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Extent of Highway Travel Time Differentials Resulting from Rainfall Intensities

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Authors' contributions

NM designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. JBE managed the analyses of the study and wrote final draft of the manuscript. RR managed the literature searches. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

Travel time on a roadway segment is what most road users are concerned about. It is a useful guide for measuring road users' perception of the quality of roadway service. Rainfall affects traffic flows by reducing drivers' visibility and road surface friction among others. These reductions have profound impacts on travel time. The aim of the paper is to determine the impact of rainfall intensities (slight, moderate and heavy) on travel time. The impact study was carried out at locations along Terengganu East Coast Highway 5, between November 2010 and February 2011. Based on the hypothesis that rainfall intensity has effect on travel time, a 'with-and-without rainfall impact study for both directions of a single carriageway was conducted. Volume, speed, headway, gaps and types of vehicles collected by way of automatic traffic counter continuously for three months estimated and compared. Rainfall data were collected and supplemented with data supplied by the Malaysian Hydrology Department. Results show that light and moderate rainfall will cause a travel time increase of about 0.43 and 0.54 minutes per kilometer by respectively; whereas heavy rainfall will account for travel time increase of 0.74 minutes per kilometer. It also shows that traffic kinematics and shockwave propagations at the onset of rainfall can also be called to account for travel time differentials. The paper concluded that rainfalls irrespective of their intensities have significant impact on roadway travel time.

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Keywords: Travel time; rainfall; traffic shockwaves; fundamental diagram.

1. INTRODUCTION

Rainfalls irrespective of their intensities have profound impact on the highway traffic operations and safety. At the onset of rain, drivers respond to the condition by lowering their operating speeds. The involuntary lowering of operating speed is partly caused by poor visibility and reduced road surface traction. Since speed is a function of distance relative to time, it can be postulated that for any fixed distance, speed reduction will trigger relative increase in travel time. According to Rahman (2012), drivers respond to rainfall by reducing speed and increasing associated time gap. Further, they tend to maintain same spatial distances between vehicles during rainfall. Previous studies suggest that speed and capacity are negatively influenced by rainfall and there is a consensus assumption that speed reduction occasioned by rainfall will ultimately lead to highway travel time increase. However, there are no clear estimations on the extent of travel time differentials resulting from rainfall intensities in previous studies. Often the effects of rainfall on passenger car equivalent values are ignored. Why, it may be queried? After all passenger car equivalent or unit is an instrument of highway capacity analysis and defined in Highway Capacity Manual (HCM) *as '*the number of passenger cars displaced in the traffic flow by truck or a bus under the prevailing roadway, traffic and ambient conditions'. Since traffic flow is usually characterised by mixed vehicles, the effect of different types of vehicle within a traffic stream is allowed for by converting vehicle volume into passenger car equivalencies (PCE or PCU). And rightly so because, It can be argued that the effects of different types of vehicle cannot be the same under dry and rainy weather conditions. Consequently, it averred that, rainfall impact study outcomes may be doubtful where the effects of dynamic passenger car equivalent values are omitted. In this paper we assumed that travel time over highway segment is a function of free flow speed, traffic flow and highway capacity. Also that density is a result of speed and flow; hence is not directly affected by rainfall intensities. This implies that travel time differentials are entirely the result of speed changes. The paper will focus on impact of rainfall on travel time concepts in the next section.

2. IMPACT OF RAINFALL ON TRAVEL TIME

Travel time on a roadway segment is what most road users are concerned about. It is a useful guide for measuring the effectiveness of roadways when used in conjunction with delay and capacity utilisation. All time spent travelling can be considered to have a value regardless of travel purpose. Broadly, the time taken over a road length is dependent on factors that include road, traffic and ambient conditions. Rainfall affects traffic flows by reducing drivers' visibility and road surface friction among others. These speed reductions have profound negative impacts on travel time. As travel time increases, the quality of roadway service deteriorates. Time is a function of distance and speed. It can be written as equation 1.

$$v = \frac{d}{t_f} \Longrightarrow t_f = \frac{d}{v} \tag{1}$$

Where; v is speed, d is distance and t_f is free flow time

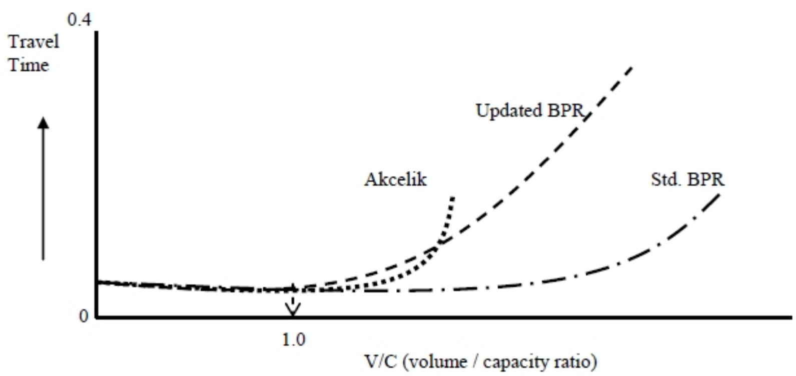
In theory, free flow travel time shown in equation 1 occurs when density is at zero, that is, there are no vehicles present on the roadway. In practice, free flow occurs when drivers can choose their operating speeds. However, when the critical traffic flow ratio of O.85 is reached, driving is constrained and drivers will have to respond to lead vehicles as well as other prevailing conditions. Consequently travel time in equation 1 can be re-written as:

$$T = t_f \left\{ 1 + a \left(\frac{q}{Q} \right)^b \right\} \tag{2}$$

Where; T = predicted travel time over length of roadway;
t_f = travel time at free flow speed; q = flow; Q = practical capacity;
'*a'* determines the ratio of free-flow speed to the speed at capacity; and
'*b'* determines how abruptly the curve drops from free-flow speed.

The US Bureau of Public Roads (BPR) uses equation 2 when predicting travel time over length of roadway. According to BPR, a high value of *b* causes speed to be insensitive to *v/c* until *v/c* gets close to 1.0; then the speed drops abruptly. BPR initially used the values '*a'* = *0.15,* and ''*b* = 4 in the 1965 version of the travel time equation. Skabadonis and Dowling (1994) evaluated the standard BPR curve against more recent speed–flow data and concluded that the BPR curve underestimated speeds at v/c ratios between 0.80 and 1.00 and overestimated speeds in queuing conditions (when the demand exceeds capacity). They refitted the BRP equation to the motorway speed-flow curves and recommended that 'a' = 0.20, and 'b' = 10. BRP 1994 version updated to '*a'* = *0.20,* and '*b'* = 10 to incorporate modern facilities as contained in Highway Capacity Manual – HCM (*1994*). HCM mentioned that the resulting speed-flow curve is flatter than the original BPR curve for v/c ratios less that 0.70 and the new curve drops much faster in the vicinity of capacity (v/c =1.00).

Dowling et al. (1998) suggested that updated curves generally involved the use of higher power functions that show relatively little sensitivity to volume changes until demand exceeds capacity, when the predicted speed drops abruptly to a very low value. The updated travel time and V/C curves shown below in see Fig. 1 have 'a' parameters that vary from 0 to 1.0 and 'b' parameters that vary from 4 to 11. Davidson (1966) proposed travel time versus flow based on queuing theory with a delay parameter accounting for the frequency of the delay-producing elements along the highway facility. The model is useful for situation where the degree of saturation is less than 1.



Source: Dowling *et al* (*1998*).

Fig. 1. Travel time against volume/capacity ratio

Akcelik (1991) while investigating the validity of BPR curve developed a speed – flow equation that showed very little departure from the BPR equation until the v/c = 0.90. Akcelik

(1991) then proposed modification of Davidson's function by redefining the delay parameter as and extending the model for situations where the degree of saturation is equal or greater than 1. The most crucial parameter in the Akcelik equation is the value of T, which is the duration of the travel demand. Larger T values will increase the queue delay for a given demand-capacity ratio because longer time periods allow more opportunity for queues to increase. Since we are only interested in predicting travel time where, *(v/c)* $\lesseqgtr$ 1, and v/c < 0.90, the BPR equation for speed- flow curve would be used where a = 0.20, and b = 10: so, there is no need to build a separate travel time predicting model. The BPR speed-curve has been validated against speed-flow data for both uninterrupted and interrupted flow facilities and could be useful in predicting travel time. Therefore, it is appropriate in this paper to use equation 3 below to predict travel time for dry and rainy conditions mindful of the role of dynamic passenger car equivalent values.

$$T = t_f \left\{1 + 0.2\left(\frac{q}{Q}\right)^{10}\right\} \tag{3}$$

One important parameter in equation 3 is roadway capacity (Q). Capacity is a central concept in road design, traffic control and management. It is far too important to be ignored in any meaningful traffic flow analysis. Estimation of empirical capacity values in practical circumstances is not a trivial problem; however, it is often very difficult to define capacity in an unambiguous manner. Highway Capacity Manual (HCM) defines capacity as 'the maximum hourly rate at which vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions. The definition recognises prevailing road and traffic conditions, the potential for substantial variations in flow during an hour, and focuses analysis on intervals of maximum flow. Highway traffic theory is concerned with the movement of discrete objects in real time over a network in 2D dimensions. It is compatible with or dependent on fundamental diagram of traffic. It has 4 basic boundary conditions: i, flow equals zero when density is zero; ii, flow equals zero when density is at jam, iii, speed equals zero at jam density, iv, speed equals free flow when density is zero. Three primary measures namely: flow, speed and density characterise the operational state of any given traffic stream. The fundamental diagram illustrates the observed relationship between the three variables as shown below:

$$q = vk \Rightarrow v = \frac{q}{k}. \tag{4}$$

$$v = v_f - \varphi k \tag{5}$$

Where; q is flow, k is density, φ is a coefficient, v_f is free-flow speed and v is a mean speed.

If equation 5 is plugged into equation 1, then

$$t_f = d\left(\frac{1}{v_f - \varphi k}\right) \tag{6}$$

Empirical capacity estimation for uninterrupted roadway sections has been studied extensively. Headways, traffic volumes, speed, and density are traffic data types used to identify four groups of empirical capacity estimation methods (selected maxima, headway, speed/flow and fundamental diagram). The choice of a particular method strongly depends on the available data. Ben-Edigbe (2005, 2011) used the quadratic relationship between flow and density in a situation of free flow to estimate roadway capacity where density was used as the control parameter and flow the objective function. The capacity theory underlying the model dictates that concavity in the flow/density curve must be present for validity. The capacity equation can be written as:

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

Where; the flow / density relationship has been used to compute roadway capacity, the critical density is reached at the apex point, beyond the apex point, flow decreases relative to increases in density.

Now, if equation 7 is plugged into equation 3, then travel time for dry and rainy conditions can be estimated using equation 8 below bearing in mind the role of dynamic passenger car equivalency.

$$T = d\left(\frac{1}{v_f - \varphi K}\right)\left\{1 + 0.2\left(\frac{v_f - \varphi k}{-c + \left(v_f\right)\frac{v_f}{2\left(\frac{v_f}{k_j}\right)} - \frac{v_f}{k_j}\left(\frac{v_f}{2\left(\frac{v_f}{k_j}\right)}\right)^2}\right)^{10}\right\} \tag{8}$$

2.1 Dynamic Passenger Car Equivalency

The use of PCE's is central to road capacity analysis where mixed traffic stream are present even though their values are not globally applicable without some modifications or if you like recalibration in the first instance. Ignoring PCE modifications could lead to grossly inaccurate road capacity estimates with consequences for road transportation modeling. The calibration of the PCE values can have a significant impact on capacity analysis computations (Seguin et al., 1998). As mentioned earlier, passenger car equivalent (PCE) values are usually relied upon when converting traffic volume into flow. The term 'passenger car equivalent' was defined in Highway Capacity Manual (HCM) as 'the number of passenger cars displaced in the traffic flow by truck or a bus under the prevailing roadway and traffic conditions'. This definition still holds today.

In Malaysia, where rainfall is nearly a weekly occurrence, drivers have to contend with traffic disturbances that include speed reduction, roadway capacity lost, poor quality of roadway service and highway travel time differentials associated with rainy conditions. The standard Malaysian PCE values are: motorcycle 0.75; passenger car 1.0; light vans 2.0; Lorries 2.5; and heavy goods vehicle/Buses/Coaches 3.0. These values were computed from studies carried out under dry and day light conditions. Consequently, it was modified for rainy conditions using a simple headway method to derive PCE values. The method involves the equation shown below;

$$PCE_i = \frac{H_i}{H_c} \tag{9}$$

Where PCE_i is the passenger car unit of vehicle class *i*. H_i is the average headway of vehicle class *i* and H_c is the average headway of passenger car. Notwithstanding, the method adopted in estimating PCE values, they will have no effect on the outcome of the study (Ben-Edigbe, 2010).

2.2 Hypothetical Rainfall Intensities against Travel Time

Travel time differentials resulting from rainfall may occur at the onset and during rainfall. It can be postulated that at the onset of rainfall, lead vehicle may slow down sometimes with an abruptness that may trigger traffic shockwaves before settling down to the prevailing driving conditions. Traffic shockwaves result from roadway capacity loss, however roadway capacity loss is not an imminent requirement for poor quality of roadway service, it can be argued. Where roadway capacity has not been reached, speed reduction irrespective of how it was acquired would still trigger travel time increase. For example, if there are very few vehicles on the roadway at the onset of rainfall, speeds would be reduced and travel time increased without consequences for roadway capacity. Therefore, it would be wrong to suggest that travel time increase occasioned by rainy condition would always lead to roadway capacity loss. It is conceded that it may lead to capacity loss.

The general concepts regarding rainfall intensities and travel time can be presented as a hypothetical non-linear curve as shown below in Fig. 2 and explained earlier. Since speed and travel time is inversely related and speed-flow relationship is curve in nature, it could be argued that the relationship between travel time and traffic flow is not a linear. As illustrated below in Fig. 2, fixed travel time would occur irrespective of whether it rains or not. Since travel time is dependent on fixed and variable time, equation 1 cannot be solely relied upon when computing travel time and there is no evidence to suggest otherwise. So, if is assumed that travel time increases with rainfall intensities, then the extent of travel time differentials would depend partly on the rainfall intensities among other factors. It can be argued.

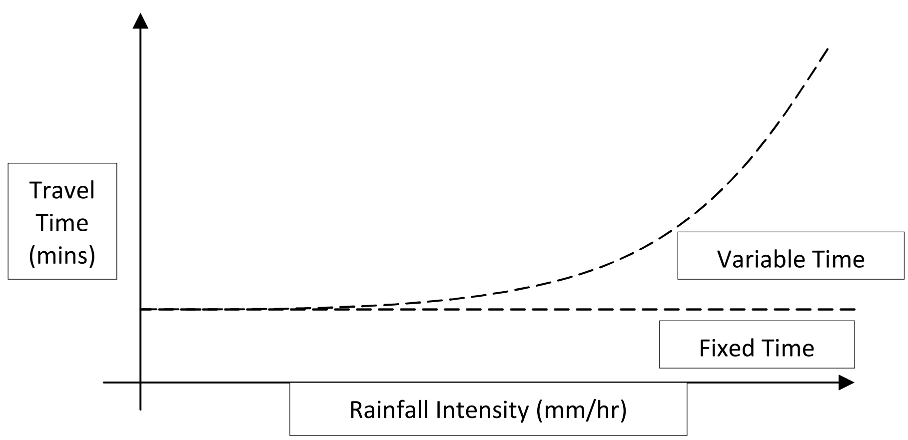


Fig. 2. Hypothetical travel time against rainfall intensity

In any case, when considering the mechanisms by which rainy condition may possibly influence highway travel time two groups of factors seem most important: the changing behaviour of drivers and the changing composition of traffic mix. Given dry weather conditions, drivers may travel at higher speeds given a certain traffic density, may keep shorter distances between vehicles ahead without lowering speed, or may choose a different lane of the carriageway. However, during rainy conditions, drivers may elect to change routes or departures times; for drivers who are familiar with the route as well as those whose are new or irregular road users travel time increase over the length of such road will result from speed/flow curve shrinkage. In the next section, the paper will focus on setup of impact study and data collection.

3. SETUP OF IMPACT STUDY AND DATA COLLECTION

Note that the surveyed roadway sections used in the study were designed to Malaysia Design guidelines (DRA 2011), classified as federal routes with functional geometry, pavement and drainage system. The surveyed road sections have flat terrain, bituminous surfaces and functional drainage. There was no evidence to suggest that the surveyed sites and their immediate vicinity have history of aquaplaning, blocked drainage, congestion and/or pavement distress problems. Within the purview of study objectives and boundary, an automatic traffic counter was installed on the road segments as shown below in Fig. 3. It recorded traffic volume, speed, headway, type of vehicle, time and date of vehicles as they traversed the observation point. Rainfall intensity data from a nearby weather station and daily local observations were recorded, compared and categorized into three rainfall intensity regimes. These are; light, medium and heavy rainfall. The rainfall classification was based on the World Meteorological Organization (WMO) Scheme where, light rain (L) ($i < 2.5$ mm/hr), moderate rain (M) ($2.5 \le i < 10.0$ mm/hr) and heavy rain (H) ($i \ge 10.0$ mm/hr). The nearest rain gauge stations are less than 1.8km away from the sites. In all 99 rainfall events were observed during the three month data collection period (November 2010 and February 2011). Vehicles were divided into three categories, passenger cars, light vans and trucks/buses/coaches. Data were collected at survey sites in Terengganu town, Malaysia. A total of 1,316,834 vehicles were observed during the period of which 75.80% were cars and 10.23% were motorcycles (Light category). The truck composition (Heavy category) was 3.51% and the remaining vehicles (Medium category) in the traffic stream were 10.46%. In the next section, results and findings are discussed.

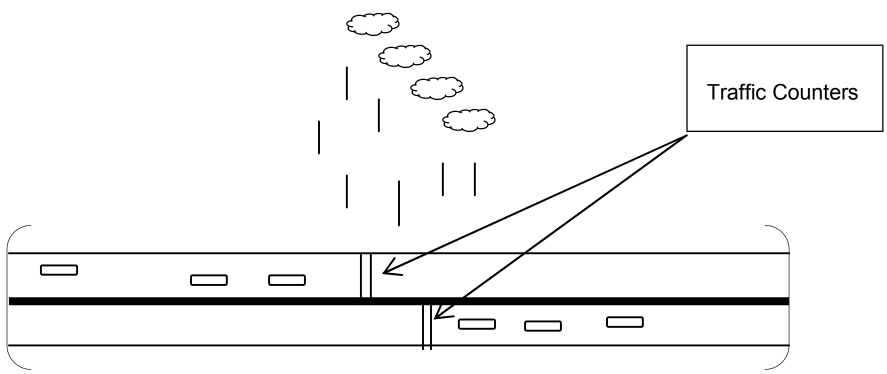


Fig. 3. Setup of rainfall impact study

4. RESULTS AND FINDINGS

The stepwise procedure used in the studies to estimate travel time can be stated as follows:

i. estimate traffic flows and speeds (using appropriate pce values)
ii. compute densities from flows and speeds; hence
iii. derive flow-density model equations using equation 7;
iv. test flow-density model equations for statistical fitness;
v. compute critical density, capacity and optimum speed model equations
vi. determine travel time using equation 8;

The paper presents sample calculations of pce values and highway travel time below:

4.1 Dynamic Passenger Car Equivalent Values

Note also that;
Headway = Spacing (m/veh) / Speed (m/sec) (10)
Spacing = (1000m/km) / Density (veh/km) (11)
Density = 1000 (m/km) / Spacing (m/veh) (12)

Plug computed densities into equation 11 so as to determine spacing; then
Compute headway for different types of vehicle (PCs, LGVs and HGVs) using equation 10
Estimate pce values using equation 9:

For example;
Spacing = 1000 / 32 = 31.250 m/veh
Headway (PC) = 31.250 / 25 = 1.250 sec / veh; Speed = 90km/h or 25 m/sec
Headway (LGV) = 31.250 / 19 = 1.645 sec / veh; Speed = 68km/h or 19 m/sec
Headway (HGV) = 31.250 / 16 = 1.953 sec / veh; Speed = 58 km/h or 16 m/sec

Where, PCE (PC) = 1.0 unit;
PCE (LGV) = 1.645 / 1.250 = 1.316unit, and PCE (HGV) = 1.953 / 1.250 = 1.563 unit

4.2 Road Section without Rainfall

Roadway capacity model equation, $q = -1.146k^2 + 88.33k - 48.08$;
For maximum flow, $\partial q / \partial k = 2(-1.146k) + 88.33 = 0$,
Hence, critical density, $k_c \cong 39$pce/km; then plug k into q, so that,
$q = -1.146(39)^2 + 88.33(39) - 48.08$ and Roadway capacity, q_c =1654pce/hr.
Optimum speed, $u_o = 1654/39 = 42.9$km/hr
Travel time per km / lane, $T = 60/42.9\ (1 + 0.2(1654/1654)^{10} = 1.68$mins

4.3 Road Section with Light Rainfall

Roadway capacity model equation, $q = -\ 1.006k^2 + 78.69k - 6.287$;
For maximum flow, $\partial q / \partial k = 2(-1.006k) + 78.69 = 0$,
Hence critical density, $k_c \cong 39$ pce/km then Plug k into q,
So that, $q = -\ 1.006(39)^2 + 78.69(39) - 6.287$ and
Roadway capacity q_c =1533pce/hr.
Optimum speed, $u_o = 1533/39 = 39.2$km/hr
Travel time per km / lane, $T = 60/39.2\ (1 + 0.2(1654/1533)^{10} = 2.19$mins

Typical observed data of traffic flow collected at survey sites are shown below in Figs. 4a and 4b.

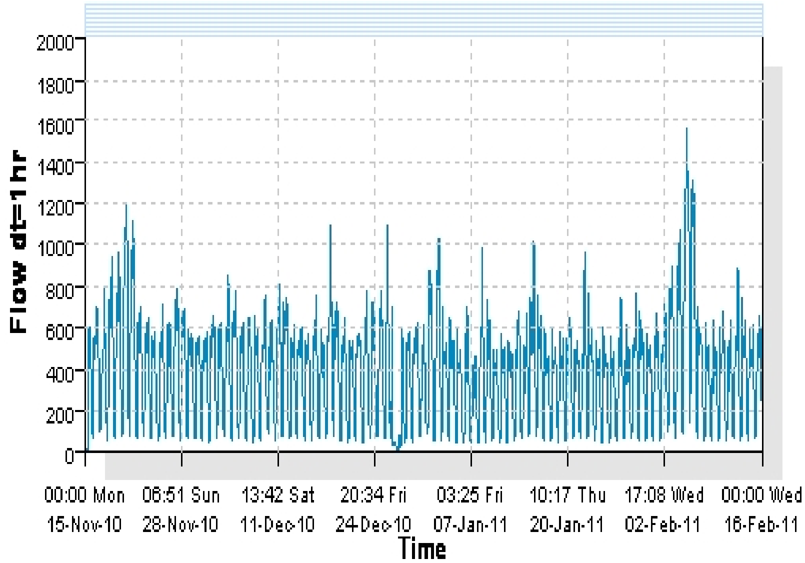


Fig. 4a. Typical empirical traffic flow data for Site 1

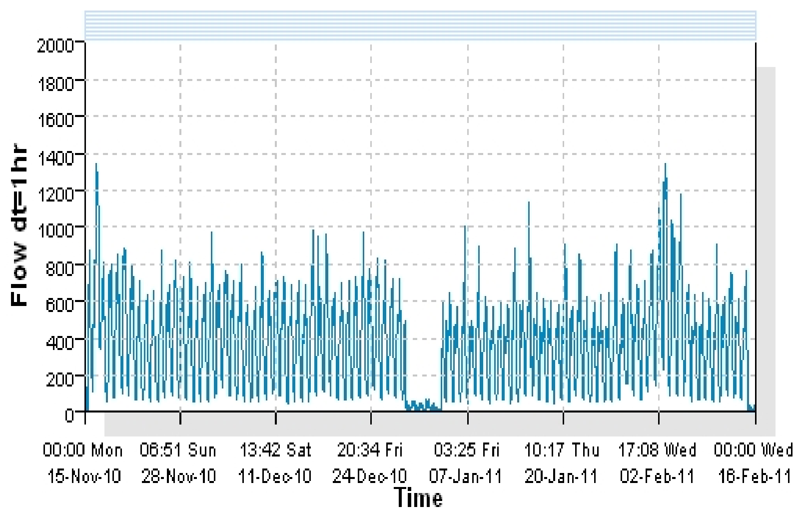


Fig. 4b. Typical empirical traffic flow data for Site 2

In Table 1 above, estimated model coefficient values have the expected signs, coefficients of determination (R^2) are more than 0.5, hence acceptable. Note that free-flow speeds for dry weather (88km/h and 90km/h) are significantly higher than the free-flow speeds during rainy conditions. At the onset of rainfall differences in free-flow speed are considerable higher at the onset of rainfall. There is an average speed reduction of about 10km/h between light rainfall and dry weather condition; whereas speed reduction during variable rainy conditions is insignificant. It shows that traffic kinematics and shockwave propagations at the onset of rainfall can be called to account for some of the loss time. Maximum densities under dry weather are smaller than those of rainy conditions suggesting that spacing reduction between vehicles resulted from rainfall.

Table 1. Estimated flow-density model equations

Site No.	Road Section	Flow vs. Density	R^2
	Without Rainfall	$q = -1.146k^2 + 88.33k - 48.08$	0.931
1	Light Rainfall	$q = -1.006k^2 + 78.69k - 6.287$	0.953
	Moderate Rainfall	$q = -0.978k^2 + 77.08k - 2.946$	0.962
	Heavy Rainfall	$q = -0.954k^2 + 76.20k - 8.131$	0.943
	Without Rainfall	$q = -1.156k^2 + 89.60k - 61.44$	0.953
2	Light Rainfall	$q = -1.028k^2 + 81.40k - 26.82$	0.978
	Moderate Rainfall	$q = -1.003k^2 + 80.05k - 29.12$	0.965
	Heavy Rainfall	$q = -0.931k^2 + 75.09k - 0.548$	0.912

From Table 2, it can be seen that when the weather changes from dry to rainfall, critical density decreases marginally and reduction in optimum speed is substantial from 43km/h to 37km/h, thus suggesting that rainfall has significant effect on optimum speed. Consequently, travel time increases considerably from 1.68mins to 2.48mins. The impact of light and moderate rainfall on travel time is not as severe as heavy rainfall. Results show that light and moderate rainfall will increase travel time per kilometer by 0.43 and 0.54 minutes respectively; whereas heavy rainfall will increase travel time by 0.74 minutes per kilometer. In any case, conclusions from the impact study are drawn in the next section.

Table 2. Estimated travel time with and without rainfall

Site No.	Road Section	Parameters				
		Road capacity pcu/hr	Critical density pcu/km	Optimum speed km/hr	Travel Time/km Min	aMin
1	Without Rain	1654	38.5	42.9	1.68	0
	Light Rain	1533	39.1	39.2	2.19	+0.51
	Moderate Rain	1516	39.4	38.5	2.31	+0.63
	Heavy Rain	1513	39.9	37.9	2.35	+0.67
2	Without Rainfall	1675	38.8	43.2	1.67	0
	Light Rainfall	1585	39.6	40.0	2.02	+0.35
	Moderate Rainfall	1568	39.9	39.3	2.12	+0.45
	Heavy Rainfall	1514	40.3	37.5	2.48	+0.81

5. CONCLUSION

This study is based on the hypothesis that rainfall irrespective of their intensities has profound impact on travel time differentials. The paper has shown that rainfall has negative influence on highway travel time. It can be concluded that:

- there is a significant change in travel time between dry and rainy conditions
- the estimated percentage of travel time loss is substantial for heavy rainy condition
- rainfall causes speed reduction,

- light and moderate rainfall can be called to account for average travel time increase of 0.43 and 0.54 minutes per kilometer whereas heavy rainfall will cause an average increase of 0.74 minutes per kilometer;
- at the onset of rainfall, relative speed reduction is quite large. If the speed reduction is abrupt traffic shockwave velocity propagations may occur and that may cause accident
- the assertion that rainfall would result in a significant travel time differential remains valid.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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