International Journal of Integrated Engineering - Special Issue on ICONCEES Vol. 4 No. 3 (2012) p. 53-58

Discriminate Modelling of Peak and Off-Peak Motorway Capacity

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Abstract: Traffic theory is concerned with the movement of discrete objects in real time over a finite network in 2 Dimensions. It is compatible with or dependent on fundamental diagram of traffic. Without question traffic flow is an essential quantitative parameter that is used in planning, designs and roadway improvements. Road capacity is significant because it is an important indicator of road performance and can point road managers in the right road maintenance and traffic management direction. In this paper four direct empirical capacity measurement methods have been considered. To test the efficacy of each method, data for peak period, off-peak and transition to peak have been used. The headway and the volume methods lack predictive capability and are suitable only for current assessment of flow rates. The product limit method is weak in its predictive capability in view of the arbitrariness in the selection of the capacity value. It is also an extreme value method; hence not all volume data can be used with this method. The fundamental diagram method has good predictive capability and furnishes capacity values consistent with the standard of the facility. Unlike other methods, it does not rely on bottleneck conditions to deliver the capacity value. The paper concluded that each method is uniquely suited to prevailing conditions and can be so employed.

Keywords: Fundamental Diagrams, Road Capacity, Traffic Flow, Headway, Modelling

1. Introduction

Traffic flow measurements are vital for the performance evaluation of existing highway facilities as well as their design and maintenance. Traffic flow rate, speed and density are usually required to completely describe the state of traffic on any roadway section. However, their measurements are time consuming and costly but often required for preliminary designs, planning and roadway improvements. Traffic flow models enable quick estimates to be made in addition to describing the relationships between flow, speed and density.

Basically, three approaches to traffic flow modelling can be pursued depending on the level of detail desired. Microscopic models describe the way individual vehicles move on the road. Vehicles in close proximity to each other may need to overtake (lane changing) or may continue behind the leading vehicle (platoon formation). In situations like these mesoscopic models are more suitable to describe traffic behaviour. At high flow rates, traffic flow needs to be described at the level of detail of the flow rather than the individual vehicles, macroscopic models are then used. Traffic flow modelling using the macroscopic approach could be by simulation or direct empirical methods.

This paper explores direct empirical traffic flow modelling approaches which yield traffic flow rates as the outcome. The aim is to determine the efficacy of these models in predicting traffic flow rates particularly at capacity. Models that utilise vehicle headway data, traffic volume data, traffic volume and speed data and volume, speed and density data shall be pursued. These methods also cover flow rates measurements during peak periods, non-peak periods as well as transitions to peak. The rest of the paper is organised as follows: section 1.2 covers the literature review on the subject; section 1.3 describes the data collection procedure. In section 1.4, we present the flow rate (capacity) modelling techniques while the results follow in section 1.5. Finally we draw the conclusions in section 1.6.

2. Concepts on Empirical Roadway Capacity Estimation Methods

Roadway capacity is central to highway traffic analysis. Capacities have sometimes been derived in many literatures with extreme values that have no resemblance to actual traffic flowrate. Determination of roadway capacity is one of the main outputs in traffic studies and traffic theory analysis. Its value is a key input for facility selection, design and rehabilitation. Capacity can be taken as the maximum number of vehicles per time period traversing a section or point along a roadway lane under prevailing circumstances. The definition suggests that roadway can be at peak, off-peak, and mixed-peak capacity per time unit under prevailing

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conditions. The peak roadway capacity under dry weather condition is often employed as the reference flowrate because it represents the worst traffic stream scenarios. Hypotheses about the reasons for the capacity drop postulated in many studies include among others: acceleration constraints, drivers behaviour and location bottleneck. Therefore the question of data collection period is pertinent to the issue of roadway capacity drop.

As contained in many literatures, capacity estimation methods include estimation with headways, estimation with traffic volumes, estimation with traffic volumes and speeds, and finally estimation with traffic volumes, speeds and densities. However, not all empirical estimation methods can be used for peak and off-peak traffic capacity prediction. It can be argued that only headway and fundamental diagram of flow can be so employed.

Highway capacity can be determined using volume and speed data but the method remains essentially the same as the extreme value method. The speed component of the data is not employed in the evaluation. It is however, used to assess the qualitative performance of the traffic flow. Capacity can be estimated using the three macroscopic parameters of volume, speed and density in bivariate relationships called fundamental diagrams. Since speed and volume data are more readily obtainable from observation sites the density is derived using the fundamental equation of traffic. Flow-Density polynomial functions are then used for quantitative prediction of the value of capacity because roadway capacity can be estimated using equation 1 below;

$$Q = (u_f)\frac{u_f}{2\left(\frac{u_f}{k_j}\right)} - \frac{u_f}{k_f}\left(\frac{u_f}{2\left(\frac{u_f}{k_j}\right)}\right)^2 \qquad (1)$$

Where: Q is capacity, u_f is free flow speed and k_j is jam density.

Traffic flow rate measurements employing direct empirical methods require observation and data collection at specific points or sections of the highway and determining the flow rate therefrom. Headway estimation methods assume traffic to be categorised into two: traffic following each other closely otherwise known as forced flow and traffic arriving in a free-flowing fashion. Two models are available to fit the headway data and deriving the capacity (maximum flow rate). These are the Branston model [1] and the Buckley model [2]. The two models are respectively stated in Equations 2 and 3 below.

$$f(h) = \theta g(h) + (1-\theta)\lambda e^{-\lambda h}\int_0^h g(h)e^{\lambda h}dh \qquad (2)$$

The model by Branston results in a generalised queuing model with the function g(h) being the probability density function of the time headway. HA et al (2010) [3] suggest that the gamma distribution given in Equation 3 provides the best fit for the time headway.

$$g(h) = \frac{\alpha^\beta (h-\tau)^{\beta-1}}{\Gamma(\beta)} e^{-\alpha(h-\tau)} x 1_{\{h\geq\tau\}}(h) \qquad (3)$$

Buckley [2] used a Semi-Poisson process to model the headway data as given in Equation 4. In both models λ is the arrival rate in the free-flowing traffic while θ represents the constrained portion of traffic.

$$f(h) = \theta g(h) + (1-\theta)\lambda e^{-\lambda h}\frac{G(h)}{g^L(\lambda)} \qquad (4)$$

In either case, estimation of the traffic capacity is made using Equation 5 below.

$$q = \frac{3600}{\sum h_p / n} \qquad (5)$$

Capacity estimation that employ observed volume methods also utilise two broad sub-models. The sub-models are the observed extreme and the expected extreme methods. Observed extreme methods may themselves be further categorised as bimodal method and the selected maxima. [4]. In the observed extreme method, probability distributions are used to fit the data similar to the headway method in which traffic is categorised into constrained and unconstrained flows. In this case, constrained flow corresponds to flows at capacity while unconstrained flows are the below capacity flows. The selected maxima method involves collecting data over a period of time and identifying the maximum flows over the period. The capacity is then assumed to be the average of the maximum flows over the period as given below.

$$q_c = \sum_i q_i / n \qquad (6)$$

Where q_c is the capacity value (vehicles per hour), q_i is the maximum flow rate observed over period i, n is the number of cycles and i is the length of cycle period over which a maximum flow rate is determined. Estimation using extreme value methods essentially use extreme value theory particularly, the Weibull distribution to fit the volume data. The parameters of the distribution are determined and cumulative distribution function is then used to obtain the capacity value. [4].

3. Data Collection

Data was obtained from a principal road in Johor Bahru 23km from Universiti Teknologi Malaysia. The J5 is a two-lane two way facility that runs along the west coast of peninsula Malaysia from the southern state of Johor to the northern state of Kedah. Two automatic traffic counters were installed. One on each lane and data was collected for two months during the monsoon period in 2010. Detailed vehicular information logged by the counters were retrieved and processed into macroscopic parameters. The headway data (also obtained from the counters) were processed separately for the headway estimation methods. Only day light traffic data have been used in this paper. Peak period, non-peak and transition to peak data have been used appropriately for the methods used in this paper. All traffic flows were converted to Passenger Car Equivalent (PCE) units prior to analysis using the standard Malaysia PCE values.

4. Analysis

Peak hour flows obtained during the observation period are shown in Table 1. For the headway method, the respective average headways were determined and were then used to compute overall average for the period of observation.

Table 1 Peak Flow Mean Headway Results

Peak Volume PCE/hr	Speed km/hr	Headway seconds	Peak Volume PCE/hr	Speed km/hr	Headway seconds
1260	65.49	2.8571429	1393	69.45	2.5843503
1335	66.99	2.6966292	1271	69.60	2.8324154
1245	66.48	2.8915663	1313	68.55	2.7418126
1255	65.72	2.8685259	1238	66.28	2.9079160
1332	65.60	2.7027027	1390	71.12	2.5899281
1251	66.39	2.8776978	1345	69.30	2.6765799
1270	65.90	2.8346457	1266	70.36	2.8436019
1284	65.78	2.8037383	1312	68.75	2.7439024
1272	65.76	2.8301887	1232	71.65	2.9220779
1383	64.83	2.6030369	1363	71.42	2.6412326
1226	66.67	2.9363785	1313	72.70	2.7418126
1399	64.95	2.5732666	1304	72.34	2.7607362
1263	63.63	2.8503563	1267	74.31	2.8413575
1262	64.88	2.8526149	1383	64.58	2.6030369
1185	62.79	3.0379747	1344	63.57	2.6785714
1288	66.40	2.7950311	1302	65.48	2.7649770
1236	73.92	2.9126214	1171	65.65	3.0742955
1377	70.81	2.6143791	1323	64.03	2.7210884
1385	73.23	2.5992780	1415	62.98	2.5441696
1286	74.61	2.7993779	1257	65.24	2.8639618
1288	75.96	2.7950311	1475	64.94	2.4406780
1358	66.63	2.6509573	1253	68.63	2.8731045
1293	67.47	2.7842227	1288	67.10	2.7950311

The mean headway from the data in table 1 is 2.78 seconds. The capacity was determined using Equation (5).

To estimate the capacity using the volumes data, the flow profiles were plotted as shown in Figure 1. The maximum flows obtained from the profiles are then used as in equation 6 to obtain the capacity value.

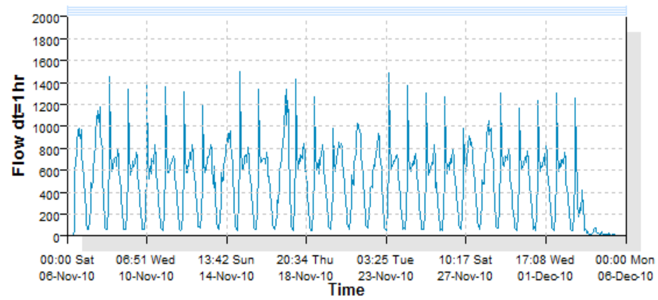

Fig. 1 Flow/Time Profile

The product limit method utilises the volumes and speed data to determine the capacity value. The method also involves classifying the data into two. Flows below the capacity value and flows at capacity and beyond. Given that G (q) is the probability that the capacity value q_c is greater than a flow rate q. The capacity cumulative distributive function is then given by

$$F(q) = 1 - G(q) \tag{6}$$

The product limit function resulting is given as:

$$G(q) = \Pi_{q^i} \frac{K_{q^i} - 1}{K_{q^i}}, q_i \in \{C\} \tag{7}$$

Where $G(q) = \text{Prob}(q_c > q)$

Equation (6) is used to compute the probabilities of capacity q_c being greater than any flow rate q. The capacity cumulative distribution function is then determined using equation (6) and shown in column 7 of Table 2. Using the median volume as the basis for defining the capacity the flow rates were divided into two: values that represent flow rates below capacity and values for flow rates at or above capacity. The ensuing plot of the cumulative distribution function is shown in Figure 2. The capacity value is taken to be the 90th percentile value of the cumulative distribution function.

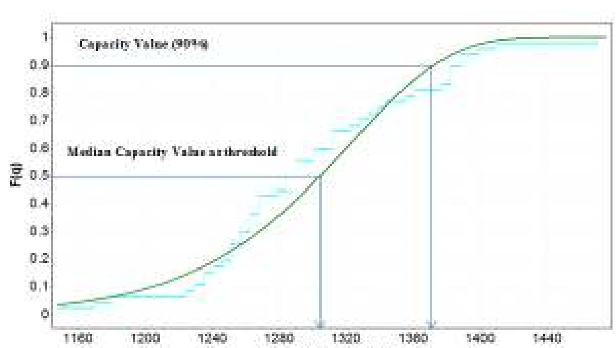

Fig. 2 Cumulative Distributions from Product Limit Method

Table 2 Computed Capacity Probabilities using Product Limit Method

1 Interval i	2 q_i	3 Set	4 Order j	5 K_q, $q_i ε\{C\}$	6 G(q)	7 F(q)
7.00-8.00	1260	Q	13	-	0.700	0.300
7.00-8.00	1335	C	31	1	0.300	0.700
7.00-8.00	1245	Q	7	-	0.825	0.175
7.00-8.00	1255	Q	10	-	0.750	0.250
7.00-8.00	1332	C	30	1	0.325	0.675
7.00-8.00	1251	Q	8	-	0.815	0.185
7.00-8.00	1272	Q	20	-	0.570	0.430
7.00-8.00	1383	C	37	1	0.110	0.890
7.00-8.00	1226	Q	3	-	0.982	0.018
7.00-8.00	1399	C	41	1	0.050	0.950
7.00-8.00	1185	Q	2	-	0.920	0.080
7.00-8.00	1288	Q	23	-	0.452	0.548
7.00-8.00	1236	Q	5	-	0.850	0.150
7.00-8.00	1377	C	36	1	0.188	0.812
7.00-8.00	1385	C	38	1	0.050	0.950
7.00-8.00	1286	Q	22	-	0.450	0.550
7.00-8.00	1393	C	40	1	0.050	0.950
7.00-8.00	1271	Q	19	-	0.573	0.427
7.00-8.00	1313	C	28	1	0.330	0.670
7.00-8.00	1238	Q	6	-	0.850	0.150
7.00-8.00	1390	C	39	1	0.050	0.950
7.00-8.00	1345	C	33	1	0.238	0.762
7.00-8.00	1266	Q	16	-	0.475	0.425
7.00-8.00	1312	C	27	1	0.338	0.662
7.00-8.00	1232	Q	4	-	0.238	0.762
7.00-8.00	1363	C	35	1	0.188	0.812
7.00-8.00	1313	C	28	1	0.188	0.812
7.00-8.00	1304	Q	26	-	0.400	0.600
7.00-8.00	1267	Q	17	-	0.650	0.350
7.00-8.00	1383	C	37	1	0.163	0.837
7.00-8.00	1344	C	32	1	0.225	0.775
7.00-8.00	1302	Q	25	-	0.400	0.600
7.00-8.00	1171	Q	1	-	0.991	0.019
7.00-8.00	1323	C	29	1	0.328	0.672
7.00-8.00	1415	C	42	1	0.025	0.975
7.00-8.00	1257	Q	12	-	0.750	0.250
7.00-8.00	1475	C	43	1	0.000	1.000
7.00-8.00	1253	Q	11	-	0.750	0.250
7.00-8.00	1288	Q	23	-	0.450	0.550
	Average	Total I =46				
	Volume	I in Q = 27				
	1305	I in C = 19				

Capacity estimation using the fundamental diagram approach utilises traffic flow parameters of volume, speed and density. To proceed, the flow-density plot is fitted to a quadratic function and the speed-density plot is fitted to linear function. These two are sufficient to derive the traffic state parameters including the capacity. The capacity value is obtained by finding the derivative of the quadratic function and determining the critical density and maximum flow rate. The plots for the two functions are shown in Figure 3. The results of the analysis for peak, non-peak and transition to peak are presented in the next section.

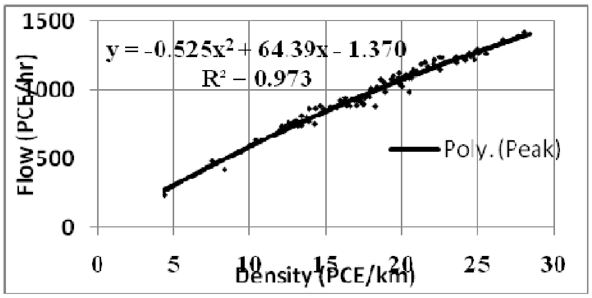

Fig. 3 Flow/Density Relationship (off-peak)

$$q = -0.5255x^2 + 64.395x - 1.3709 \qquad R^2 = 0.97 \qquad (8)$$

The model coefficients in equations in the paper have the expected signs and the coefficients of determinations (R^2) for both road directions A are much greater than 0.85, thus, it can be suggested that a strong relationship between flows and densities exists and the model could be used to estimate roadway capacity for the highway sections. The F – observed statistics at 10 degree of freedom is much greater than F critical value of 4.94 suggesting that the relationship did not occur by chance. Also the t – observed statistic at 10 degree of freedom tested at 5 % significance level is much greater than 2 thus suggesting that density is an important variable when estimating flow. For maximum flowrate;

$\partial q / \partial x = 1.051k + 64.395 = 0 \rightarrow k_c = 61.27$vehicles/km
Estimated capacity (Q) = 1972pcu/hr

5. Results and Discussion

The results of the remainder capacity evaluations for peak, off-peak and transition to peak are shown in Table 3. The headway, volume and product limit methods gave similar results for the peak period data. The fundamental diagram approach returned a value higher than the other methods. The headway method produced the least capacity value. This may be due to the large average headways obtained. The headway of 2.78 seconds is above the perception-reaction time of drivers normally stated as 2.50 seconds. The implication is that drivers travelled with less hindrance on the facility and consequently a low capacity value would result. The average headways for the off-peak and transition to peak data are respectively 5.86 and 5.88 sec. The volume method capacity value was 7.38% higher than the value returned using the headways method. The selected maxima method simply requires identification of the maximum flow rates average over the observation period. In addition, the method requires a bottleneck location to observe the maximum flows. However, the traffic on the facility was free flowing and bottlenecks did not occur. The maximum flow rates therefore coincided with the peak periods and the capacity value returned depicts the operating conditions on the facility.

Type of Data	Headway Method	Volume Method	Product Limit Method	Fundamental Diagram Method
Peak	1297	1400	1373	1972
Non-Peak	614	1033	-	1869
Transition to Peak	611	1045	-	2089

The product limit method and the fundamental diagram both require indirect data handling. Unlike the two earlier methods, these ones are modelled and projected to the capacity level. The implication is that the values returned by these methods are futuristic values which were not attained on the facility. In the case of the product limit method, the cumulative capacity distribution function is used to scale off the capacity value. The point to use is debatable as no consensus has yet been reached by researchers. In this paper the 90th percentile value was used which was 5.56% higher than the headways method and 1.93% lower than the volume method. No results were returned for the off-peak and transition to peak methods using the product limit method. This is understandable because off-peak and transition to peak data are not extreme values as is required before the method can be used.

In the fundamental diagram method, a value of 1972.73 PCE per.hour was obtained which is 26.06% higher than the headway method. This value is more consistent with highways of principal road standard obtained elsewhere[5]. The fundamental diagram method has further advantages over the other methods; it gives the state of the traffic which other methods cannot provide. In all, the methods used each have their individual merits and the operating conditions on a facility should dictate which method to employ in capacity evaluations.

In sum, four empirical capacity estimation methods employed in this paper have their strengths and weaknesses. The headway and volume methods do not have predictive capability. Hence, they are suitable for on the spot assessments and scheduled maintenance purposes. The product limit method is weak in its predictive capability because the arbitrariness in the selection of the capacity values from the cumulative distribution function brings about inconsistent results. Furthermore as the method specifies, only extreme value data can be modelled using the product limit method. The fundamental diagram approach is suited for all operating conditions of a roadway.

6. Conclusions

The headway and the volumes methods lack predictive capability and are suitable only for current assessment of flow rates. The product limit method is weak in its predictive capability in view of the arbitrariness in the selection of the capacity value. It is also an extreme value method, hence not all volume data can be used with this method. The fundamental diagram method has good predictive capability and furnishes capacity values consistent with the standard of the facility. Unlike other methods, it does not rely on bottleneck conditions to deliver the capacity value. The paper concluded that each method is uniquely suited to prevailing conditions and can be so employed.

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