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Highway Capacity Prediction in Adverse Weather

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Abstract: The purpose of this study was to find out the effects of rainfall on traffic flow rates and the implications on highway capacities. Data was generated from a pneumatic tube detector placed on a 2 km straight section of a principal road that was operating in the free flow regime. This is with a view to isolating all bottlenecks and incidences that could affect traffic flows and to see the direct effect of the rainfall on traffic. Data from nearby rain gauge station was used to identify dry and wet traffic flow conditions. Empirical evidence exists for traffic flow contraction, speed reduction and increase in density. A speed reduction of 3.52% resulted in a flow rate change of 8.64% under rainfall conditions. Furthermore, the fundamental diagram was used to predict the capacity flows in both dry and wet conditions. A 42.27% loss of capacity was obtained at critical densities of 186.82 and 111.97 vehs km^{-1} for both dry and wet conditions respectively. It is concluded that adverse weather can seriously degrade the capacities of highways. At higher flow rates, the instabilities that could result from adverse weather effects can cause prolong delays to drivers with its attendant economic losses. Rainfall intensity variation should be investigated to determine capacity loss thresholds at which resources can be placed to manage traffic in adverse weather.

Key words: Dry weather, fundamental diagram, rainfall, traffic flow rates, wet weather

INTRODUCTION

The management of urban road networks and freeways is often challenged by variabilities in both the supply and demand aspects of the transportation system. Variability on the supply side comes from ambient conditions such as weather, road accidents, special events and road closures. Road and traffic conditions including peak hour flows, control devices, road works, surface conditions, drainage and geometric features also constraints the supply aspect of the system. These differing disturbances to the traffic flow affects the driving behaviour and hence the capacity of the highway (Lam *et al*., 2008).

The demand aspect of the transportation system emanate from trips generated from households, central business areas, institutions and trips between attraction and generation zones. How the trips generated from these various areas are distributed on the links in a road network constitute the demand side of the system.

Travel demand has exerted considerable pressure on governments, transportation researchers and road network managers in view of the increasing population of vehicles on roads and the extreme congestion being experienced in cities across the world (McDonald *et al*., 2006). Measures taken to curb the growth of vehicular traffic include introduction and encouragement of mass transit, light rail transit, congestion charging, delineation of parking and non-parking zones and enforcement of traffic regulations. In spite of all these, vehicle population growth has not abated and transportation researchers are forced to abandon traditional supply (capacity) improvement schemes such lane addition for more technical and efficient use of the road network system. This has been made possible by advances in computer and communications technology for real time monitoring of the road network system (McDonald *et al*., 2006).

Rainfall affects the supply side and its effect on traffic flow is similar to disturbances from fixed bottlenecks which could result in congestion depending on the traffic flow rate and intensity of rainfall (Alhassan and Edigbe, 2010). Rainfall is spatio-temporal in its occurrence and intensity and so are traffic flow rates. It inhibits speed, increases headways and contracts flow. This paper focuses on the influence of rainfall on traffic flow rates and the implications of these on highway capacity.

Studies on highway capacity reveal variation in the value of capacity across location, number of lanes, time of day and segment type (Jiyoun *et al*., 2009). Earlier efforts on capacity studies had concentrated on finding the numerical value of capacity to be used in designs and transportation systems management. Works of this nature include Persaud and Hurdle (1991) and Hall and

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Agyemang-Duah (1991). The breakdown phenomenon prior to capacity flows at highway bottlenecks has been reported by Kerner (2000). This leads to temporary losses of capacity with resulting impacts on performance (Chin *et al.*, 2002). The different values of highway capacity obtained made Minderhoud *et al.* (1997) to consider capacity as a stochastic parameter after a comprehensive critique on the methods of capacity estimation. Wu (2002) used the fundamental diagram approach to predict the capacity of highways without the need to measure it directly. Researchers are now focussed on accurate measurements and prediction of the capacity of highways to be used in performance evaluation, incident detection and prediction, as well as the production of counter measures for safe and efficient operation of highways. These needs have stimulated research interest in capacity measurements and prediction. Elefteriadou *et al.* (1995) observed a breakdown in flow in the vicinity of capacity and Evans *et al.* (2001) explored this area further and found that the breakdown is probabilistic in nature. Lorenz and Elefteriadou (2001) defined capacity as a function of breakdown probability. They concluded that the breakdown is due to vehicle-section cluster rather than vehicle-vehicle interaction.

Rainfall events add their own variability to traffic flows and hence on capacity. The mechanism through which rainfall affects the flow is explained by Alhassan and Edigbe (2010). Earlier studies have however, detected reduction in speed, contraction in volume, increase in headways and change in travel demand, as in the works by Tanner (1952) and subsequently by Hogema (1996), Keay and Simmonds (2005) and Chung *et al.* (2005). The effect of rainfall on accidents is reported by FHWA (2008) and on safety by Cools *et al.* (2010) and Maze *et al.* (2006).

To understand the effect of rainfall on surface traffic flow conditions, it will be useful to couple rainfall and traffic data with a view to developing a relationship between them. Dailey (2006) has developed a model for the response of traffic to rainfall rate as shown in Eq. 1:

$$\hat{y}(t) = \bar{y}(t) + z(t) - \int h(\tau) r(t-\tau) d\tau \tag{1}$$

Where:

$\hat{y}(t)$ = Is the measured traffic speed?
$\bar{y}(t)$ = Is the normal traffic speed
r (t) = Is the contribution to slowing from the rain fall rate
z (t) = All other contributions

Dailey used weather radar data mine and traffic data from inductive loop detectors. The radar data were converted to rain fall rates and the speed data from the inductance loop speed traps were used to measure the deviation from normal performance. These were used to generate an impulse response function and applied to radar measurements to predict traffic speed reduction. The study showed that the largest effects on traffic will be 1 hour after radar reflections of a significant scale begin. The state of the traffic in Dailey's approach cannot be ascertained.

The fundamental diagram approach could also be used to predict traffic conditions on sections of a highway especially at capacity as in the pioneering studies of Greenshields *et al.* (1935) and Wu (2002). The relationship between speed and density is such that as density increases speed decreases. These two parameters enable traffic engineers to relate travel demand directly to congestion on the freeway. Greenshields *et al.* (1935) reported a linear relationship between speed and density. Thus:

$$u_s = u_f - \frac{u_f}{k_j} k \tag{2}$$

where, μ_s is the space mean speed, μ_f is free flow speed, k is the density and k_j is the density at jam. The relationship between flow and density is obtained by substituting:

$$u = \frac{q}{k} \tag{3}$$

into Eq. 2, assuming q = uk, the fundamental equation of traffic is valid. This gives:

$$q = u_f k - \frac{u_f}{k_j} k^2 \tag{4}$$

The capacity of the section can be obtained by finding the derivative of the function and equating to zero. This yield:

$$u_f - 2k \frac{u_f}{k_j} = 0 \tag{5}$$

$$u_f = 2k \frac{u_f}{k_j} \tag{6}$$

The critical density is given by:

$$k_c = \frac{k_j}{2} \tag{7}$$

The general form of the quadratic is, $q = -\beta + \beta k - \beta k^2$. This will be used to model the empirical data for the flow density relationship and to predict the capacity at critical density under both normal and adverse weather.

Flow density bivariate relationship and fundamental diagram: The flow density relationship can be used to construct fundamental diagrams to show wet and dry weather conditions of a highway. The dry conditions represent the normal operations on the highway and the wet (rainfall) represents adverse weather as shown in Fig. 1. In normal operations, traffic in the free flow regime may either reach the peak flow i.e. capacity or may continue to operate in the free flow regime. The peak flow and the critical density are respectively indicated as Q_d and K_d for the dry (normal) operations. The second fundamental diagram with parameters Qw and Kw respectively for peak flow and critical density depicts the traffic operations in adverse weather (rainfall). Rainfall causes a contraction in flow because drivers' sight distance deteriorates and they adjust to this situation by reducing speed. The drop in flow observed by Elefteriadou *et al*. (1995) and Kerner (2000) is shown by the difference in the peaks of the two fundamental diagrams. The congestion side of the fundamental diagram in adverse weather replaces the congestion side of the fundamental diagram in normal weather. Prior to the capacity flow, only the fundamental diagram of dry weather (normal) is relevant as the highway has not entered into adverse weather condition. In adverse weather, due to flow contraction, vehicles on the highways are dispersed with small headways such that their behaviour resembles a typical traffic flow in the congestion regime. The characteristics of the flow will depend on the amplitude of the rainfall disturbance and the traffic flow rate.

The change from normal traffic condition to adverse weather traffic condition need not occur at capacity. It could occur in the free flow regime as well as in the congestion regime. If it occurs in the free flow regime, there is a capacity drop as opposed to a capacity loss if it occurs in the congested regime.

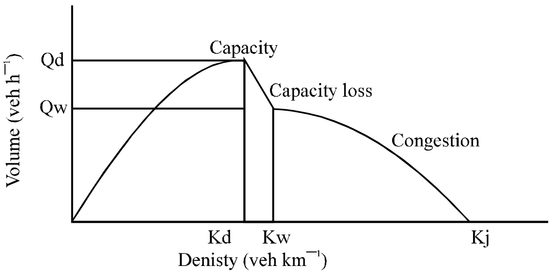

Fig. 1: Fundamental diagram showing normal and adverse weather conditions

Data: Data for this study was collected from Skudai-Pontian Highway in the month of June 2010. It is a two-way two lane principal highway that connects the southern state of Johor Bahru to the northern part of the Malaysian Peninsula. A two kilometre straight section located 43 km from Johor Bahru was used as the data collection site. Two pneumatic tubes were laid in parallel 1 meter apart across either lane and were connected to an automatic counter. Vehicles hitting the tubes as they travel generate air pulses in the tubes, which move towards the counter, as the other ends of the tubes are airtight. Data on each vehicle is logged in by the vehicle classifier, which can be retrieved from the classifier during or after the data collection exercise. Rainfall data supplied by the Department of Irrigation and Drainage of Malaysia from a rain gauge station located 750 m from the site was used to identify the rainy days as well as the rainfall rates for traffic data abstraction. Days for which rainfall events were recorded were used to select the corresponding traffic data for analysis. Such data are referred to as wet traffic data. Days for which no rainfall events occurred are regarded as dry traffic data. The traffic data collection period lasted for 30 days during which 31 rainfall events were recorded.

RESULTS

Empirical evidence and modelling: The study approach in this work utilises only gauged rainfall data and direct empirical observations in contrast to other studies for instance, Chung *et al*. (2006), Dailey (2006) and Billot (2009) that used weather radar rain rates and historical inductive loop traffic data. The use of weather radar data and historical loop detector data is useful if it is required to only model the relationships between rainfall rates and traffic flow. However, the extraneous effects such as curves, grades, recurrent congestion, accidents, work zones, hydroplaning and other incidences cannot be discerned from historical data. Furthermore, the state of the traffic cannot be determined at the time of rainfall occurrence. In order to clearly see the effect of rainfall on the flow, it is important to remove all such disturbances to the flow. The state of the traffic during the period of the observation is shown in Fig. 2-4.

Figure 2 describes the speed-density relationships in both dry and wet weather conditions. The Posted Speed Limit (PSL) on this facility is 60 km h^{-1}. There are greater

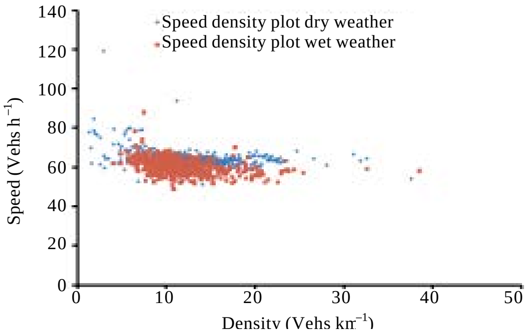

Fig. 2: Speed density plot for both dry and wet conditions

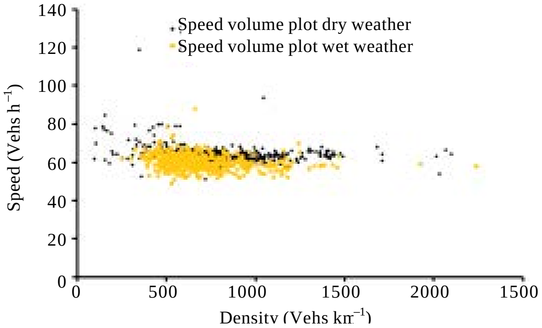

Fig. 3: Speed volume plot for both dry and wet conditions

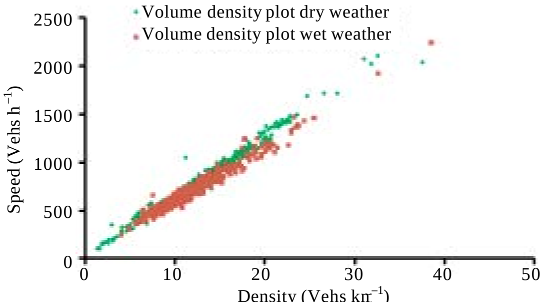

Fig. 4: Volume density plot for both dry and wet conditions

numbers of high speed vehicles exceeding the PSL in dry weather than in wet weather. Such drivers are more prone to changes in weather condition than their counterparts travelling within the speed limit. The sight distance reduction caused by clouding the view of the driver in rain induces the driver to reduce speed. Thus a contraction of flow occurs. This can be seen in the dispersion plots in Fig. 2. The density of the flow falling between 0.5 and 25 vehs km^{-1} attests to the free flow conditions on the facility.

The bivariate relationship between speed and volume follows a similar trend as the speed density plot. Higher proportions of vehicles with speed above the PSL are observed in dry weather than wet weather. Vehicles in wet weather are bunched whereas those in dry weather are dispersed. Speed flow relationships are modelled to contain the three regions of traffic flow: free-flow, capacity and congestion regions. On this facility, the empirical evidence is strongly in favour of the free flow regime. Thus only the linear portion of the free flow regime is depicted in Fig. 3. The traffic states of capacity and congestion are non-existence on this facility. In adverse weather, the free flow regime is still maintained in spite of the bunching of the traffic flow.

Figure 4 together with Fig. 2 and 3; clearly depict the state of the traffic under both dry and wet conditions. The traffic is operating in the free flow region in both weather conditions. A closer look at the plots shows a contraction of the macroscopic parameters of speed, volume and density in wet condition. Drivers travelling at higher speeds are disturbed most by the rain and consequently reduce their speed. The disturbance comes in the form of sight distance reduction resulting from clouding of the drivers' sight. It is synonymous with viewing the road through a cloud of smoke. Drivers are thus forced to reduce their speed to feel safe. A driver travelling with large gaps between leading and lagging vehicles does not respond spontaneously to changes in weather conditions, instead the driver continues until he catches up with a slower driver or the clouding effect takes place. In both cases, a noticeable change in behaviour is observed. In the case of a driver travelling with a small headway (less than 2 sec) between leading and lagging vehicles, a platooning of the vehicles could take place depending on the behaviour of the leading vehicle, the intensity of the rain, traffic flow rate and opportunities for overtaking. A localised cluster would form if the driver does not overtake and it may grow. It is common to see groups of localised clusters interspersed with large headways under rainfall conditions. In the free flow regime, these localised clusters do not grow, as overtaking opportunities soon become available or the rainfall subsides. Thus there is empirical evidence for flow contraction, speed reduction and vehicle clustering under rainfall conditions. The statistical properties of speed for the two flow conditions are shown in Table 1. A mean speed drop of 3.52% was recorded between dry and wet flow conditions. To predict the capacity flows for the two conditions, the empirical data is modelled using the flow-density relations of the fundamental diagrams.

Capacity prediction: Capacity prediction is useful in highway operations. It will enable road network operators

Table 1: Speed characteristics for dry and wet flow

Speed characteristics (km h^{-1})	Dry weather	Wet weather
Mean	64.00	60.48
Median	63.52	60.52
S.D.	4.02	4.03
Min	51.30	48.74
Max	119.01	87.96
85% speed	65.92	64.42
95% speed	68.50	66.45
Variance	16.16	16.20
C.I. (95%)	64.00±0.30	60.48±0.37

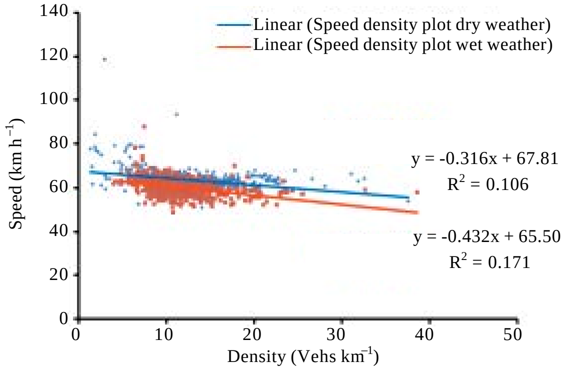

Fig. 5: Speed density model for both dry and wet conditions

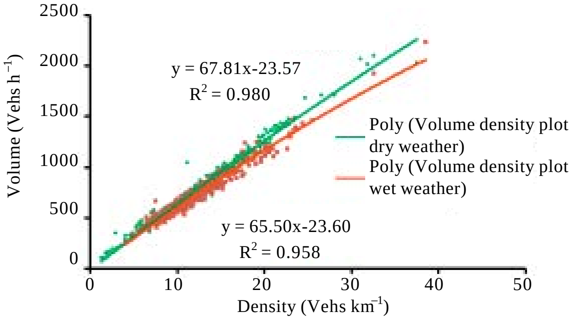

Fig. 6: Flow density model for both dry and wet conditions

to see the traffic flow scenarios that will emerge under capacity flows and the consequences of that on safety and congestion management. Figure 5 is a model of the speed density relationships for both dry and wet weather. Clearly, there is a speed drop with a corresponding increase in density as revealed by comparison of the two models.

The best fit model equations for the flow density relationships are as shown in Fig. 6. The free flow speed drops from 67.814 km h^{-1} in dry weather to 65.502 km h^{-1} in wet weather. The mean speeds and densities observed in both dry and wet conditions are 64 km h^{-1}, 12.03 vehs km^{-1} and 60.48 km h^{-1}, 11.63 vehs km^{-1}, respectively. The reduction in flow rate due to rainfall in the current state of traffic is 8.64%. The predicted state of the traffic at capacity is summarised in Table 2.

Table 2: Predicted traffic state parameters at capacity

Highway condition	Speed at capacity (Km h^{-1})	Critical density (Vehs km^{-1})	Volume (Vehs/hr/l)	Capacity loss
Dry condition	8.67	186.82	3155.39	
Wet condition	17.12	111.97	1821.75	1333.64 (42.27%)

The traffic speed at critical density under dry weather conditions is 8.67 km h^{-1}. The critical density is predicted to be 186.82 vehicles per km and a flow rate or capacity of 3155.39 vehs h^{-1} per lane. The corresponding traffic flows for the wet conditions are speed; 17.12 km h^{-1}, critical density, 111.97 vehs Km^{-1} and capacity, 1821.75 vehs/hr/lane. It can be seen that the traffic flow speed in wet weather is higher than the speed in dry weather at capacity. This is explained by viewing that rainfall does not act as a physical barrier to flow, thus higher speeds are attainable commiserate with the safety level in adverse weather. Similarly, there is less dense packing of vehicles in adverse weather than there will be in dry weather but still results in volume contraction. The capacity loss due to rainfall at critical density is 42.27%. Thus a traffic speed reduction of 3.52% in wet weather will result to 8.64% reduction in capacity. However, if this is projected to capacity flows, more dramatic reduction in capacity will be seen, up to 42.27% in this research. It is reasonable to mobilise resources to avoid capacity losses in adverse weather conditions, particularly where flow rates are in the vicinity of capacity. This will reduce the economic losses due to delays and accidents that may occur during adverse weather conditions.

CONCLUSIONS

This study considered the effect of rainfall on traffic flow rates and the consequences of that on highway capacity. For a highway currently operating in the free flow regime, empirical evidence exists for flow contraction and speed reduction in adverse weather conditions. The conclusions and recommendations from this study are as follows.

- Rainfall affects traffic flow rates and speed. The speed reduction is as a result of the "clouding effect" of rainfall caused by the raindrops. The clouding effect causes sight distance deterioration. Consequently drivers reduce speed and a contraction of flow occurs
- The speed drop observed in this study is 3.52%. This caused a flow rate change of 8.62%

- The projected capacity flows at critical density for both dry and wet weather conditions are 3155.39 vehs/l/hr and 1821 vehs/l/hr respectively. This results in a capacity drop of 42.27%
- The traffic flow speed at critical density is higher for wet condition than for dry condition. This is explained by viewing that rainfall does not constitute a physical restraint to traffic flow and drivers maintain a certain minimum headway in adverse weather for safety
- Rainfall can seriously degrade highway capacities. To identify resources to be employed to manage congestion related problems in adverse weather, rainfall intensity variation should be investigated on traffic flow to identify capacity loss thresholds at which such resources can be placed to assist drivers.

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REFERENCES

Alhassan, H.M. and J.B. Edigbe, 2010. Influence of rainfall intensity on traffic flow rates modelling techniques. Proceedings 3rd International Graduate Conference on Science, Engineering and Humanities, Nov. 2-4, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia, pp: 1-6.

Billot, R., 2009. Integrating the effects of adverse weather conditions on traffic: Methodology, empirical analysis and bayesian modelling. http://www.ectri.org/YRS09/Papiers/Session3/Billot_R_Session3_Traffic(2).pdf.

Chin, S.M., O. Franzese, D.L. Greene, H.L. Hwang and R.C. Gibson, 2002. Temporary losses of highway capacity and impacts on performance. Oak Ridge National Laboratory, US. Department of Energy, ORNL/TM-2002/3. http://www.osti.gov/bridge/product.biblio.jsp?osti_id=814401.

Chung, E., O. Ohtani and M. Kuwahara, 2005. Effect of rainfall on travel time and travel demand. Proceedings of the 5th ITS European Congress, June 1-3, Germany, pp: 1-8.

Chung, E., O. Othani, H. Warita, M. Kuwahara and H. Morita, 2006. Does weather affect highway capacity. http://www.transport.iis.u-tokyo.ac.jp/publications /2006-026.pdf.

Cools, M., E. Moons and G. Wets, 2010. Assessing the impact of weather on traffic intensity. Weather Climate Soc. Am. Meteorol. Soc., 2: 60-68.

Dailey, D.J., 2006. The use of weather data to predict non-recurring traffic congestion. Technical Report, Agreement T2695, Task 54, Washington State Transportation Center, USA. http://www.wsdot.wa.gov/research/reports/fullreports/655.1.pdf.

Elefteriadou, L., R.P. Roess and W.R. McShane, 1995. The probabilistic nature of breakdown at freeways merge junctions. Trans. Res. Record, 1484: 80-89.

Evans, J.L., L. Elefteriadou and G. Natarajan, 2001. Probability of breakdown at freeway merges using markov chains. Transp. Res. Part B: Methodol., 35: 237-254.

FHWA, 2008. Road weather management overview. http://ops.fhwa.dot.gov/weather/overview.htm.

Greenshields, B.D., J.R. Bibbins, W.S. Channing and H.H. Miller, 1935. A study of traffic capacity. Highway Res. Board Proc., 14: 448-477.

Hall, F.L. and K. Agyemang-Duah, 1991. Freeway capacity drop and the definition of capacity. Transportation Research Record, No. 1320, pp: 91-98. http://pubsindex.trb.org/view.aspx?id=365591.

Hogema, J.H., 1996. Effects of rain on daily traffic volume and on driving behavior. TNO Report TM-96-B019, TNO Human Factors Research Institute, Soesterberg, Te Netherlands.

Jiyoun, Y., H. Sarah and L. Elefteriadou, 2009. Differences in freeway capacity by day of the week, time of day and segment type. J. Transp. Eng., 135: 416-426.

Keay, K. and I. Simmonds, 2005. The association of rainfall and other weather variables with road traffic volume in Melbourne, Australia. Accident Anal. Prev., 37: 109-124.

Kerner, B.S., 2000. Theory of breakdown phenomenon at highway bottlenecks. Trans. Res. Record, 1710: 136-144.

Lam, W.H.K., H. Shao and A. Sumalee, 2008. Modeling impacts of adverse conditions on a road network with uncertainties in demand and supply. Trans. Res. Part B, 42: 890-910.

Lorenz, M.R. and L. Elefteriadou, 2001. Defining highway capacity as a function of the breakdown probability. Transp. Res. Record: J. Transp. Res. Board, 1776: 43-51.

Maze, T.H., M. Aggarwal and G. Burchett, 2006. Whether weather matters to traffic demand: Traffic safety, traffic operations and flow. Transp. Res. Record: J. Transp. Res. Board, 1948: 170-176.

McDonald, M., H. Keller, J. Klijnhout, V. Mauro and R. Hall *et al*., 2006. Intelligent Transport Systems in Europe: Opportunities for Future Research. Chapt. 2, World Scientific Co Pvt. Ltd., London, ISBN: 981-270-082-X, pp: 8-17.

Minderhoud, M.M., H. Botma and P.H.L. Bovy, 1997. Assessment of roadway capacity estimation methods. Transp. Res. Record: J. Transp. Res. Board, 1572: 59-67.

Persaud, B.N. and V.F. Hurdle, 1991. Freeway Capacity: Definition and Measurement Issues. In: Highway Capacity and Level of Service, Brannolte, U. (Ed.). Balkema, Rotterdam, South Holland.

Tanner, J.C., 1952. Effect of weather on traffic flow. Nature, 169: 107-107.

Wu, N., 2002. A new approach for modelling of fundamental diagrams. Trans. Res. Part A, 36: 867-884.