EFFECT OF RAINY DARKNESS INTENSITY AT TWO-LANE HIGHWAY ON TRAVEL TIME DIFFERENTIALS

Makinde, Opeyemi Oluyemisi[1,3] and Ben-Edigbe, Johnnie[2]
[1] University of KwaZulu-Natal, South Africa
[2] University of KwaZulu-Natal, South Africa
[3] 216073398@stu.ukzn.ac.za

Abstract: In this paper travel time differentials prompted by rainy darkness on Two-Lane Highway were investigated. The investigation raises the issue of night travel on roads without lights. Even though drivers react to rainfall and darkness simultaneously, studies have not been carried out insufficiently. Hence the paper wants to provoke debate on this issue. Based on the hypothesis that rainy darkness irrespective of intensity will cause travel time increase, with and without rainy darkness studies were carried out at three selected sites in Nigeria during the rainy season (June-August). Traffic and rainfall data were collected continuously for eight weeks. Rainfall intensity was classified according to the conventional rate of precipitation: Light rain — when the precipitation rate is < 2.5 mm (0.098 in) per hour. Moderate rain — when the precipitation rate is between 2.5 mm (0.098 in) - 7.6 mm (0.30 in) or 10 mm (0.39 in) per hour. Collated data on which the study was based were analyzed. Travel times for with and without rainy darkness were estimated and compared. Results show that there is speed reduction of 4.1% due to light rain effect, 8.6% and 14.8% due to moderate and heavy rain effect respectively. Further, travel time increase relative to speed decrease during rainy darkness, thus suggesting that motorists reduce vehicle speed when it is dark and rainy irrespective of intensity. The paper concluded that rainy darkness has a significant effect on travel time.

1   Introduction

The highway is an important element of transportation because it connects all other forms of transportation. Traffic flows on the highway are expected to be safe, efficient, give good driving comfort and with minimum delay. Vehicle performance on highway depends on the road geometry, traffic volume, traffic composition and weather condition like fog, snow, wind, darkness and rainfall. These weather conditions can be mild and could be harsh depending on the intensity of rain and fog, wind speed and their duration.   Harsh weather condition can bring about total traffic flow disruption on the highway. The weather impacts on traffic flows affect delays, safety, travel demand, and road accident (FHWA, 2008 and Cools *et al.* 2010). Weather impact on traffic flow may increase accident, delay, speed reduction and traffic flow contraction (Alhassan and Ben-Edigbe, 2014). Rainfall disrupts traffic flow by reducing driver's visibility, thereby leading to speed reduction, and increase in headways (Ben-Edigbe, 2010). Other studies by Chung et al, (2005) and Mukhlas et al (2016) showed that increase in rainfall intensity causes speed and capacity decrease and increase in travel time. Under darkness condition where there is no road lightning, there is poor or no illumination, drivers are dependent on the performance of their vehicle headlights. This condition affects the driver's visibility because of deterioration in colour vision which could lead to a reduction in sight distance. If rainfall is thrown in the mix, then driving conditions deteriorate even further. Rainy darkness depicts rainfall and darkness conditions. When driving under rainy darkness, the driver will be subjected to the combined effect of rainfall and darkness. This might

make the reaction of the driver to rainfall under daylight to be different from under darkness. No research has been carried out on the effect of rainy-darkness on the travel time. Hence, the need for this study. This study is not about comparing the difference in the rain effect under daylight and darkness but the rainfall effect on travel time under darkness. Based on the hypothesis that travel time increases irrespective of rain intensity under dark weather condition, the remainder of this paper is divided four sections; the immediate section is the literature review, section 3.0 is on materials and methodology, and section 4.0 is the findings and discussion. In section 5, conclusions are drawn.

2   Literature Review

Rainfall as a major cause of road hazard occurs more frequently than other weather conditions (Alhassan and Ben-Edigbe, 2011a). The spatiotemporal nature of rainfall accounts for its effects on traffic flow. The effects of rainfall on road traffic majorly are poor visibility and aquaplaning which may result in flow contraction, speed reduction and increase in headways. The extent of the rainfall effect is a function of the variability in rainfall intensity. These rainfall problems affect the behaviour of traffic on road. The behaviour of traffic flow is crucial and important in planning, designing and managing of highway and its facilities. The major traffic flow parameters are speed, flow, density and headway. Travel time is a function of speed and traffic flow with optimum interest for highways planners and designers. Traffic parameters are used to analyse traffic flow processes and highway performances with respect to changes in any or all the traffic parameters. As contained in previous studies the fundamental relationship traffic stream parameters is expressed in equations 1 and 2.

[1] $q = uk \implies u = \frac{k}{q} \implies k = \frac{q}{u}$

[2] $u = u_f - \varphi k$

where: q = flow, u = mean speed, k = density, u_f = free-flow speed, and φ = a coefficient.

The parameters speed and density are empirically related and are used to evaluate the quantity of flow on a roadway and to assess the congestion level of a freeway. These parameters though inter-related are dependent on various factors such as vehicle type, size and composition, weather conditions such as rainfall, snow, ice, fog, daylight and darkness. The individual effect of the various factors varies in magnitude and time of occurrence.

2.1   Travel Time

Travel time described as the average time spent by vehicles in moving through a highway segment (HCM,2000). Travel time is important to both road users and highway designers in measuring road performance. Travel time used together with delay and capacity, is used for measuring the effectiveness of roadway (Mashros et al 2012). The studies showed that travel time effectiveness is affected by road, traffic and rainfall under daylight conditions.

Travel time equations are shown in 3 and 4 below:

[3] $u = \frac{d}{t_f} \implies t_f = \frac{d}{u}$

where: u = speed, d = distance, t_f = travel time at free flow.

t_f occurs when density is zero i.e no vehicle on the road and/or operating speed are determined and controlled by drivers themselves. In general, prediction of travel time over a length of roadway is calculated using the equation postulated by US Bureau of Public Roads (US-BPR).

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

where T = predicted travel time over the length of roadway

   t_f = travel time at free flow speed

x = degree of saturation (v/Q) (defined as 115% of speed at capacity)

v = demand flow ($q = uk$)

Q = capacity (80% of actual capacity)

ρ = ratio of free-flow speed to the speed at capacity

β = abrupt drop of curve from the free flow speed

Equation 4 can be re-written as:

$$[5]\ T = t_f \left\{ 1 + \rho \left(\frac{v}{Q} \right)^{\beta} \right\}$$

BPR further stated that a high value of β causes speed to be unresponsive to "x" but as "x" tends to 1, the speed drops suddenly. BPR 1965 version initially proposed the values 0.15 and 4 for "ρ" and "β" respectively in the travel time equation. However, studies conducted on the BPR curve by Dowling and Skabardonis (1993) reported an underestimation of speed and re-plotted the BPR equation by proposing 0.2 for ρ and 10 for β. The new proposed values were later adopted and updated by BPR 1994.

For this study, our focus is on off-peak traffic period which implies that the degree of saturation v/c < 0.9, the values ρ = 0.2 and β = 10 are acceptable. The choice of off-peak is premised on the reasoning that peak travel data is biased and skewed towards unstable traffic flow. Equation 5 is appropriate for dry and rainy darkness conditions and can be re-written as

$$[6]\ T = t_f \{ 1 + 0.2(x)^{10} \} \Longrightarrow T = t_f \left\{ 1 + 0.2 \left(\frac{v}{Q} \right)^{10} \right\}$$

From equation 6, the parameter Q known as capacity is very important in road design both in terms of planning and management. It plays an indispensable part in defining the performance of a road. Estimation of road capacity is used in assessing the conditions of the road relative to congestion, delay and the number of traffic expected to be involved. Capacity is the maximum hourly flow rate by which vehicles or persons are expected to pass a certain point or uniform section of a roadway for a certain period of the specific roadway, traffic, geometric, control and environmental conditions (HCM, 2000).

Estimation methods of roadway capacity using traffic headway, volume, speed and density data include headway, product limit, bimodal distribution, selected maxima and fundamental diagram (Minderhound, 1996). Nevertheless, the use of any method is a function of traffic data available. Fundamental diagram employs the relationship existing between the three macroscopic flow parameters which are volume (q), speed (u) and density estimate capacity. The fundamental relationships constructed using any two variables are speed-density, flow-density and flow-speed diagrams. The speed-density is fitted to a linear function while a quadratic equation represents the flow-density.

With the flow-density relationship, it is possible to estimate capacity, critical density (density at which capacity is reached) with its corresponding traffic mean speed and jam density (density at which traffic volume and mean speed is zero). The capacity value can be obtained from the fundamental diagram or by finding the derivative value of the quadratic function. The capacity equation is written as:

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

The capacity equation above has been shown in past studies (Ben-Edigbe and Ferguson, 2005, Anais et al., 2010) to be reliable for off-peak traffic stream characteristics.

Now plug equation 7 into equation 6.

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

Recall that $t_f = \frac{d}{v}$ and $u = u_f - \varphi k$, therefore equation 8 can be re-written as:

$$[9]\ T = \frac{d}{u_f - \varphi k}\left\{1 + 0.2\left(\frac{uk}{-c+(v_f)\frac{v_f}{2\left(\frac{v_f}{k_j}\right)} - \frac{v_f}{k_j}\left(\frac{v_f}{2\left(\frac{v_f}{k_j}\right)}\right)^2}\right)^{10}\right\}$$

Equation 9 above can then be used to determine the travel time for both dry and rainy conditions based on the advantage of the fundamental diagram which allows traffic state to be determined at any point along the road section irrespective of whether capacity is reached or not.

2.1.1 Impact of Rainy Darkness on Travel Time

Rainy darkness can affect the travel time of a vehicle on a roadway. Based on past research work, darkness is known to affect visibility which impacts negatively on travel time while rainfall irrespective of its intensity leads to speed reduction. Alhassan and Ben-Edigbe (2011b) described the impact of rainfall as "clouding effect" that leads to speed reduction. Often drivers tend to reduce their speed once darkness set in due to poor and limited visibility, but a situation of darkness coupled with rainfall i.e. rainy darkness calls for an in-depth knowledge. The extent of the rainy-darkness effect on travel time could be argued to depend on the intensity of the rainfall at the period of darkness. Vehicles travelling in darkness irrespective of the fact that the degree of saturation < 0.9 (i.e off-peak) road are bound to reduce their speed which consequently leads to travel time increase.

3 Methodology

Three sites were selected in Nigeria for this rainy-darkness impact study. The selected road sections were characterised with a good drainage system, straight and flat terrain, void of attractions and free of structural pavement deterioration. The selected roads were without road lightning. Rainfall precipitation was collected with a rain gauge and the precipitation amount was converted to rain intensity. Rainfall was divided into three intensity classes viz light (i < 2.5mm/hr), moderate (2.5 ≤ i < 10 mm/hr) and heavy (10 ≤ i < 50 mm/hr) in accordance with World Meteorological Organisation (WMO) rainfall classification. Very heavy rainfall (i > 50mm/hr) was not considered for the study because of drag force, aquaplaning and water splash on vehicles which might cause aggression and anxiety in driver's reaction. These effects might be difficult to separate from the rainy-darkness effect on travel time. As shown in figure 1, automatic traffic counter (ATC) was used to collect traffic volume, headway, type of vehicle, speed, date and time of vehicle tires hit on ATC pneumatic tubes continuously for eight weeks during the rainy season at the selected sites. The continuous traffic data collection allows traffic under darkness to be captured. Off-peak traffic data were used for the study in order to separate the effect of peak traffic flow from rainy-darkness effect. The separated off-peak traffic data was synchronised with equivalent rainfall data obtained.
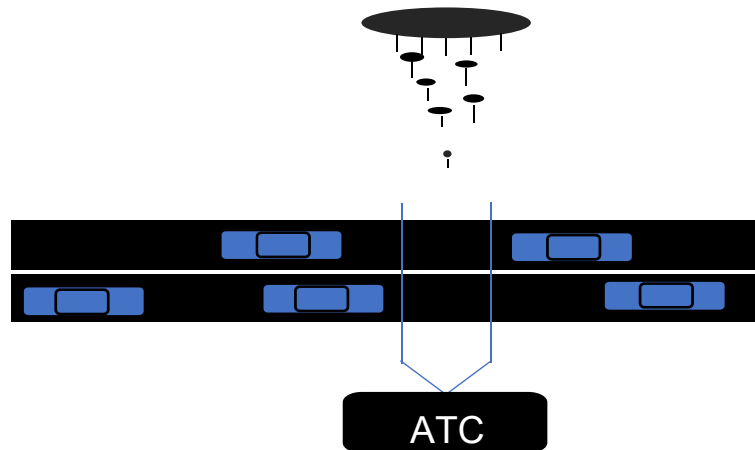
Figure 1: Set up of rainy darkness impact study

4   Results and Discussions

The stepwise method of analysis is used for simplicity and clarity.

Step 1: The traffic and rainfall data collected were separated into daylight and darkness. The traffic data under darkness falls into the off-peak period which eliminates the effect of the peal period. The rainfall data under darkness was classified into light rainfall (i < 2.5mm/hr), moderate rainfall (2.5 ≤ i ≤ 10mm/hr) and heavy rainfall (10 ≤ i ≤ 50mm/hr) based on its intensity. The traffic data under darkness were separated into traffic data with and without rainfall. The traffic data under darkness was synchronized with the rainfall data to generate rainy-darkness traffic data. The rainy darkness traffic data was divided into a passenger car, light vans, and heavy trucks.

Step 2: The passenger car equivalent was modified under rainy darkness. The modified passenger car was used in the conversion of traffic volume to traffic flow.

Step 3: The speed and traffic flow were used in computing the density using equation 10.

[10] $q = uk$

As an example, when the speed = 71km/h, and flow = 540pce/h,

Then density (k) = $\frac{q}{u}$ = $\frac{540}{71}$ = 8pce/km

This was estimated for all conditions under dry, light, moderate and heavy rainy conditions under darkness.

Step 4: The estimated density was related to traffic flow to determine the speed - density flow quadratic relationship as shown in figures 2 to 5 under dry and rainy darkness conditions. The model equations were statistically tested. The coefficient of determinant (R^2) was more than 0,5 which shows that the variables are significant, the two-tail t-test result if more than 2.2 which shows that the variables are significant, the F-test is more than 4.0 which suggests that the equation did not occur by chance. This show that the model equations are statistically satisfactory and could be used for prediction.
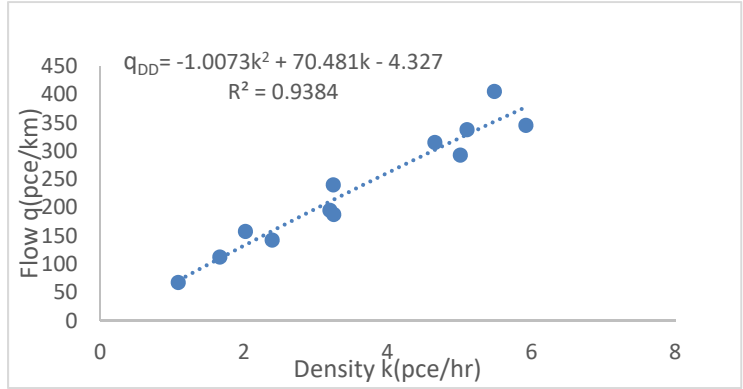
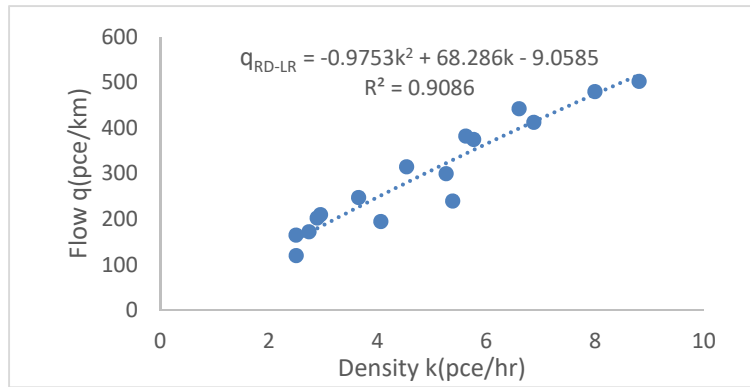Figure 2: Flow-density relationship of dry darkness condition

$q_{DD} = -1.0073k^2 + 70.481k - 4.327$
$R^2 = 0.9384$

Figure 3: Flow-density relationship of rainy darkness under light rainfall

$q_{RD-LR} = -0.9753k^2 + 68.286k - 9.0585$
$R^2 = 0.9086$
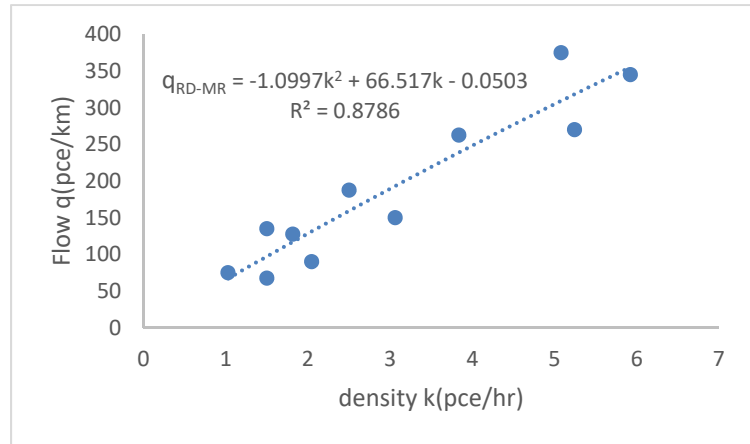
Figure 4: Flow-density relationship of rainy darkness under moderate rainfall

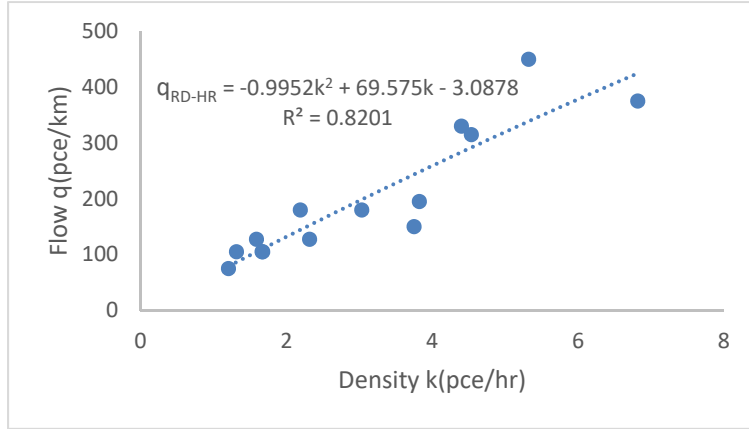$q_{RD-MR} = -1.0997k^2 + 66.517k - 0.0503$
$R^2 = 0.8786$

Figure 5: Flow-density relationship of rainy darkness under heavy rainfall

Step 5: The capacity was computed using the model equation. Under dry darkness, the model equation is

[11] $q_{DD} = -1.0073k^2 + 70.481k - 4.3270$

Equation 11 was differentiated as shown in equation 12 and the result is set to 0 to determine the critical density because the maximum flow occurs when the critical density is reached.

[12] $\frac{dq}{dk} = -2 \times 1.0073k + 70.481$

$-2.0146k + 70.481 = 0$

$k = \frac{70.481}{2.0146}$

$k = 34.99 \, pce/km$

$q_{DD} = -1.0073(34.99^2) + 70.481(35.01) - 4.327$

$= 1228.91 pce/h$

The capacity is estimated under dry and rainy darkness at the three selected sites. The summary of the capacity result is presented in table 1.

Step 6: The maximum speed was estimated using equation 10. Under dry darkness, the speed is calculated as

$S = \frac{1228.91}{34.99}$

$= 35.12 km/hr$

The maximum speed is estimated under dry and rainy darkness for the three sites. The summary of speed result is presented in table 1.

Step 7: Travel time for dry and rainy darkness conditions were calculated using equation 13

[13] $T = \frac{d}{u_f - \varphi k} \left\{ 1 + 0.2 \left(\frac{uk}{-c + (v_f)\frac{v_f}{2\left(\frac{v_f}{k_j}\right)} - \frac{v_f}{k_j}\left(\frac{v_f}{2\left(\frac{v_f}{k_j}\right)}\right)} \right)^2 \right\}^{10} \Rightarrow \frac{d}{v}\left\{ 1 + 0.2 \left(\frac{v}{Q}\right)^{10} \right\}$

$$T_{DD} = \frac{60}{35.12}\left\{1 + 0.2\left(\frac{1228.91}{1228.91}\right)^{10}\right\}$$

= 2.05min

Typical highway maximum flow calculations from the model coefficients in Table 3 are shown below and the remainder results are shown in Table 4: Where flow and density quadratic function is used:

The travel times for dry and rainy conditions for the selected sites were computed. Table 1 shows the summary of the model equations, maximum flow, speed, travel time and travel time differentials for with and without rainfall under conditions for the selected sites.

Table 1: Estimated flow-density model equations and travel time for rainy-darkness

Site	Weather condition	Model Equation	*Q (Pce/h)	*U (km/h)	*T (min)	*ΔT (min)
1	Dry darkness	$q = -1.0073k^2 + 70.481k - 4.3270$	1229	35	2.05	N/A
	Light rain (Darkness)	$q = -0.9753k^2 + 62.286k - 9.0585$	1186	34	2.28	0.23
	Moderate rain (Darkness)	$q = -1.0997k^2 + 66.512k - 0.0503$	1006	33	4.49	2.24
	Heavy rain (Darkness)	$q = -0.9952k^2 + 60.575k - 3.0878$	918	30	8.45	6.40
2	Dry darkness	$q = -0.9872k^2 + 71.257k - 4.3292$	1281	36	2.03	N/A
	Light rain (Darkness)	$q = -0.9895k^2 + 65.753k - 7.8339$	1085	33	3.79	1.76
	Moderate rain (Darkness)	$q = -0.9939k^2 + 62.844k - 6.3467$	987	31	7.13	5.10
	Heavy rain (Darkness)	$q = -0.9150k^2 + 60.443k - 0.9252$	997	30	6.86	4.83
3	Dry darkness	$q = -1.024k^2 + 75.176k - 1.0089$	1379	38	1.92	N/A
	Light rain (Darkness)	$q = -1.1001k^2 + 74.753k - 4.7826$	1265	37	2.37	0.45
	Moderate rain (Darkness)	$q = -1.0420k^2 + 68.809k - 0.057$	1136	34	4.17	2.25
	Heavy rain (Darkness)	$q = -0.9953k^2 + 63.575k - 4.0848$	1015	32	9.98	8.06

*Q ~ Capacity, U ~ optimum speed, T ~ Travel time, ΔT ~ Travel time differential.

The result in table 1.0 shows that the capacity and speed reduce with the increase in rain intensity under darkness. The reason is that as the rain intensity increases, the drivers become more cautious due to increase in impaired visibility and reduction in frictional coefficient between tires and road pavement. As the rain intensity increases, the travel time increase as shown in table 1.0. This is because as the drivers become more cautious by reducing the speed and keep the gap from the leading vehicle. It is expected that as the gap increases with reduction in speed, the travel time might increase. Under light rainy darkness, the travel time increases from 2.05min to 2.28min with an increase of 0.23min at site 01. It increases from 2.03min to 3.79min with an increase of 1.76min at site 02. At site 03 the increase is from 1.92min to 2.37min with an increase of 0.45min. Under moderate rain the increase in travel time is 2.24min, 5.10min, 2.25min at sites 01 to 03 respectively. Under heavy rainy darkness the travel time increase by 6.40min, 4.83min, 8.06min at sites 01 to 03 respectively. The results follow the same trend at all the sites as the travel time increases with increase in rain intensity under darkness. At site 02 the travel time under moderate and heavy rain are close in value. This is because the heavy and moderate rain at this site might be at the borderline of the moderate and heavy rain. This rain intensity at the borderline cannot be taken as fixed because of the rain fluctuation. The moderate and heavy rain intensity at this site might be fluctuating between the moderate and heavy rain. At all the sites, the travel time differential under light rainy darkness has an insignificant travel time differential, this is because light rain

with the intensity of less 2.5mm/h has little effect on the driver's visibility and at times the rain drizzle is taking as light rain and drivers react less to light rain.

Taking the average, the speed reduces from 36.06km/h to 34.59km/h with reduction of 1.47km/h or 4.1% under light rain. Under moderate rain it reduces to 32.96km/h with reduction of 8.6% and it reduces to 30.72km/h under heavy rain with reduction of 5.34km/h or 14.8%. The average travel time under dry darkness is 1.59min, 2.07min under light rainy darkness, 3.93min and 5.58min under moderate and heavy rainy darkness respectively. The travel time differential is 0.49min, 2.34min and 4.00min under the light, moderate and heavy rainy darkness conditions respectively. This shows that as the driver responds to rainfall effect by speed reduction, travel time increases with increase in rain intensity under darkness.

5   Conclusion

Based on the synthesis evidence obtained from travel time changes under rainy-darkness, drivers reduce speed as the rain intensity increases. The travel time increases in response to the speed reduction. The light rain has the lowest effect and heavy rain has the highest effect on travel time under darkness. It is therefore correct to conclude that as driver reduces speed, travel time increases with increase in rain intensity under darkness.

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