Transport
Volume 167 Issue TR5

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ice | proceedings

Proceedings of the Institution of Civil Engineers
Transport 167 October 2014 Issue TR5
Pages 334–342 http://dx.doi.org/10.1680/tran.11.00057
Paper 1100057
Received 08/10/2011 Accepted 28/01/2013
Published online 13/05/2013
Keywords: traffic engineering/transport management

ice
Institution of Civil Engineers
publishing

Determining the quality of highway service caused by rainfall

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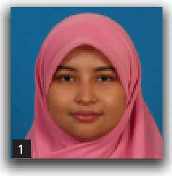

Previous studies on the impact of rainfall on highways have focused on quantitative appraisal and vehicle speed reduction. This study is based on the quality of highway service during rainfall. It presents a novel approach to qualitative assessment of highway service using criteria based on road provider and user perceptions. It describes a method to evaluate speed/flow curves using direct empirical data and the concept of the fundamental relationship of flow, speed and density. On-site studies for volume and speed were observed for roadways, during daylight dry weather and rainfall conditions. Results show a slight reduction in qualitative service during light and moderate rainfall, and significant reduction during heavy rainfall in all cases. The paper concludes that heavy rainfall has a significant impact on the quality of highway service and that this may lead to traffic shockwave velocity propagations.

Notation

c	constant
k	traffic density
k_c	critical traffic density
k_f	traffic density prior to change in conditions
k_j	jam density
n	random sample size
Q	capacity
q	flow
R^2	coefficient of determination
S	sample variance
S_w	traffic shockwave
T	predicted travel time
t_f	travel time at free-flow speed
u	average speed
u_f	free-flow speed
u_o	optimum speed
V	volume

1. Introduction

Highways that provide good services are expected to deliver operational performance that is consistent with their design specifications. However, the extent of good highway service delivery depends on prevailing traffic, road and ambient conditions among others. Rainfall is an ambient condition that varies with time and space. It affects drivers' visibility, driving comfort, traffic flowrate contraction and quality of highway service. Previous studies on the impact of rainfall on highway traffic focused mainly on quantitative assessment and level of service, often with conflicting outcomes. According to the *Highway Capacity Manual* (HCM), free-flow speed can be reduced by 2 to 13% in light rain and by 6 to 17% in heavy rain. Light rain can decrease freeway capacity by 4 to 11% and heavy rain can cause capacity reductions of 10 to 30% (TRB, 2010). In studies conducted on Dutch highways, Hogema (1996) suggested that there is no significant difference in traffic volume during rainfall even though headway distribution changes significantly. In another study, Smith *et al.* (2004) showed that 4–10% highway capacity loss would result from light rainfall, whereas heavy rainfall would trigger 25–30% capacity loss. It also concluded that 3–5% speed decrease would result from rainfall regardless of intensity, thus suggesting that heavy rain does not impact vehicle speed any more (or less) than light rain. In another study about 15% capacity loss was attributed to heavy rainfall: the impacts of light and moderate rainfall were considered to be insignificant (Ibrahim and Hall, 1994). Application of dynamic passenger car equivalency was largely ignored in previous studies on the premise that it has a paltry impact on traffic flow estimation. Passenger car equivalency, however, is an instrument of capacity estimation which cannot be ignored arbitrarily in capacity analysis. Consider the vexing issue of level of service (LOS): LOS is a measure of effectiveness based on road providers' perception, and thus cannot be construed as quality of highway service. Recently, the Transport Research Board (TRB, 2010) committee on highway capacity and quality of service recommended that LOS should be used in conjunction with average speed, queue and delay and that it should serve as a criterion for investment decisions and provide information on current conditions of the highway traffic system. One can only assume that the recommendation is based on the premise that quality of service should reflect both the road providers' and users' perception of traffic performance. Based on the hypothesis that rainfall has an effect on the quality of highway service, the remainder of the paper has been divided into four sections. In Section 2, qualitative traffic assessment concepts are reviewed. It focuses on the quality of highway service assessment criteria. Section 3 is on the set-up of the impact study and field data collection. In Section 4, empirical findings from the studies are discussed, and conclusions are drawn in Section 5.

2. Qualitative highway traffic assessment concepts

Qualitative assessment of roadway service is a subjective yet scientific measurement of road providers' and users' perception of value derived from using the highway. In many studies, speed/flow is often used for qualitative measurements. In the United States, observed speed/flow data are often superimposed on a predetermined LOS chart in order to determine the prevailing LOS. The HCM uses speed/flow as the control variables to describe six LOS experienced by road users. It can be argued that LOS describes the perception of road providers not users, after all there is nothing in the manual to suggest that road users' experience was assessed. Rather, LOS divides the level of traffic flows into six levels ranging from level A to level F, where level A is the highest quality of highway service and level F the lowest. Level of service E denotes traffic operation at capacity. Capacity is taken as 2000 vehicles per hour per lane; optimum speed is approximately 80 km/h and critical density is 25 vehicles per km (TRB, 2010). In Malaysia, the speed limit on principal roadways is 80 km/h. Consequently, it is difficult to visualise a traffic stream that is operating at 80 km/h on a two-lane highway in Malaysia as unstable and at a critical stage. The vagueness of LOS assessment criteria makes them unsuitable for use in Malaysia, even though they are in use at the moment. In any case, the concept has not gained significant traction in Europe; in the United Kingdom LOS is sparingly used in practice. The paper recognises that quality of highway service hinges on two important assessment inputs: the service providers' (traffic class, traffic control and safety) and the road users' (travel time, comfort, delay and queues). It uses traffic class distribution instead of LOS to describe road providers' perception of traffic stream performance.

2.1 Road providers' quality of highway service input

Since traffic control and safety are a management issue, it shall be assumed that the control system is functional and is set aside in this paper. However, given that rainfall has been shown in previous studies to have an effect on visibility, it can be assumed that headway, gap and the probability of shockwave velocity propagation occurring are factors that may be influenced by rainfall-induced poor visibility. The gap is a measure of the time between the rear bumper of the first vehicle and the front bumper of the second vehicle, whereas headway is a measurement of the distance or time between two successive vehicles in a traffic stream. They are contained in speed/flow and volume/capacity parameters, so there is no need to look into them separately. Attention is focused here on traffic class distribution, and speed/flow estimation.

2.1.1 Traffic class distribution

This is a function of speed and volume/capacity ratio. In order to assess the prevailing highway traffic class, there is a need to have a control traffic class that reflects traffic performance at peak under dry and daylight conditions. In this paper the control traffic class is divided into six classes (A–F) as shown below in Figure 1, where A is the highest and F is the lowest. Traffic flow oscillates between class A and D. Class A describes traffic flow within the 15th percentile and free-flow speeds. It also shows that traffic flow is between zero and 15% of capacity. Class B describes traffic flow within the 15th percentile and 50th percentile speeds. It also shows that traffic flow is between 15 and 50% of capacity. Class C describes traffic flow within the 50th percentile and 85th percentile speeds. It also shows that traffic flow is between 50 and 85% of capacity. Class D describes traffic flow within the 85th percentile and optimum speeds. It also shows that traffic flow is between 85% of capacity and capacity. Beyond capacity, traffic flowrate contraction sets in; class E describes flowrate contraction within the shockwave velocity propagation zone. It suggests that traffic congestion at this stage may be construed as 'temporary'; class F describes traffic congestion where a vehicle moves in lockstep with the vehicle in front of it. Additional vehicles entering the traffic stream may trigger a traffic jam. Note that in Figure 1, u_f denotes free flow speed, u_o is optimum speed and u_c is constrained speed.

2.1.2 Determining the coordinates of speed/flow curve

In the paper 'flow' is synonymous with volume/capacity ratio. Volume/capacity ratio depicts the proportion of traffic flow traversing a roadway and is used to predict its effectiveness. The ultimate value is 1·00. The ratios are classified in the paper into four main groups: $\leqslant$ 0·15, 0·15 to 0·50, 0·50 to 0·85 and $>$ 0·85 to 1·00. The volume/capacity critical ratio is often taken in many studies as 0·85, therefore traffic flow at and beyond 0·85 is considered to be approaching capacity. There is no need to suggest otherwise. The general concept in the United Kingdom is that the maximum speed limits should be based primarily on an established 85th percentile speed. The TRB (1998) special report on managing speeds states that the 85th percentile is an important descriptive statistic in evaluating road safety. The general concept is that maximum speed limits

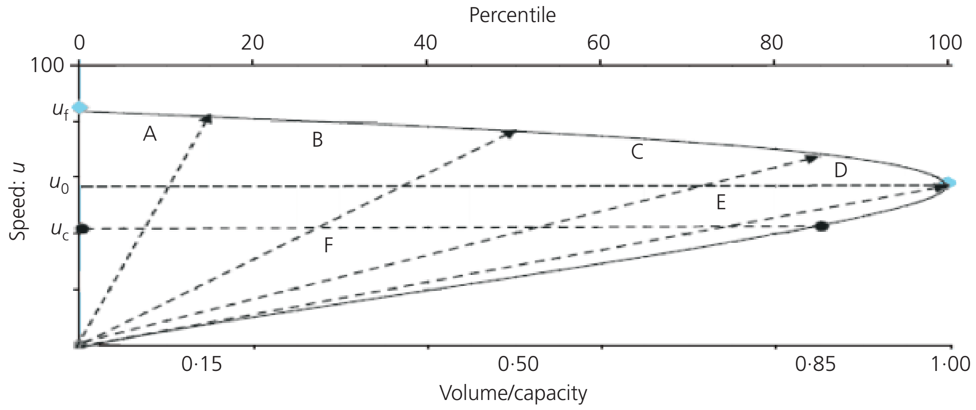

Figure 1. Hypothetical speed, percentile and volume/capacity relationship

should be based primarily on an established 85th percentile speed under good traffic conditions. Most cumulative speed distribution curves indent at around the 15th percentile and the 85th percentile of the total number of vehicle observations. In many studies, 85% is considered as the critical volume/capacity ratio and 15% ascribed to free-flow speed distribution; consequently cumulative speed distribution curves indent at around 15 percentile and 85 percentile of the total number of vehicle observations. Consequently, the upper section of the speed/flow curve can be divided into four classes (A, B, C and D) and the lower section into two (E and F) as shown in Figure 1. The speed/flow curve has two corresponding speeds for every traffic flow apart from capacity where the optimum speed is reached. From the discussion so far it has been shown that a simplistic approach can be used to classify traffic stream performance. Quantitative and qualitative assessments of highway traffic are intrinsically linked by the fundamental diagram of flow. In any case, flow, density and speed have often been used in many studies to describe highway traffic where

$$q = uk \Rightarrow \nu = \frac{q}{\kappa} \Rightarrow \kappa = \frac{q}{u} \tag{1}$$

It has been shown in previous studies by Ben-Edigbe (2010; Ben-Edigbe and Ferguson, 2005) that roadway capacity can be estimated with Equation 2, so that

$$Q = -c + (u_\mathrm{f})\frac{u_\mathrm{f}}{2(u_\mathrm{f}/k_\mathrm{j})} - \frac{u_\mathrm{f}}{k_\mathrm{j}}\left(\frac{u_\mathrm{f}}{2(u_\mathrm{f}/k_\mathrm{j})}\right)^2 \tag{2}$$

As flow, density and speed are related as shown in Equation 1, the function for speed/flow curve shown below as Equation 3 can be considered as a subordinate of Equation 2

$$Q_\mathrm{s} = -c + (u_\mathrm{f})\frac{u_\mathrm{f}}{2(u_\mathrm{f}/k_\mathrm{j})} - \frac{u_\mathrm{f}}{k_\mathrm{j}}\left(\frac{u_\mathrm{f}}{2(u_\mathrm{f}/k_\mathrm{j})}\right)^2 \tag{3}$$

where u_f denotes free-flow speed, k_j is jam density and c is a constant.

As roadway capacity is dynamic and speed/flow function hinges on the roadway capacity model equation, it can be postulated that the resultant speed/flow curve is dynamic. Although it is not the focus of this paper, it can nonetheless be mentioned in passing that all associated instruments of capacity computations must be dynamic. Since passenger car equivalent (pce) values or units (pcu) are the convertor from volume to flow, it makes sense to assume that they are dynamic. The calibration of the pce values can have a significant impact on capacity analysis computations where the presence of commercial vehicles is significant. Seguin *et al.* (1998), defined pce as the ratio of the mean lagging headway of a subject vehicle divided by the mean lagging headway of the basic passenger car. A simplistic passenger car equivalent calculation method based on headway was used in the paper where

$$\mathrm{pce}_{ij} = \frac{h_{ij}}{h_{\mathrm{pcj}}} \tag{4}$$

where $\mathrm{pce}_{ij} = \mathrm{pce}$ of vehicle type i under conditions j; h_{ij}, h_{pcj} = average headway for vehicle type i and passenger car for conditions j.

2.1.3 Mean speed and cumulative speed distribution statistical tests

As shown below in Figure 2, the cumulative percentiles are two descriptive parameters that are commonly used to compare different traffic conditions. Given the curves of $V(x_1, t)$ and $V(x_2, t)$ for dry (x_1) and rainfall (x_2) conditions the vertical distance between the curves represents the number of vehicles between points x_1 and x_2, whereas the horizontal distance represents trip time and the area between the curves describes the total trip time of all vehicles.

In Figure 2 above, $V(x, t)$ = cumulative number of vehicles to pass point x by time t. According to Lighthill and Whitham (1955), Equation 5 is valid at any point where q and k are continuous as shown below

$$\frac{\partial V(x, t)}{\partial t} = q\left(\frac{-\partial V(x, t)}{\partial x}, x\right) \tag{5}$$

Therefore from $V(x, t)$, density can be evaluated as

$$k(x, t) = \frac{-\partial V(x, t)}{\partial x}, \; q(x, t)\frac{\partial V(x, t)}{\partial t} \tag{6}$$

The 85th and 15th percentiles are two parameters that are commonly used to evaluate the effectiveness of highway service. In many studies, non-parametric double bootstrapping, the quantile regression, averaging 85th percentile methods or using the binomial test have been used to assess the statistical difference between two percentile samples. Bootstrapping is a method of resampling existing data by using simulation. Often the focus is on sampling distribution of the mean instead of the sampling distribution of the percentile, because there is a lack of statistical test for percentiles that can be easily applied and theoretically sound in much of the available literature. A statistical test based on Crammer's theory of asymptotic sample distribution has also been suggested by Sun *et al.* (2012) where the random variable can be used as the standard normal test statistic for examining the difference between two population percentiles. Where $X_{(n0\cdot85)}$ and $Y_{(n0\cdot85)}$ are 85th percentile random variables, n_x, n_y are random sample sizes, and S_x and S_y are sample variances

$$\frac{\left\{X_{[(n0\cdot85)+1]} - Y_{[(n0\cdot85)+1]}\right\} - 0}{1\cdot530\sqrt{S_x^2/n_x + S_y^2/n_y}} \tag{7}$$

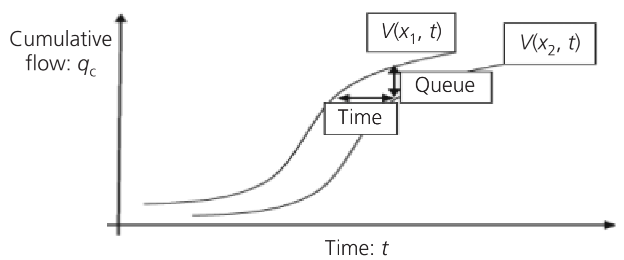

Figure 2. Cumulative percentile distribution of flow

2.2 Traffic shockwave velocity propagation

In considering the mechanisms by which rainfall conditions may possibly influence the quality of highway service, two groups of factors seem most important: the changing behaviour of drivers and the changing composition of traffic. Given dry weather and daylight 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 (multi-lanes). They may elect to change routes or departure times because of improved weather and traffic conditions. Where the traffic stream is moving at speed in close proximity and the lead vehicle brakes abruptly, this action will trigger shock waves that propagate along a line of vehicles in response to changing conditions at the front of the line. Shockwave velocity propagation is an indicator of drivers' behaviour during rainfall. When it rains, poor visibility and poor traction can force the drivers to reduce speed abruptly while adjusting to the prevailing weather condition. Abrupt speed reduction in turn may lead to traffic shockwave velocity propagation. In any case, rainfall influences travel time by shrinking the speed/flow curve; however, the extent of shrinkage and the behaviour of the traffic shockwave relative to rainfall intensities are of interest to the study. Traffic shock wave is a temporary, physical condition that can be estimated with Equation 8

$$S_w = \frac{q_f - Q_c}{k_f - k_c} \tag{8}$$

where S_w = propagation velocity of shock wave (km/h); q_f = flow prior to change in conditions; Q_c = flow after change in conditions; k_f = traffic density prior to change in conditions; k_c = critical traffic density after change in condition. If Equation 8 is combined with Equation 2 then the shockwave velocity propagation equation can be re-written as

$$S_w = \frac{q_f - \left\{(u_f)\frac{u_f}{2(u_f/k_j)} - \frac{u_f}{k_j}\left(\frac{u_f}{2(u_f/k_j)}\right)^2 - c\right\}}{k_f - k_c} \tag{9}$$

2.3 Road users input in context

Travel time is what most road users are concerned about and it is a useful guide for measuring the effectiveness of roads, when used in conjunction with delay and capacity utilisation. All time spent on travelling can be considered to have a value regardless of whether the travel is for business, recreation, social purposes or for other reasons. However, it could be argued that not all time savings should be considered as benefits since they cannot all be economically productive. In any case, the general concepts regarding rainfall intensities and travel time can be presented as a hypothetical non-linear curve, where it can be postulated that, irrespective of whether it rains or not, motorists will incur a fixed travel time. As the quality of highway service deteriorates due to rainfall intensities, average travel time will increase relative to speed reduction.

2.3.1 Travel time

The speed/flow relationship discussed previously is based on a decision to accept loss of time as the factor with which drivers are most concerned. However, when predicting travel time over length of roadway as shown below in Equation 10

$$T = t_{\mathrm{f}}\left\{1 + a\left(\frac{q}{Q}\right)^{b}\right\} \text{ for } \int_0^1 x = \frac{q}{Q} \tag{10}$$

where T = predicted travel time over length of roadway; q = flow; Q = capacity; t_{f} = travel time at free flow speed; 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. 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 $a = 0{\cdot}15$, and $b = 4$ in the 1965 version of the travel time equation and later updated (BPR, 1964) to $a = 0{\cdot}20$, and $b = 10$ to incorporate modern facilities according to HCM (TRB, 1994). The resulting speed–flow curve is flatter than the original BPR curve for v/c ratios less than 0·70 and the new curve drops much faster in the vicinity of capacity ($v/c = 1{\cdot}00$). The BPR equation was then refitted to the motorway speed–flow curves and it was recommended (TRB, 1994) that $a = 0{\cdot}20$, and $b = 10$. Dowling *et al.* (1997) recommended updated BPR speed–flow curves for motorway links to improve the accuracy of speed estimates used in transportation demand models. These 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 BPR curves have a parameters that vary from 0 to 1·0 and b parameters that vary from 4 to 11. In any case the BPR speed–flow curve has been validated against speed–flow data for both uninterrupted and interrupted flow facilities and could be useful in predicting travel time. There is no need to build a new model, if Equations 1 and 2 are merged into 10; superscript a is taken as 0·20 and $b = 10$ since we are interested in predicting travel time where $v/c < 0{\cdot}90$, then travel time can be re-written as

$$T = t_f[1 + X] \text{ where}$$

$$\mathrm{X} = 0{\cdot}20\left\{\frac{uk}{-c + (u_{\mathrm{f}})\dfrac{u_{\mathrm{f}}}{2(u_{\mathrm{f}}/k_{\mathrm{j}})} - \dfrac{u_{\mathrm{f}}}{k_{\mathrm{j}}}\left[\dfrac{u_{\mathrm{f}}}{2(u_{\mathrm{f}}/k_{\mathrm{j}})}\right]^2}\right\}^{10}$$

$$\text{for } \int_0^1 1x = \frac{q}{Q} \tag{11}$$

2.4 Summary of hypothetical quality of highway service assessment criteria

Hypothetical quality of highway service assessment criteria can be summarised as shown in Table 1.

3. Set-up of impact study and data collection

In peninsular Malaysia the rainy season is between September and December in the west, October and February in the east, with November to January as the wettest period. Consequently, the main studies were carried out at two sites (Highway 5 west, Pontian and Highway 3 east, Terengganu) in Malaysia between November and January 2009 and 2010. Typical setup of impact study sites is shown below in Figure 3. The sites were chosen to represent eastern (Terengganu) and western (Pontian). It is pertinent that rain gauges be located near the highway section under study, therefore study sites are located at less than 1 km from the nearest rain gauge. Skudai principal Highway 5 south was used for pilot tests that were carried out between May and July 2009. On-site volume, speed, headway and vehicle type data were captured continuously for three months. Two pneumatic tubes were set at 1 m apart across the carriageway lane width and connected to an automatic recorder (ATC). Three classes of rainfall intensity (light for precipitation less than 2·5 mm/h,

Variables	Travel class	Travel time: min	Speed distribution U (±%)					Obs. V/Q	Predicted flow V/Q			
			U_{f}	U_{o}	X_{v}	85%ile	15%ile		0·15	0·50	0·85	1·00
Sample 1												
Sample 2												
Change (±)												
Comment												

X_{v} mean speed; U_{f} free flow; U_{o} optimum; %ile percentile; S_{w} shockwave; Q capacity; v volume

Table 1. Hypothetical quality of service assessment criteria

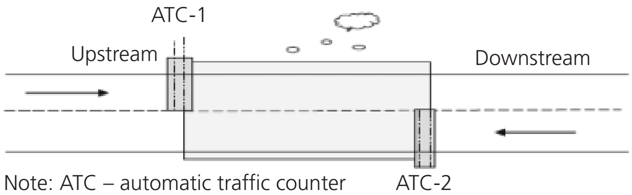

Figure 3. Two scenarios per roadway section under investigation

moderate for precipitation between 2·5 mm/h and less than 10 mm/h and heavy for precipitation more than 10 mm/h and less than 50 mm/h) were used in the study. Three types of vehicles, private cars, light trucks (4·8 and 11·1 m length) and heavy trucks > 11·1 m length were identified.

4. Empirical findings and discussion

The paper is exciting because it presents a novel approach to quality of roadway service prediction. The following steps are used to assess the quality of roadway service under dry and rainfall conditions.

Step 1. Determine the quality of roadway service assessment criteria and note that assessment is twofold: observed (traffic class, travel time, shockwave, mean speed, cumulated speed distribution and flow) and predicted (*V/Q*, capacity, optimum speed, free-flow speed) data.

Step 2. Estimate flow, speed and density using appropriate passenger car equivalent values.

Step 3. Determine control traffic class distribution based on traffic peak flow characteristics.

Step 4. Determine flow/density functions, hence speed/flow coordinates using Equation 2.

Step 5. Compute mean speed, optimum speed, free-flow speeds and variances; test statistics.

Step 6. Determine observed and predictive volume/capacity ratios.

Step 7. Estimate cumulative speed distribution and variances; test statistics.

Step 8. Estimate constrained travel time using Equation 11.

Step 9. Estimate traffic shockwave velocity propagations using Equation 9.

Step 10. Compare dry and rainfall outcomes in the assessment criteria table.

Step 11. Test the hypothesis that sample differentials are same.

Step 12. Accept or reject null hypothesis and comment.

4.1 Speed/flow curve coordinates

Flow, speed and density were estimated using appropriate passenger car equivalent values where applicable. In all cases, the model coefficients have the correct signs; a strong coefficient of determination suggests a good relationship between flow and density. The F-observed statistics at 10 degrees of freedom is much greater than F critical (4·94), suggesting that the relationship did not occur by chance. Also the t-observed statistic at 10 degrees of freedom tested at 5% significance level is much greater than 2, suggesting that density is an important variable when estimating flow. For example in Pontian Kecil–West Coast highway link, speed/flow curve coordinates for peak hour traffic flow characteristics were determined from the computation shown below. In Equation 12, flow density is modelled with a constant, whereas in Equation 13 the intersect of Equation 12 was set at zero so as to meet the basic requirement of the asymmetric flow/density curve.

$$q = -1{\cdot}9883k^2 + 160{\cdot}53k - 1112{\cdot}8$$

12. $$R^2 = 0{\cdot}93, \quad t > 2{\cdot}5, \quad F > 5$$

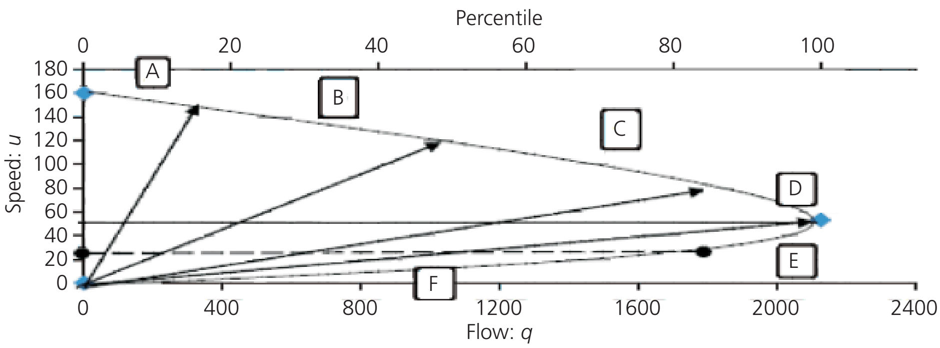

Figure 4. Traffic class distribution (Pontian Kecil–West Coast)

$\partial q/\partial k = 2(-1{\cdot}9883k) + 160{\cdot}53$; so that $-3{\cdot}9766k + 160{\cdot}53 = 0$.

Hence, critical density $k_c \approx 40$ veh/km; and free-flow speed is 160 km/h.

Plug the critical density into Equation 12 in order to determine the maximum flowrate (Q).

Hence, capacity, $Q = -1{\cdot}988(40)^2 + 160{\cdot}53(40) - 1112{\cdot}8 = 2120$ pcu/h.

And optimum speed, $u_o = 2120/40 \approx 50$ km/h

$$q = -0{\cdot}4145k^2 + 75{\cdot}034k$$

13. $R^2 = 0{\cdot}91,\ t > 2{\cdot}5,\ F > 5$

Where $q = uk$ (see Equation 1), then, $u = -0{\cdot}4145k + 75{\cdot}034$; for $k_j = 75{\cdot}034/0{\cdot}4145$; hence jam density, $k_j \approx 180$ veh/km.

Control traffic class distribution based on traffic peak flow characteristics is shown in Figure 4. Note that the speed/flow curve has been divided into six classes (A to F). Traffic flow will oscillate from class A to D and contract from D to F. In essence this is the control traffic class distribution of Pontian Kecil-West Coast highway link qualitative service.

4.2 Summary of findings

Tables 2, 3 and 4 summarise the findings from the study.

4.3 Summary of rainfall impact on qualitative assessment findings

This study is based on the hypothesis that rainfall will have a significant impact on the quality of roadway service irrespective of the intensity. The aim behind this exercise is to establish the extent to which travel time, speed and volume can be sustained in the presence of rainfall. Roadway capacity was estimated using the quadratic function and fundamental relationship between flow, speed and density. In the flow/density relationship, density is used as the control parameter and flow is the objective function. In the ensuing model equations flows were differentiated with respect to densities for maximum value of flows and critical densities were estimated from the differential equations. Although not the focus of the paper, road capacity loss resulted from variable rainfalls. Modification of the pce values did not affect the outcome of the study as speed reduction resulted from variable rainfall. Vehicle speeds drop significantly at the onset and during rainfall. Speed distribution fluctuates on the road section during dry weather, suggesting that drivers are not constrained by rainfall and hence

	S_w	Travel class	Travel time: min	Speed/cum. speed distribution U (±6%)					Obs. V/Q	Predicted flow V/Q			
				U_f	U_o	X_v	85%ile	15%ile		0·15	0·50	0·85	1·00
Dry	n/a	C	0·69	88	42	71	75	67	0·73	236	786	1337	1573
L	21	C	0·76	79	39	66	73	62	0·65	217	724	1232	1468
M	21	C	0·78	77	38	67	72	63	0·67	216	722	1228	1458
H	21	C	0·80	75	37	66	74	61	0·60	215	719	1223	1440

X_v mean speed; light <2·5 mm/h; moderate 2·5–10 mm/h; heavy 10–50 mm/h; %ile percentile; S_w shockwave; Q capacity

Table 2. Quality of service assessment (Pontian Kecil–West Coast highway link)

	S_w	Travel class	Travel time: min	Speed/cum. speed distribution U (±5%)					Obs. V/Q	Predicted flow V/Q			
				U_f	U_o	X_v	85%ile	15%ile		0·15	0·50	0·85	1·00
Dry	n/a	C	0·72	85	40	62	66	60	0·77	257	856	1456	1713
L	16	C	0·72	85	39	61	63	59	0·79	256	852	1449	1705
M	17	C	0·74	82	38	58	60	55	0·75	250	834	1418	1669
H	16	C	0·84	73	35	55	61	50	0·79	245	815	1386	1631

X_v mean speed; light < 2·5 mm/h; moderate 2·5–10 mm/h; heavy 10–50 mm/h, %ile percentile; S_w shockwave; Q capacity

Table 3. Quality of service assessment (Skudai–South Coast Highway Link)

	S_w	Travel class	Travel time: min	Speed/cum. speed distribution U (±6%)					Obs. V/Q	Predicted flow V/Q			
				U_f	U_o	X_v	85%^{ile}	15%^{ile}		0·15	0·50	0·85	1·00
Dry	n/a	C	0·68	90	42	65	68	62	0·76	253	842	1431	1684
L	21	C	0·76	79	38	62	65	59	0·70	240	799	1357	1597
M	24	C	0·77	78	37	60	61	55	0·63	239	795	1352	1590
H	13	D	0·91	68	33	53	57	50	0·83	226	754	1282	1509

X_v mean speed; light <2·5 mm/h; moderate 2·5–10 mm/h; heavy 10–50 mm/h, %^{ile} percentile; S_w shockwave; Q capacity

Table 4. Quality of Service Assessment (Terengganu Highway Link)

can choose their speed, whereas during rainfall speed distribution is almost flat, suggesting that drivers were constrained by rainfall condition. From Tables 2, 3 and 4, it can be seen that observed traffic flows ranging from 60 to 80% are not at peak, probably explaining why observed speed reductions, although significant, are not excessive. However, with predicted flows, it is shown in the tables that the road sections will not achieve the maximum flowrate of 2120 pcu/h during rainfall. Interestingly, free-flow speeds drop significantly because of rainfall, thus suggesting that at reduced traffic flow, even if it is one vehicle on the roadway, maximum free-flow speed cannot be reached. In any case statistical tests of the model equations indicated vehicle speed as the most significant factor affecting the quality of roadway service in this study. The effects of rainfall on the quality of roadway service were observed to be particularly pronounced in cases where the percentage of traffic flows was high. Since time is a function of distance relative to speed, as shown in Tables 2, 3 and 4 travel times increase relative to rainfall and are significantly excessive during heavy rainfall.

4.4 Summary of findings based on traffic shockwave velocity propagations

As shown in Tables 2, 3 and 4 below, traffic shockwaves have no clear trend relative to rainfall intensities, suggesting that motorists merely reacted temporarily to rainfall, irrespective of the intensity, and later adjusted to the ensuing driving conditions. In sum, the findings from this study indicate that the impact of rainfall on the quality of roadway service is more significant than currently reported in the HCM. The prescriptions in the Malaysian Road Work Manual (Malaysia Arahan Teknik, 1996) that is linked to HCM indicate the possibility of susceptible traffic management decision-making; so there is a need to carefully re-examine highway traffic operational strategies during rainfall events in Malaysia.

5. Conclusion

The study shows that significant reduction in the quality of roadway service will result from rainfall, irrespective of the intensity. Based on the synthesis of evidences obtained from the relationship between quality of roadway service and rainfall, it is correct to conclude that there is a significant change in speed reduction, and by extension increase in travel time due to rainfall especially during a heavy downpour. Temporary traffic shockwave velocity propagation may be caused at the onset of rainfall but not exacerbated by its intensity. It has long been clear that reliance on LOS for qualitative assessment is questionable at best. This implies that the development of a conceptual framework for assessing the quality of roadway service will be the way forward. It is hoped that this paper will provoke debate on qualitative assessment of roadway service.

Acknowledgements

The authors would like to thank the Malaysian Royal Police and Malaysia Public Works Department for ensuring safety during equipment installation and removal, also the Department of Irrigation and Drainage of Malaysia for providing supplementary rainfall data.

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