

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