

Speed–Flow–Geometry Relationships and Capacity for Two–Lane Single Carriageway Roads

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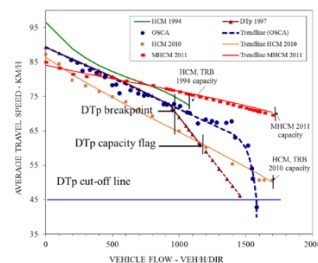
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Graphical abstract



Abstract

The current Malaysian practice in road capacity analysis, Malaysian Highway Capacity Manual 2011 (MHCM) is based on a method adopted from the Highway Capacity Manual (HCM) of the United States. All the analysis elements appear to be taken directly from the manual. The rationale for using such a method for Malaysian conditions is not well defined. This paper deliberates the background of the methodology used in the development of speed, flow and geometry relationships and the capacity for single carriageway roads. A microscopic traffic simulation model which is capable of simulating traffic operations on single carriageway roads for a range of road geometry configurations and traffic flow conditions was developed and used to evaluate the potential capacity of a single carriageway road. The results of the analysis indicate that a two-lane single carriageway road is capable of accommodating traffic flow higher than the values derived from the previous HCM. The current version of the HCM also appears to underestimate the vehicles' travel speed for a range of traffic flows when compared with the results of the simulation model. The MHCM 2011, on the other hand, estimated travel speeds higher than the travels speeds predicted by both the HCM 2010 and simulation model. It shows that there is a different interpretation of LOS F in term of speed between HCM 2010 and MHCM 2011.

Keywords: Capacity; analysis methods; Average Travel Speed (ATS); two lanes single carriageway

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1.0 INTRODUCTION

The fundamental aim of traffic analysis is to quantify a roadway's performance with respect to specific traffic volumes. This performance can be measured in term of travel delay as well as other factors. The relative performance of various roadway segments is important because it can be applied as a basis to allocate limited roadway construction and improvement funds. In a broad sense, one of the measures used to define the performance of a road section is capacity. The main challenge of such a process is to adapt the theoretical formulation to the wide range of conditions that occur in the field. Capacity is simply defined as the highest traffic flow rate that the roadway is capable of accommodating [1]. Capacity of a road section is often inferred from fundamental relationships between speed, flow and density, but as they are traditionally understood are in a parabolic form. However, because such a form is difficult to obtain from the site data, various possible shapes have been investigated and suggested by many researchers [2]. Duncan [3], for example, has speculated that 'the parabolic or other curved shaped (as used to describe speed/flow relationship) is based on inadequate understanding of the underlying statistical effects'. However, a

linear speed and flow relationship, such as those proposed by Duncan [4] and Lee *et al.* [5] has no indication of flow rate at road capacity. Consequently, the selection of flow at which the capacity of a specified road section is achieved may vary according to the interpretations of the individual researchers.

There are many different ways of interpretation and understanding of capacity by researchers. The general definition as given by the American Transportation Research Board (TRB) [6], is,

"the maximum number of vehicles that can pass a given point during a specified period under prevailing roadway, traffic, and control condition"

The prevailing conditions can occur in three groups [6]:

- (i) Roadway conditions established by the physical features of the road that do not change unless construction work or wet condition is undertaken.
- (ii) Traffic conditions, which depend on the nature of the traffic on the roadway and directional distribution; the conditions may change from time to time.

(iii) The control condition is influenced by the restriction on either junction, traffic signal, on kerb parking or land use; the conditions also may change time to time depend on the new regulation.

TRB [7] also states that, “capacity normally refers to a point or uniform segment of the facility. Capacity analysis is conducted for segments of a facility having uniform traffic, roadway, and control conditions. Because capacity depends on these factors, segments with different prevailing conditions will have different capacities. The point or segment with the poorest operating conditions often determines the overall level of service for the facility.”

The U.K. Department of Transport (DTp) Departmental Advice Note TA 46/97 [8] measure the performance of road link using Congestion Reference Flow (CRF). The CRF of a link is an estimate of the Annual Average Daily Traffic (AADT) flow at which the carriageway is likely to be ‘congested’ in the peak periods on an average day. DTp defines congestion as the situation when the hourly traffic demand exceeds the maximum sustainable hourly throughput of the link. At this point, there is a breakdown of flow accompanying considerable variations in speeds, a substantial drop in average speeds, and the formation of queues of stationary or slow moving vehicles.

This paper deliberates capacity based on the MHCM 2011 and compares with HCM 2010, the previous HCM 1994, British approach and the microscopic traffic simulation model, namely Operation of Single Carriageways Assessment (OSCA), which was developed for the analysis of traffic operations on single-carriageway roads.

2.0 LITERATURE REVIEW

A consistent and reasonably precise method of determining capacity must be developed within the definition of capacity. Capacity of a road section is a function of factors such as road type, speed, number of lanes, width of lanes and shoulders and also gradient. Therefore, the method of capacity determination clearly must account for a wide range of physical and operational roadway characteristics.

It is difficult to achieve in practice the observation of the traffic flow rate during a congested condition. Peterson [9] summarised that since the publication of the first edition of the HCM in 1965, there has been a great deal of discussion on the methods for evaluating capacity. He also suggested that different methods have arrived at different solutions of the same problem.

2.1 Fundamental Elements of Capacity Assessment

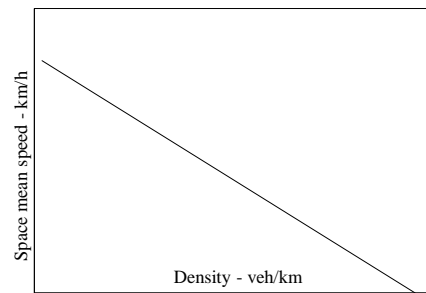
It is rather difficult to determine the traffic capacity of road from the observation station without a rather elaborate set up. When driving only, the driver can feel when the traffic is delaying the movement [10]. When the delaying exists, the traffic will begin to congest. Then, the capacity can be observed at this point of flow. Therefore, to simplify the phenomena, the fundamental diagram of traffic flow has been produced by Greenshield [10] using a fundamental Equation 1.

$$q = u_s \times k \tag{1}$$

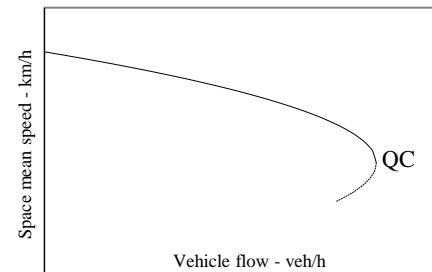
where q is flow, measured in vehicles per hour, u_s is space mean speed and k is density, measured in vehicles per km [11,12].

Capacity can be obtained using the fundamental diagram of traffic flow. The relationship between the speed/flow/density is referred as a fundamental diagram of traffic flow. The diagram of the relationships is illustrated in Figure 1(a-c).

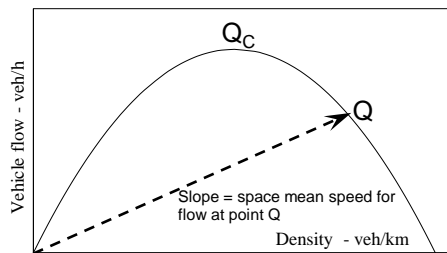
The plotted points shown in Figure 1(a) seem to represent the straight line or linear relationship between speed and density. The jam condition occurs when the density achieves zero speed. The condition is also known as jam density, k_j . The following theory has been postulated with respect to the shape of the curve depicting this relationship: (i) If the density is equal to zero, the flow is also zero (no vehicle on the road), (ii) As the density increases, the flow also increases, (iii) If the density reaches its maximum (jam density), the flow must be zero because vehicles will tend to line up bumper to bumper, (iv) If the density increases from zero, the flow will also initially increase from zero to a maximum value [12]. Further, continuous increase in density will then result in a continuous reduction of flow, which will eventually be zero when the density is equal to the jam density.



(a) Speed and Density Relationship



(b) Speed and Flow Relationship



(c) Flow and Density Relationship

Figure 1(a-c) Speed–flow–density fundamental relationships

From Figure 1(a), the Greenshield [10] model of the relationship between speed and density is given as in Equation 2.

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

where, u_s is the space mean speed, u_f is the space mean speed for free flow conditions, k is the density, and k_j is the jam density. This linear interaction of the equation represents as the higher the density the lower the space mean speed. A parabolic flow and density relationship can be derived by substituting Equation 2 into Equation 1 which will relate the three basic traffic variables.

Hence, the flow and density relationship may be written Equation 3.

$$q = u_f \times k - \frac{u_f}{k_j} \times k^2 \tag{3}$$

Similarly, a speed and flow relationship is obtained by rearranging Equation 2 for k and substituting the new equation of k into Equation 1 to yield Equation 4.

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

Two identical points on the parabolic curves describing flow/density and speed and flow relationships are as shown in Figures 1(b) and 1(c), respectively. The maximum flow rate, Q_c , in Figure 1(c) represents the highest rate of traffic flow that the section is capable. Speed for any flow may also be obtained from Figure 1(c) by taking the slope of a line drawn from the origin to a point on the curve as represented by a dotted line in the diagram.

2.2 American and Malaysian Approaches

The measurement of the quality of road performance considers many factors such as road geometry, demand flow rate in both directions of travel, speed, safety, comfortability and traffic behaviour. Transportation Research Board [6] has introduced ‘level of service (LOS)’ as an indicator to measure the quality of flow in assessing road capacity. The three measures of effectiveness used for the determination of LOS of two-lane single carriageway roads in HCM [6] and MHCM [13] are the average travel speed (ATS), percent time spent following (PTSF) and percent of free flow speed (PFFS).

There are six LOS as defined in the HCM 2010 [6] as represented in Table 1. The corresponding operational characteristics are summarised in Table 2.

American practice views the capacity of single carriageway roads as a capacity in both directions of traffic as opposed to the one direction approach used in the analysis of motorways and multilane highways. The proportion of traffic flowing in each direction becomes a major consideration. The base conditions for two-lane single carriageway are as follows [6]:

- Lane width greater than or equal to 12 ft,
- Clear shoulders wider than equal to 6 ft,
- No no-passing zones,
- All passenger cars in the traffic stream,
- Level terrain, and
- No impediments to through traffic (e.g., traffic signals, turning vehicles)

The capacity of two-lane single carriageway capacity under base conditions is 1,700 pc/h in one direction, with a limit of 3,200 pc/h for the two-way volume. When the capacity of 1,700 pc/h is reached in one direction, the maximum opposing flow would be limited to 1,500 pc/h due to the interactions between directional flows [6].

Table 1 Summary of level of service characteristics of U.S. two lanes single carriageway roads [6]

Level of Service	Characteristics		
	Class I	Class II	Class III
A	Motorist experience high operating speeds and little difficulty in passing. Platoons of three or more vehicles are rare.	Speed would be controlled primarily by roadway condition. A small amount of platooning would be expected.	Drivers should be able to maintain operating speeds close or equal to the free flow speed (FFS) of the facility.
B	Passing demand and passing capacity are balanced.		Difficult to maintain FFS operation but the speed reduction is relatively small.
	The degree of platooning becomes noticeable.		
C	Some speed reductions are present.		Most vehicles are travelling in platoons. Speeds are noticeably curtailed.
D	Platooning increase significantly.		The falls-off from FFS is now significant.
	Passing demand is high but passing capacity is approaching zero. High percentage vehicles are now traveling in platoon and PTSF is quite noticeable.		
E	Demand is approaching capacity.		Speeds are < 2/3 the FFS. The lower limit of this is represents capacity.
	Passing is virtually impossible and PTSF is >80%. Speeds are seriously curtailed.		
F	Demand flow in one or both directions exceeds the capacity of the segment. Operating conditions are unstable and heavy congestion exists.		

Table 2 The LOS for two-lane single carriageway [6]

LOS	Class I Highways		Class II Highways	Class III Highways
	ATS (mi/h)	PTSF (%)	PTSF (%)	PFFS (%)
A	>55	≤ 35.0	≤40.0	>91.7
B	>50 – 55	>35.0 – 50.0	>40.0 – 55.0	>83.3 – 91.7
C	>45 – 50	>50.0 – 65.0	>55.0 – 70.0	>75.0 – 83.3
D	>40 – 45	>65.0 – 80.0	>70.0 – 85.0	>66.7 – 75.0
E	≤ 40	>80.0	>85.0	≤66.7

In practice, ideal or base conditions as defined earlier seldom exist. A highway facility has restricted elements, which adversely affect traffic operations. All the values given in the HCM for the analysis of single carriageway roads are adjusted to include the combined effects of different terrain types and different percentages of no-passing zones. The maximum flow attainable under such conditions (i.e., the prevailing conditions) was also known as the possible or absolute capacity. HCM defines such a capacity as the maximum attainable service flow or service volume, which implies the maximum flow carried on a particular level of service as given in Table 1 [6]. This led to the basic service flow equation for single carriageway roads. Since LOS depends on ATS, PTSF and PFFS, the equations for single carriageway road are as Equations 5–9.

$$ATS_d = FFS - 0.00776 (v_d, ATS + v_o, ATS) - f_{np, ATS} \tag{5}$$

Where

- ATS_d = average travel speed in the analysis direction (mi/h);
 FFS = free flow speed (mi/h);
 V_{d, ATS} = demand flow rate for ATS determination in the analysis direction (pc/h);
 V_{o, ATS} = demand flow rate for ATS determination in the opposing direction (pc/h); and
 f_{np, ATS} = adjustment factor for ATS determination for the percentage of no passing zones in the analysis direction.

While,

$$PTSF_d = BPTSF_d + f_{np, PTSF} \{V_{d, PTSF} / (V_{d, PTSF} + V_{o, PTSF})\} \quad (6)$$

Where

- PTSF_d = percent time spent following in the analysis direction (decimal);
 BPTSF_d = base percent time-spent-following in the analysis direction;
 f_{np, PTSF} = adjustment to PTSF for the percentage of no-passing zone in the analysis segment;
 V_{d, PTSF} = demand flow rate in the analysis direction for estimation of PTSF (pc/h);
 V_{o, PTSF} = demand flow rate in the opposing direction for estimation of PTSF (pc/h);

And

$$PFFS = ATS_d / FFS \quad (7)$$

All terms are as previously defined.

The determination of capacity in the analysis under prevailing conditions based on ATS (pc/h), C_{d, ATS} and PTSF (pc/h), C_{d, PTSF} as Equation 8 and 9, respectively.

$$C_{d, ATS} = 1,700 \times f_{g, ATS} \times f_{HV, ATS} \quad (8)$$

$$C_{d, PTSF} = 1,700 \times f_{g, PTSF} \times f_{HV, PTSF} \quad (9)$$

In general, for a given layout with a specified LOS, capacity is matched to the predicted design hour flow for the design year.

The Malaysian Highway Capacity Manual (MHCM 2011) [13] produced a model to estimate average travel for Malaysian traffic conditions as shown in Equation 10.

$$ATS = FFS - 0.009V_d - f_{np} \quad (10)$$

Where

- ATS = average travel speed (km/h);
 V_d = demand flow rate in the analysis direction (pc/h);
 f_{np} = adjustment factor for no passing zones in the analysis.

In general, the Malaysian Highway Capacity Manual (MHCM 2011) [13] was established based on the procedures stipulated in the HCM 2010 and therefore would not be discussed in this paper.

2.3 British Approach

U.K has not adopted the HCM approach for road capacity analysis and design. DTp measures road link performance by Congestion Reference Flow (CRF) [8]. CRF, which can be calculated using equation 11, is an estimate of the Annual Average Daily Traffic (AADT) flow at which the carriageway is likely to be congested

in the peak periods on an average day. Congestion, in this approach, is defined as the situation when the hourly traffic demand exceeds the maximum sustainable hourly throughput of the link. At this point there is high possibility of delay due to breaking vehicles. Vehicles also tend to queue bumper to bumper. The average speed will drop significantly. Different road link standard will give a different value of the CRF.

$$CRF = \text{Capacity} \times NL \times Wf \times 100/PkF \times 100/PkD \times AADT/AAWT \quad (11)$$

where, Capacity is the maximum hourly lane throughput, NL is the Number of Lanes per direction, Wf is a Width Factor (see Equation 12 for single carriageway roads), PkF is the proportion (percentage) of the total daily flow (2-way) that occurs in the peak hour, PkD is the directional split (percentage) of the peak hour flow, AADT is the Annual Average Daily Traffic flow on the link, and AAWT is the Annual Average Weekday Traffic flow on the link.

$$Wf = (0.171 \times \text{Carriageway Width}) - 0.25 \quad (12)$$

As indicated in Equation 10, British DTp [8] defines capacity as the maximum sustainable hourly lane throughput and for a single carriageway road it can be estimated using Equation 13.

$$\text{Capacity} = 1350 - 15 \times Pk\%H \quad (13)$$

Where, Pk%H is the percentage of heavy vehicles.

The speed and flow relationship for single carriageway roads is based on the data established by Lee *et al.* [5], and is interpreted differently from that of the traditional interpretation. The speed–flow–geometry relationships were based on two types of vehicles, i.e. light (V_L) and heavy goods vehicles (V_H), as Equation 14 and 15, respectively.

$$\begin{aligned} V_L = & + 72.1 - ((0.09 - (0.075 \times \text{NEW})) \times \text{BENDS} \\ & - (0.0007 \times ((\text{RISES} + \text{FALLS}) \times \text{BENDS})) \\ & - (0.11 \times \text{NETGRAD}) \quad [\text{For one-way links only}] \\ & - ((0.015 + (0.027 \times P)) \times F \\ & + (2.0 \times \text{CWIDTH}) + (1.6 \times \text{CONEDGE}) \\ & + (1.1 \times \text{SWIDTH}) + (0.3 \times \text{VERGE}) \\ & - (1.9 \times \text{JCNS}) + (0.005 \times \text{VISI}) \end{aligned} \quad (14)$$

$$\begin{aligned} V_H = & + 78.2 - ((0.10 - (0.10 \times \text{NEW})) \times \text{BENDS} \\ & - (0.07 \times ((\text{RISES} + \text{FALLS})) \\ & - (0.13 \times \text{NETGRAD}) \quad [\text{For one-way links only}] \\ & - (0.0052 \times F) + (0.3 \times \text{VERGE}) \\ & - (1.1 \times \text{JCNS}) + (0.007 \times \text{VISI}) \end{aligned} \quad (15)$$

Where

- V_L = speed for light vehicles;
 V_H = speed for heavy vehicles;
 NEW = modern designed road (0 = no, 1 = yes);
 BENDS = bendiness in degrees/km;
 RISES = upgrade in metres/km;
 FALLS = downgrade in metres/km;
 NETGRAD = net gradient in metres;
 P = proportion of heavy vehicles;
 F = total vehicle flow in veh/hour/direction;
 CWIDTH = Carriageway width (between kerbs, or white edge lines where present) in metres;

CONEDGE = Continuous edge lining (0 = no, 1 = yes);
 SWIDTH = Hardstrip width, average of the two sides of the road (where continuous edge-lining is present) in metres;
 VERGE = Verge width, average of the two sides of the road in metres;
 JCNS = intersections in no/km; and
 VISI = visibility in metres

It is clear that the published results as shown in Equation 14 and 15 of the study by Lee *et al.* [5] do not provide any justification for the breakpoint for both light and heavy vehicles, as they did not find a ‘knee’ in the respective speed/flow relationship. The linear speed/flow curve is set to change its slope at a breakpoint flow, Q_B , equal to 80 per cent of the capacity, Q_C , i.e.

$$Q_B = 0.8 \times Q_C \quad (16)$$

The term Q_C in Equation 16 is referred to by DT_p as the capacity flag, which is defined as the maximum realistic value of flow in veh/h/direction and can be estimated using the previous Equation 13. The break point at 80% of the capacity set in British speed/flow relationships coincides with the popular belief that speeds decline rapidly once the volume/capacity ratio exceeds about 0.80 [14].

A typical form of speed and flow relationship for a single carriageway road based on Equation 14 is shown in Figure 2. The plot is based on the parameters indicated in the figure and with a 15% HGV.

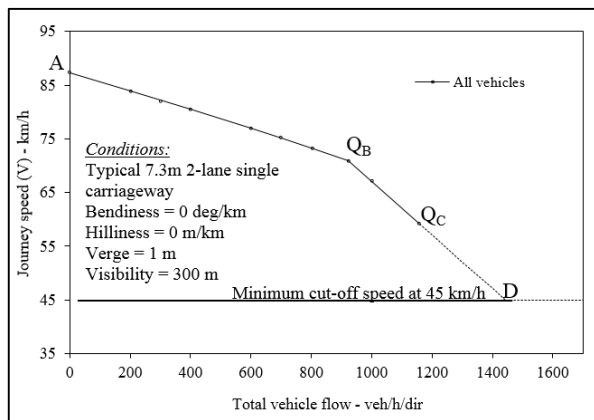


Figure 2 Typical form of British speed–flow relationship for a typical single carriageway road

It can be seen from Figure 2 that the speed–flow relationship can be divided into 3 components, i.e. an uncongested flow represented by segment AQ_B , congested flow (segment Q_BQ_C) and over capacity flow represented by the segment beyond Q_C . The basis of the British speed/flow relationship is that for uncongested flow, the speed of vehicles continues to drop gradually to a breakpoint Q_B at which the slope changes abruptly.

3.0 METHODOLOGY

In this paper, the speed–flow–geometry relationships and hence the capacity of a single carriageway road are analysed based on

the HCM 2010 and compares with the previous HCM 1994 [15], British approach and the microscopic traffic simulation model, OSCA, which was developed for the analysis of traffic operations on single-carriageway roads. The HCM 1994 [15] is used in the analysis because the performance analysis of a single carriageway in the HCM 1994 was based on the volume to capacity ratio, while in the HCM 2010 it is based on the percent time spent following.

3.1 Overview of the Simulation Model

Numerous researchers have demonstrated the application of simulation models to the analysis of various aspects of traffic operation. Mahdi [16] developed one of the models, namely OSCA, for British traffic conditions.

OSCA is a time scan microscopic simulation model of vehicle movements and interactions on single carriageway roads in Great Britain. The model is based on a detailed study of overtaking behaviour for different types of overtaking manoeuvre in Great Britain. The model was then redeveloped by Othman [2] to include the capability to simulate traffic operations at priority junctions and Malaysia traffic characteristics. The flexibility of the model to represent a wide range of situations was assessed during the development by an extensive series of evaluations in which the response of the model was assessed for key measures of performance by comparison with published data.

3.2 Characteristics of the Road Segment

The characteristics of the road segment used in the analysis are summarised in Table 3. The design speed for the road segment is 96 km/h (60 mi/h).

Table 3 Parameter used for the analysis

Parameter	Value
Lane Width	7.3 m
Shoulder	1.0 m
Access Point	0
Design Speed Limit	96 km/h (60 mi/h)
Hilliness	0 m/km
Bendiness	0 deg/km
Overtaking Provision	100%
Directional Split	50/50
HGV	15%
Visibility	550 m

For the simulation procedure, a total of 6 km length of road containing the 4 km length of the evaluation section was used in the simulation runs. The road was divided into 3 sections; warm up section (1 km), evaluation section (4 km), and cool-off section (1 km). Figure 3 shows the arrangement the simulated road system used in the simulation runs. Both the warm up and cool-off sections were assumed flat and straight. The road section was also assumed isolated (i.e. no access was allowed within the simulated section). The road markings for the warm up and cool-off sections are as shown in Figure 3.

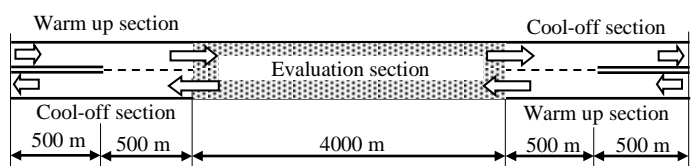


Figure 3 Arrangement of the simulated road system used in the analysis

4.0 RESULTS AND DISCUSSION

Figure 4 shows the scatter plot of the speed/flow relationships for the specified road and traffic conditions obtained from the simulation results, MHCM 2011, HCM 2010, HCM 1994 and DTp. In general, the plot of the simulation results indicates a curved speed–flow relationship. As would be expected from the traditional interpretations of the relationship, the simulation data shows that speed decreases as flow increases until a region is reached at which flow stops increasing.

It is difficult to deduce the true form of the relationship without the data representing the lower region of the plot, i.e. a region in which speed continues to decrease with flow. Such a region is possible to define if there is a bottleneck in the downstream traffic causing the arrival rate of the vehicles at the back of the queue to exceed the departure rate of the vehicles leaving the queue.

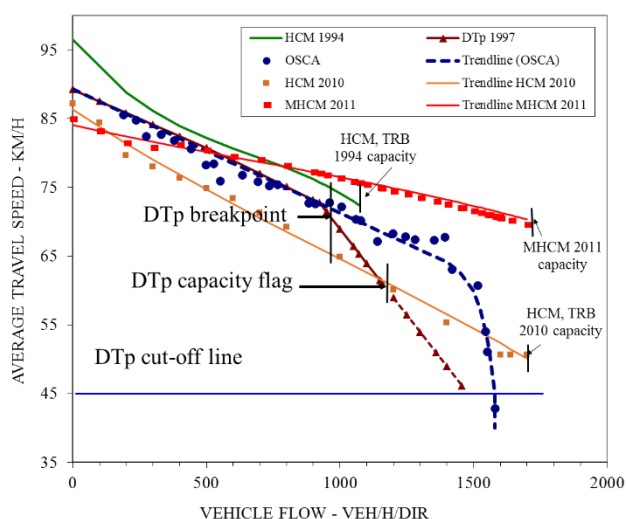


Figure 4 Speed/flow relationships based on MHCM, HCM, DTp, and simulation model

For speed–flow relationship and capacity evaluation using the HCM methods, the design speed of the road section was assumed ≥ 60 mile/h (i.e. ≥ 96.5 km/h) because the calculated desired speed for cars is greater than 90 km/h. The HCM 1994 speed–flow curve was obtained by calculating the expected capacity for the specified road and traffic conditions. The expected capacity was used with the flow rate to compute the flow/capacity ratio for each flow. The travel speed for each flow was then obtained by interpolation from Table 8-1 of the HCM 1994 manual. For the HCM 2010 and MHCM 2011 speed–flow curves, the average travel speed for each flow was estimated using Equation 5 and Equation 10, respectively. The British DTp speed–flow relationship was determined using Equations 13–16. Because a 50/50 directional split was used, the directional flow is simply half of the two-way flow at the corresponding speed and the one-way capacity is half of the expected two-way capacity. Therefore, for the specified road and traffic conditions, all speed–flow curves shown in Figure 4 are directly comparable with each other.

It can be seen from Figure 4 that under uncongested flow conditions the speed/flow curves derived from the HCM 1994, HCM 2010, British DTp and the simulation model appear to be consistent in terms of the effect of flow on travel speed. The

reduction in the average travel speed is about 2.0 km/h per 100 veh/h increase in flow. For comparison, the values of most practical interest from each speed–flow curve are tabulated in Table 4.

For the specified road and traffic conditions, the HCM 1994 considered the capacity is reached at a volume of about 1072 veh/h/direction even though the travel speed is still relatively high. The British DTp, on the other hand, would set the capacity flag for such a facility at 1155 veh/h/direction with travel speed of 60 km/h, i.e. much lower than the speed set by the HCM 1994. The simulation model, however, demonstrates that, if the road segment is assumed to operate at capacity when the average operating speed is about 60 km/h, then the capacity of the particular road can be set at 1580 veh/h/direction.

Table 4 Values of interest extracted from Figure 4

Method	Flow at break-point (veh/h/dir)	Capacity (veh/h/dir)	Speed at break-point (km/h)	Speed at capacity (km/h)	Max. flow (veh/h/dir)	Speed at max. flow (km/h)
HCM 1994	n.a	1,072 ^[a]	n.a	72.4	n.a	n.a
HCM 2010	n.a	1,700	n.a	50.1 ^[b]	n.a	n.a
British DTp	924	1,155	72.8	61.2	1483	45
MHCM 2011	n.a	1,700	n.a	72.0 ^[b]	n.a	n.a
Simulation	n.a	1,580	n.a	45	1580	45

^{n.a} Information not available.

^[a] Capacity calculated for level of service E.

^[b] ATS calculated for flow rate at capacity using Equation 5.

The MHCM 2011, on the other hand, produces a speed–flow relationship which indicates a much lower effect of flow on travel speed when compared with the relationships obtained from the other four methods. The MHCM 2011 shows that for the type of road used in the analysis, the average travel speed is reduced at a rate of 0.76 km/h for every 100 veh/h increase in flow.

The current version of HCM 2010 and subsequently the MHCM 2011 appear to suggest that a single carriageway based on a modern design standard is expected to be able to accommodate a capacity of 1700 veh/h/direction, which is much higher than the figure derived based on HCM 1994. For the particular road segment used in the analysis, the HCM 2010 estimated that the capacity would be reached when the average travel speed dropped to about 50 km/h. In general, HCM 2010 gives estimates of the average travel speed for each traffic volume, lower than the estimates given by the previous HCM 1994, i.e. a different of about 22.3 km/h. The MHCM 2011, on the other hand, estimated that the travel speed at capacity is about 72 km/h, which is somewhat similar to the speed at capacity set by the previous HCM 1994.

The HCM and British capacities are probably based on a flow, which is considered to produce a minimum acceptable travel speed. This flow is often referred as the practical capacity [17]. The British method considers the flows beyond the capacity flag as over capacity and can reach to a maximum value at a journey speed of about 45 km/h. But as shown in Figure 4, the results obtained from the HCM 2010 analysis method are in line with the results of the simulation which indicates that a single carriageway road is capable of accommodating traffic higher than the value used in the previous manual. The average travel speeds at capacity

based on the British DTp and HCM 2010 approaches are almost similar, i.e. 45 km/h and 50 km/h, respectively.

■ 5.0 CONCLUSION

The paper highlights the importance of speed–flow relationships and capacity as measures of the functional effectiveness of single carriageways. For single carriageway roads, the HCM approach appears to provide a more direct and flexible method of assessing the relative merits of alternative improvement schemes than the British approach. This is in relation to travel speeds where the calculation of travel times adopted in the British approach is less precise.

In terms of capacity, in practice, it is difficult to observe traffic operations at capacity because currently few highways operate at volumes approaching capacity. Furthermore, operation at capacity usually occurs for a short period and at a random point along the roadway. For this reason, the observation of capacity operations in the field is extremely difficult. However, it is possible to produce reasonable estimates of capacity by using stochastic simulation to model traffic operations for a given set of highway and vehicle characteristics, which include driver behaviour. The simulation model described in this paper demonstrates that a substantial increase in the capacity of a single carriageway road might be achieved at reasonable practical traffic operating conditions.

Such results suggest the need for further exploration of the speed–flow relationships for Malaysian roads to assess the applicability of the HCM method for capacity analysis for Malaysian conditions.

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