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# Night-Time Rainfall and Free-Flow Speed on Two-Way Highway with No Light: Implications for Travel Time

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***Abstract*** *— Travel time is an intrinsic measure used in assessing roadway performances and it is affected by environmental factors such as weather changes. The study investigates the implication of nighttime rainfall on travel time of a two-way highway without light. In Akure, for a period of eight weeks, rainfall and traffic data were obtained across four different sites. The data obtained were filtered, sorted into dry and night-time conditions. Observed traffic volumes were converted to flows using modified passenger car equivalent values. Subsequently, regression methodologies were employed to establish functional relationships between flow and traffic density. For all the models obtained, the coefficient of determinant $R^2$ varies between 0.79 and 0.98 for all the weather conditions across the four sites. The $R^2$ values were greater than 0.5, which confirmed that the models were satisfactory for prediction. The results obtained show significant decrease in free-flow speed with corresponding increase in travel time for rainy nighttime. Travel time increased as rainfall intensity increases. The average travel time for dry nighttime was 0.73 min, which increased to 0.78 min (6.8%) for light rain, 0.81 min (11.0%) and 0.96 min (31.5%) for heavy rain. Heavy rainfall intensity has a more significant effect on travel time increase as compared to other rainfall intensities. The paper concludes that the influence of rainfall as a weather factor is evident on roadways without light, hence the combination of rainfall and darkness impacts travel time greatly. Irrespective of rainfall intensity, travel time increases under nighttime condition of a two-way highway.*

***Keywords*** *—* ***Nighttime, rainfall, traffic flow, travel time, two-way highway***

## I. INTRODUCTION

Highways are regarded as an important element of transportation and as a means of communication. It serves as a vital connection between other types of transportation mode hence it is expected that traffic flow on such highway should be safe, efficient and be with little or no delay as the case maybe. However, it had been discovered that traffic movement on highways is often time incapacitated due to many influencing factors such as traffic, roadway, weather conditions amongst others. These factors affect traffic behaviour in terms of both its microscopic and macroscopic properties.

Weather events are a global phenomenon in which their occurrence varies from place to place over time. Its impacts either constructively or otherwise. This weather event occurs in various forms such as fog, wind, darkness and rainfall with varying intensities of either being mild or harsh. Rain as a weather condition may occur in terms of its intensity such as light rainfall, moderate rainfall, heavy and at times very heavy. Rainfall occurrence during driving


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on the roadway calls for attention and study as it affects the performance of the road and its services. Makinde and Ben-Edigbe (2020) reported reduction in travel speed on a two-way road because of weather (rainfall) condition.

Darkness is another weather condition that occurs due to the absence of naturally occurring light. It is a natural phenomenon that cannot controlled by man however it could be mitigated using artificial lighting. Gallen et. al. (2015) reported that larger proportion of road accidents occur during nighttime due to altered visibility. The Highway Capacity Manual recognized darkness as a contributing factor capable of affecting traffic parameters with consequent reduction in roadway capacity though the quantification in terms of the effect remains limited. It is therefore correct to say the combination of rainfall and darkness will significantly affect traffic on roadways in terms of safety and operations. Anarkooli and Hosseilou (2016) reported that roadways without road lighting are prone to accident occurrence while drivers travel at lower speeds on such roads.

Many research works have reported different influences of weather, especially rainfall on traffic flow parameters in terms of travel, speed, headway, service quality, capacity and many more. Ibijola 2018 studied the impact of rainfall on quality of service at multilane roundabouts and reported a significant adverse effect on functional quality service at roundabout. Oyaro and Ben-Edigbe (2020) considered the impact of rainfall on capacity loss at signalised intersection and reported speed reduction at signalised intersections while Makinde 2020 assessed the influence of rainfall on service quality of road without light and reported significant deterioration of service quality.

As travel time is an intrinsic measure used in assessing roadway performance, little is known about it relative to weather influence, hence this leaves a research gap. This research is therefore aimed at studying the effect of both nighttime and rainfall combined with travel time of a two-lane highway.

The rest of this paper is presented as thus – section two is the literature review while section three gives the methodology of the research. Section four is for results and discussions while conclusion and recommendations are presented in section five.

## II. THEORY

A two-way highway is complex in nature due to the bidirectional nature of traffic flow. The complexity gives rise to the possibility of head-on collisions amongst drivers. This raises the question of safety risks which become more complicated when considering weather conditions such as rainfall and darkness on such roadways.

Rainfall is a spatiotemporal naturally occurring weather condition capable of affecting traffic flow on the roadways. One common effect of rainfall on traffic flow is poor visibility. Driving on roads while the rain is falling impairs the vision of drivers, however the extent of the impact is subjected to the intensity of the rainfall. The consequent effects of rainfall during driving often lead to various impacts such as speed reduction and headway increase amongst others. These impacts affect the behaviour of traffic in terms of its parameters on roadways. Mathew and Pulugurtha (2022) reported that rainfall and poor visibility disrupt the performance of road operation in different ways. Tobin et al. 2019 reported that 8.6% of vehicle-related fatalities occurred during rainfall occurrences on roadways.

Speed, headways, flow and density are the major traffic flow parameters in designing highways, but travel time is considered paramount for use in assessing the service performance of a roadway. Past studies were centred on the influence of rainfall on the major traffic flow parameters with little report on travel time. The few literatures on travel time were focused on freeways. Zhang and Chen (2019) reported that the impact from weather events is more prominent on the reliability of travel time.

Travel time according to HCM 2020 is defined as the average time a vehicle traverse through a segment of a roadway. It is useful in measuring and assessing the performances of a roadway in terms of its delivery either qualitatively or quantitively. Travel time is useful to both the highway designers, traffic planners and the road users as everyone desires to accomplish a journey within the shortest possible time with little or no delay. Thus, the time taken to traverse a road length is a function of road, traffic and weather conditions. Travel time used in conjunction with delay and capacity is useful in measuring the effectiveness of roadways (Mashros et al. 2012). The general travel time equation is given as


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$$t = \frac{d}{u} \quad (1)$$

where t = travel time, d = distance travelled and u = speed of travelling

According to the US Bureau of Public Roads (US-BPR), travel time over a length of a roadway could be determined using equation 2

$$T = t_f[1 + \rho(x)^{\beta}] \quad (2)$$

where T = travel time for the length of the roadway

$t_f$ = travel time at free flow speed

$\rho$ = ratio of free-flow speed to the speed at capacity

$\beta$ = abrupt drop of curve from the free flow speed

$x$ = degree of saturation $(v/Q)$

$v$ = demand flow $(q = uk)$

$Q$ = roadway capacity taken as 80% of actual capacity

In determining $\rho$ and $\beta$, the 1965 BPR version suggested $p = 0.14$ and $\beta = 4$ in solving travel time however more studies by Dowling and Skarbadonis (1993) on the BPR curve faulted the underestimation of the values of $\rho$ and $\beta$. They suggested higher values of $p = 0.2$ and $\beta = 10$, therefore equation 2 can be re-written as

$$T = t_f[1 + 0.2(x)^{10}] \quad (3)$$

Recall that $x = v/Q$, therefore equation 3 becomes

$$T = t_f\left[1 + 0.2\left(\frac{v}{Q}\right)^{10}\right] \quad (4)$$

For this paper, the condition considered is the free flow situation where drivers choose their individual speed because of no vehicles on the road. The capacity $Q$ in equation 4 is defined as the maximum hourly flow rate at which vehicles or persons are expected to pass a certain point or a uniform section of a roadway for a certain period under prevailing roadway and traffic conditions (HCM 2020) is obtainable using the fundamental flow diagram. Estimating the capacity is possible using different methods such as headway, selected maxima, product limit, fundamental diagram. The choice of capacity estimation method depends on the available data, hence, for this paper, the availability of enough empirical data encouraged the adoption of the fundamental diagram method. The fundamental flow diagram features the relationship that co-exists amongst the three basic traffic parameters. The relationships are bi-variable in nature and exist as flow-density, speed-density and speed-flow diagrams as shown in figure 1.

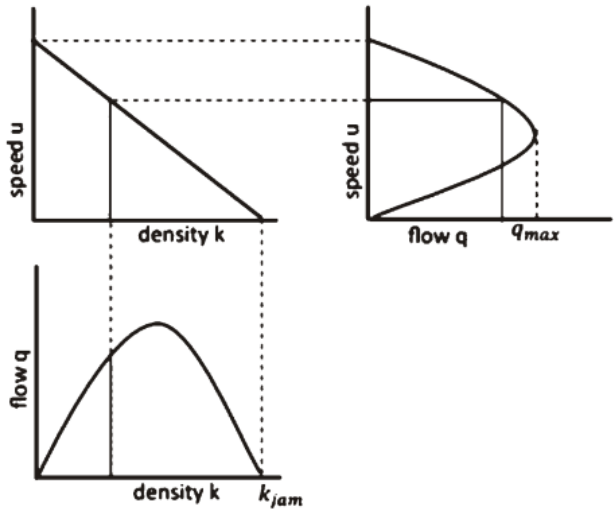



*Fig.1: Fundamental flow diagram showing the bi-variable relationship of flow, density and speed*

In analysing the relationships, the speed-density is a linear function (Greenshield, 1934) as given in equation 5

$$u = u_f - \varphi k \quad (5)$$

where u = mean speed, $u_f$ = free-flow speed, $\varphi$ = coefficient = $\frac{u_f}{k_j}$, k = density

equation 5 is further written as

$$u = u_f - \frac{u_f}{k_j}k$$

The flow-density is represented using quadratic equation (equation 6) while the speed-density is a linear function (Greenshield, 1934) as given in equation 6 however the speed-flow cannot prescribe any model equation because the graph is not a function. Wang and Luo (2016) studied the impact of rainfall on freeway traffic flow using the speed-density distribution. They reported decrease in flow rate and free flow speed as rainfall intensity increases. The flow-density relationship had been used by various studies to analyse traffic stream relationships. Ipindola and Falana (2019) and Makinde (2020) reported the suitability of the flow-density relationship to study traffic streams on a two-lane highway. The flow-density relationship is given as

$$q = -ak^2 + bk - c \quad (6)$$


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where q = flow, k = density

Based on the usefulness of the flow-density relationship, it is possible to determine density (both jam and critical), their corresponding speed values and roadway capacity, therefore equation 6 is further expressed to give equation 7

$$Q = -\frac{v_f}{k_j}\left(\frac{v_f}{2\left(\frac{v_f}{k_j}\right)}\right)^2 + (v_f)\frac{v_f}{2\left(\frac{v_f}{k_j}\right)} - c \qquad 7$$

Equation 7 is inserted into equation 4 to give equation 8

$$T = t_f\left[1 + 0.2\left(\frac{v}{Q}\right)^{10}\right] \Rightarrow T = t_f\left[1 + 0.2\left(\frac{v}{-\frac{v_f}{k_j}\left(\frac{v_f}{2\left(\frac{v_f}{k_j}\right)}\right)^2 + (v_f)\frac{v_f}{2\left(\frac{v_f}{k_j}\right)} - c}\right)^{10}\right] \qquad 8$$

According to Makinde and Ben-Edigbe (2019), equation 8 can be used to estimate travel time. They further stated that the equation is suitable for both rainy and dry conditions during daylight and night-time periods.

## III. METHODOLOGY

The method employed for this research study was collection of empirical data which were obtained from four selected roadways sites in Akure, Nigeria. The selected sites were ensured to be sites with good road pavement, devoid of all forms of distractions and unusual illumination. The lighting used at night during data collection solely relied on car headlamps as this helped to ensure that the darkness condition was maintained to achieve the research objectives. Traffic data was collected continuously using automatic traffic counter (ATC) machine which was placed across the selected roadways. The ATC had two pneumatic tubes placed across the roadway and laid 1m apart. For the rainfall data, the use of rain gauge was employed, the precipitation data from it retrieved and converted into rainfall intensity according to using World Metrological Organization (WMO) standard.

Traffic data were separated into both daylight (from 5am to 6pm) and nighttime (6pm to 5am). The nighttime period of 6pm to 5am was used in sorting the rainfall data into its respective intensity based on the WMO standard. The WMO rainfall intensity $i$ standard is light rain ($i$ < 2.5mm/hr), moderate rain (2.5 ≤ $i$ < 10 mm/hr), heavy rain (10 ≤ $i$ < 50 mm/hr) and very heavy rain ($i$ > 50mm/hr). The very heavy rain for this study was disregarded because of possible drag force and aquaplaning. Traffic and rainfall data between the hours of 12 am to 5 am were not considered due to inconsistency in traffic flow.

## IV. RESULTS AND DISCUSSION

The method used in analysing data was simple and clear enough for proper understanding. Both rainfall and traffic data obtained were separated into daylight and darkness periods using the time frame allotted to each. Traffic data under the nighttime period were separated into data with and without rainfall. The rainfall during the nighttime period was separated into light rain, moderate rain and heavy rain intensities and synchronised with traffic data with rainfall that corresponds with each rainfall intensity.

The synchronised traffic data for each rainfall intensity was further divided into passenger cars, light vehicles and heavy vehicles to allow for proper configuration of the vehicles involved in obtaining the traffic volume. The traffic volume was converted into traffic flow using the appropriate passenger car equivalent which was modified to reflect the prevailing condition under which the data was obtained. Subsequently, regression methodologies were employed to establish functional relationships between free-flow speed and traffic density.

Using equation $q = uk$, density was obtained for typical speed and its corresponding flow as shown in table 1 below. Density was obtained for all conditions of dry and varying rainfall intensity conditions at nighttime.


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*Table 1: Dry nighttime condition for site 1*

| Period | PC | MV | HV | vol | MV | HV | Q | q | u | k |
|---|---|---|---|---|---|---|---|---|---|---|
| *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* |
| | | | | | *3*1.15* | *4*1.34* | *2+6+7* | *8 *12* | | *9/10* |
| 1 | 72 | 7 | 4 | 83 | 8.05 | 5.36 | 85.41 | 1025 | 73 | 14 |
| 2 | 74 | 4 | 5 | 83 | 4.6 | 6.7 | 85.3 | 1024 | 65 | 16 |
| 3 | 67 | 7 | 3 | 77 | 8.05 | 4.02 | 79.07 | 950 | 63 | 15 |
| 4 | 60 | 10 | 5 | 75 | 11.5 | 6.7 | 78.2 | 938 | 66 | 14 |
| 5 | 84 | 5 | 7 | 96 | 5.75 | 9.38 | 99.13 | 1190 | 65 | 18 |
| 6 | 68 | 5 | 5 | 78 | 5.75 | 6.7 | 80.45 | 965 | 73 | 13 |
| 7 | 52 | 3 | 3 | 58 | 3.45 | 4.02 | 59.47 | 713 | 65 | 11 |
| 8 | 53 | 2 | 2 | 57 | 2.3 | 2.68 | 57.98 | 700 | 68 | 10 |
| 9 | 61 | 9 | 6 | 76 | 10.35 | 8.04 | 79.39 | 952 | 69 | 14 |
| 10 | 75 | 8 | 4 | 87 | 9.2 | 5.36 | 89.56 | 1075 | 64 | 17 |
| 11 | 69 | 6 | 4 | 79 | 6.9 | 5.36 | 81.26 | 975 | 65 | 15 |
| 12 | 55 | 2 | 1 | 58 | 2.3 | 1.34 | 58.64 | 703 | 74 | 10 |

*Note: 1, 2, 3...11 = column numbers, column 2 – 5 = volume by 5mins, column 6 - 8 = flow (pce/5mins), q = total flow (pce/h.), u = speed (km/h), k = density (pce/km), PC = passenger car, MV = medium vehicle, HV = heavy vehicle*

Density and flow for each weather condition were related graphically (fig 2) to obtain the quadratic model given in equation 9. The statistical testing of the model confirmed that the coefficient of determinant $R^2 = 0.93$ was more than 0.5 with a t-test greater than 2.2. The results of the statistical test showed that the variables are significant, hence the models are satisfactory for event prediction.

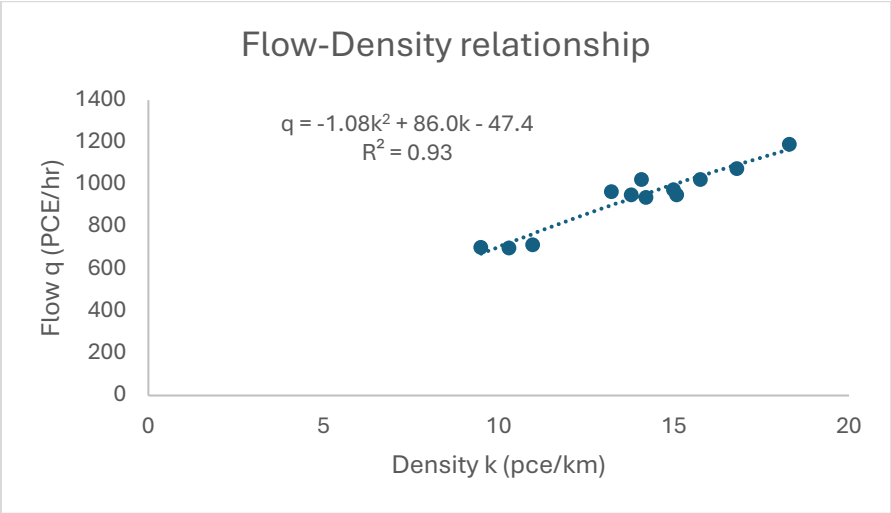



*Fig 2: Graphical representation of flow-density relationship*

Consider the model equation of the dry night condition as given in equation 9,

$$q = -1.08k^2 + 86.0k - 47.4 \quad (9)$$

The equation was differentiated to determine the critical density, and its corresponding capacity is shown below.

$$\frac{dq}{dk} = -2 * 1.08k + 86.0 = 0$$

$$-2.16k + 86.0 = 0$$


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$$k_c = \frac{86.0}{2.16} = 39.8pce/km$$

Insert the value of $k_c$ obtained into equation 9 to obtain maximum capacity

$$q = -1.08k^2 + 86.0k - 47.4$$

$$q = -1.08 * (39.8)^2 + 86.0 * 39.8 - 47.4$$

$$q = 1664.63pce/h$$

Furthermore, the maximum speed was calculated using equation $q = uk \Leftrightarrow u = \frac{q}{k}$

$$u = \frac{q}{k} = \frac{1664.63}{39.8}$$

$$u = 41.8km/h$$

Recalling equation 8, the travel time is thus obtained as

$$T = t_f\left[1 + 0.2\left(\frac{v}{Q}\right)^{10}\right] \Rightarrow T$$

$$= t_f\left[1 + 0.2\left(\frac{v}{-\frac{v_f}{k_j}\left(\frac{v_f}{2\left(\frac{v_f}{k_j}\right)}\right)^2 + (v_f)\frac{v_f}{2\left(\frac{v_f}{k_j}\right)} - c}\right)^{10}\right]$$

The free flow speeds and travel times for all weather conditions of the selected sites are summarised and presented in tables 2 - 5

*Table 2: Free flow speeds and travel times for site 1*

| Weather condition | Flow-density relationship equation | $R^2$ | Free flow $u_f$ | Travel time T (min) |
|---|---|---|---|---|
| Dry NT | $-1.08k^2 + 86.0k - 47.4$ | 0.93 | 86.0 | 0.75 |
| Light rain NT | $-1.01k^2 + 81.7k - 43.9$ | 0.92 | 81.7 | 0.79 |
| Moderate rain NT | $-0.96k^2 + 79.4k - 18.2$ | 0.94 | 79.4 | 0.81 |
| Heavy rain NT | $-0.92k^2 + 69.4k - 16.4$ | 0.86 | 69.4 | 0.93 |

*Table 3: Free flow speeds and travel times for site 2*

| Weather condition | Flow-density relationship equation | $R^2$ | Free flow $u_f$ | Travel time T (min) |
|---|---|---|---|---|
| Dry NT | $-1.07k^2 + 88.9k - 63.9$ | 0.92 | 88.9 | 0.72 |
| Light rain NT | $-1.03k^2 + 78.9k - 40.1$ | 0.84 | 78.9 | 0.81 |
| Moderate rain NT | $-1.02k^2 + 72.8k - 8.0$ | 0.79 | 72.8 | 0.88 |
| Heavy rain NT | $-1.08k^2 + 70.2k - 18.5$ | 0.85 | 70.2 | 0.92 |

*Table 4: Free flow speeds and travel times for site 3*

| Weather condition | Flow-density relationship equation | $R^2$ | Free flow $u_f$ | Travel time T (min) |
|---|---|---|---|---|
| Dry NT | $-0.99k^2 + 93.5k - 89.0$ | 0.86 | 93.5 | 0.67 |
| Light rain NT | $-1.14k^2 + 80.2k - 0.24$ | 0.98 | 80.2 | 0.80 |
| Moderate rain NT | $-1.05k^2 + 75.5k - 2.42$ | 0.87 | 75.5 | 0.85 |
| Heavy rain NT | $-1.11k^2 + 71.4k - 2.93$ | 0.98 | 71.4 | 0.90 |


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*Table 5: Free flow speeds and travel times for site 4*

| Weather condition | Flow-density relationship equation | $R^2$ | Free flow $u_f$ | Travel time T (min) |
|---|---|---|---|---|
| Dry NT | $-1.11k^2 + 87.9k - 13.7$ | 0.88 | 87.9 | 0.73 |
| Light rain NT | $-0.91k^2 + 82.1k - 86.3$ | 0.90 | 82.1 | 0.78 |
| Moderate rain NT | $-1.03k^2 + 78.9k - 21.9$ | 0.87 | 78.9 | 0.81 |
| Heavy rain NT | $-1.09k^2 + 67.3k - 15.6$ | 0.89 | 67.3 | 0.96 |

From the tables for the four sites considered, the $R^2$ values for the flow-density relationship equations were above 0.5 which implies that the variables are significant.

At site 1, the free-flow speeds and travel times varied for the identified weather conditions. The free-flow speed decreases as the condition changes from dry nighttime to rainy nighttime while travel time increases as the weather changes from dry nighttime to rainy nighttime. Free flow speed of 86 km/h with a corresponding travel of 0.75 minutes was obtained for the dry nighttime condition. For the rainy nighttime condition, the travel time is 0.79 minutes for light nighttime rainfall, 0.81 minutes for moderate nighttime rainfall and 0.93 minutes for heavy nighttime rainfall. The difference in travel time is 0.04 minutes (5.3%) for light rain intensity, 0.06 minutes for moderate rain intensity while heavy rain intensity is 0.18 minutes (24%)

In similar manner, sites 2, 3 and 4 also experienced decrease in free-flow speed with corresponding increase in travel time as the conditions change from dry nighttime to rainy nighttime. The decrease in free-flow speed and increase in travel time do not follow any trend in terms of the differences, however a significant increase in travel time under heavy rainfall intensity was observed across the four sites as presented in table 6.

*Table 6: Summary of change in travel time across the four sites*

| Site | Weather condition | Free flow speed | Travel time | Change in travel time | Percentage change in travel time |
|---|---|---|---|---|---|
| 1 | D - NT | 86.0 | 0.75 | | |
| | LR - NT | 81.7 | 0.79 | 0.04 | 5.3 |
| | MR - NT | 79.4 | 0.81 | 0.06 | 8.0 |
| | HR - NT | 69.4 | 0.93 | 0.18 | 24.0 |
| 2 | D - NT | 88.9 | 0.72 | | |
| | LR - NT | 78.9 | 0.81 | 0.09 | 12.5 |
| | MR - NT | 72.8 | 0.88 | 0.16 | 22.2 |
| | HR - NT | 70.2 | 0.92 | 0.20 | 27.8 |
| 3 | D - NT | 93.5 | 0.67 | | |
| | LR - NT | 80.2 | 0.80 | 0.13 | 19.4 |
| | MR - NT | 75.5 | 0.85 | 0.18 | 26.9 |
| | HR - NT | 71.4 | 0.90 | 0.23 | 34.3 |
| 4 | D - NT | 87.9 | 0.73 | | |
| | LR - NT | 82.1 | 0.78 | 0.05 | 6.9 |
| | MR - NT | 78.9 | 0.81 | 0.08 | 11.0 |
| | HR - NT | 67.3 | 0.96 | 0.23 | 31.5 |


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Considering the changes in travel time across the four sites, the average increase in travel time for light-rain nighttime condition is 0.08 min (11%), moderate rain nighttime accounts for 0.12 min (16.7%) while the heavy rain nighttime is 0.21 min (29.2%). Heavy rainfall intensity is of more significant impact on travel time as compared to both light rain and moderate rain intensities.

## V. CONCLUSION

Driving on roadways without light at night experiences many challenges while the addition of rainfall with the absence of light aggravates the problems. This paper addresses the impact of nighttime rainfall on travel time of a two-way highway without light. The result of the study shows significant impact of nighttime rainfall on travel speed.

Travel time increases as rainfall intensity increases, in which the increase is more pronounced with heavy rainfall intensity. Based on the evidence obtained between the nighttime rainfall and roadway without light, it is evident to conclude that rainfall encourages drivers to drive with less speed under a no-light condition on roadways. The reduction in speed leads to increase in the time spent on roadways under the condition of no-light on roadways.

It is therefore correct to say that travel time increases on a two-lane highway under nighttime rain irrespective of its intensity is correct. The cumulative effect of both rainfall and darkness on travel time is significant enough in the consideration of safety of road users by highway designers. In ensuring proper and efficient usage of road to enhance performance, road lightings are recommended to be made available to aid visibility under rainfall conditions at nighttime.

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