EVALUATING SIGNALIZED INTERSECTION CAPACITY BASED ON MALAYSIAN ROAD CONDITIONS

NURIKHWANI IDAYU BINTI ZAINAL ABIDIN

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by

NURIKHWANI IDAYU BINTI ZAINAL ABIDIN

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LIST OF SYMBOLS

S	Estimated saturation flow rate
S_o	Ideal saturation flow rate
N	Number of lanes in lane group
f_a	Adjustment factor for area type
f_w	Adjustment factor for lane width
f_g	Adjustment factor for gradient
f_{RT}	Adjustment factor for right-turning movements
f_{LT}	Adjustment factor for left-turning movements
f_c	Adjustment factor for vehicle composition
f_{HV}	Adjustment factor for heavy vehicles
f_{bb}	Adjustment factor for bus blockage
f_p	Adjustment factor for parking activity
f_{LU}	Adjustment factor for lane utilisation
G	Gradient
w	Lane width
P_{RT}	Proportion of right turning vehicles
P_{LT}	Proportion of left turning vehicles
%HV	Percentage of heavy vehicles
d_1	Uniform control delay
d_2	Incremental delay
d_3	Initial queue delay
d	Control delay
Q	Total vehicle flow
q_{car}	Flow of cars
q_{motor}	Flow of motorcycles
q_{lorry}	Flow of lorries
q_{bus}	Flow of buses
$q_{trailer}$	Flow of trailers
f_{car}	Traffic composition factor for cars
f_{motor}	Traffic composition factor for motorcycles
f_{lorry}	Traffic composition factor for lorries
f_{bus}	Traffic composition factor for buses
$f_{trailer}$	Traffic composition factor for trailers
e_{car}	Passenger car equivalent for cars

e_{motor}	Passenger car equivalent for motorcycles
e_{lorry}	Passenger car equivalent for lorries
e_{bus}	Passenger car equivalent for buses
$e_{trailer}$	Passenger car equivalent for trailers
c	Capacity
C	Average cycle time
g	Average effective green time
R	All red intervals
A	Amber time
I	Inter-green time
C_o	Optimum cycle time
L	Lost time
F_r	Factor for right turning
F_l	Factor for left turning
y	Ratio of flow to saturation flow
v/c ratio	Ratio of volume towards capacity
λ	Proportion of cycle that is effectively green (g/C)

LIST OF ABBREVIATION

aaSIDRA	Akcelik and Associates, Traffic Signalized and Unsignalized Intersection Design and Research Aid
CBD	Central business district
nonCBD	Non central business district
HCM 2000	Highway Capacity Manual 2000
LOS	Level of service
MHCM 2006	Malaysian Highway Capacity Manual 2006
MOE	Measures of effectiveness
pce	Passenger car equivalents
pcu	Passenger car unit
pcu/hr/ln	Passenger car units per hour per lane
sec	Seconds
sec/veh	Seconds per vehicle
U.S. HCM	United States Highway Capacity Manual
veh/hr	Vehicles per hour

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PENILAIAN KAPASITI PERSIMPANGAN BERLAMPU ISYARAT BERDASARKAN KEADAAN JALAN RAYA DI MALAYSIA

ABSTRAK

Sehingga kini, Malaysia telah menjalankan analisis kapasiti lebuh raya berdasarkan kaedah-kaedah dari negara lain. Walaubagaimanapun, dengan kemajuan di dalam kajian kejuruteraan lalu lintas tempatan, sebuah manual tentang analisis kapasiti berdasarkan keadaan jalan raya di Malaysia telah dikeluarkan. Manual ini diharapkan dapat membantu jurutera-jurutera tempatan dalam menjalankan analisis kapasiti bagi persimpangan berlampu isyarat.

Salah satu keunikan aliran lalu lintas di Malaysia adalah bilangan motorsikal di atas jalan raya yang agak tinggi. Keadaan ini adalah salah satu sebab pihak berkuasa ingin menilai semula kaedah-kaedah analisis kapasiti yang sering digunakan sekarang. Peratusan motorsikal di Malaysia agak tinggi berbanding di negara-negara barat dan manual-manual dari negara-negara tersebut tidak mengambil kira kesan motorsikal di dalam aliran. Walau bagaimanapun, berdasarkan keadaan jalan raya tempatan, adalah dipercayai bahawa bilangan motorsikal yang tinggi ini akan mempengaruhi kapasiti persimpangan berlampu isyarat.

Oleh kerana Malaysian Highway Capacity Manual (MHCM 2006) ini masih baru di dalam bidang kejuruteraan lalaulintas tempatan, tiada kajian pernah dijalankan untuk menguji ketepatan manual. Di dalam kajian ini, perbandingan antara MHCM 2006 dengan manual-manual lain yang digunakan sekarang (i.e. HCM 2000, aaSIDRA and Arahan Teknik (Jalan) 13/87) telah dijalankan.

Kajian ini telah dijalankan untuk menentukan ketepatan hasil analisis kapasiti berdasarkan MHCM 2006 dengan keadaan sebenar di lapangan. Di dalam kajian ini,

pengumpulan data telah dilakukan di beberapa persimpangan berlampu isyarat di bahagian pantai barat Semenanjung Malaysia. Selain dari mencerap isipadu lalulintas di persimpangan berlampu isyarat, data kelengahan berhenti juga dicerap dengan menggunakan JAMAR TDC-8. Di dalam kajian ini, kesan motorsikal terhadap aliran tepu juga dikaji.

Seperti yang dijangka, bilangan motorsikal di atas jalan raya tempatan yang agak tinggi amat mempengaruhi hasil akhir analisis kapasiti dan beberapa cadangan telah dikemukakan, yang berkaitan dengan aliran motorsikal, untuk diamibilkira semasa menjalankan analisis kapasiti. Untuk pembandingan manual-manual, telah didapati bahawa MHCM 2006 memberikan nilai kelengahan yang lebih tepat dengan nilai dilapangan apabila dibandingkan dengan nilai yang diberi oleh manual-manual lain.

EVALUATING SIGNALIZED INTERSECTION CAPACITY BASED ON MALAYSIAN ROAD CONDITIONS

ABSTRACT

Until now, Malaysia has been using capacity analysis methods from other countries. However, with the advances in traffic engineering research in Malaysia, a manual on capacity analysis based on Malaysian road conditions has been developed. This manual is hoped to be used by engineers and practitioners when designing or conducting operational analysis for signalized intersections.

One unique characteristic of Malaysian traffic that prompted the authorities to review the current capacity analysis methods is due to the uniqueness of vehicle composition on Malaysian roads. The percentage of motorcycles is very high as compared to other western countries. However, all of the existing highway capacity manuals from western countries do not take into consideration the effect of motorcycles. Yet, considering the situation in Malaysia, the high percentage of motorcycles can greatly influence the design and operational analysis of signalized intersections.

Since the Malaysian Highway Capacity Manual (MHCM 2006) is just published, no studies have been carried out to verify the accuracy of the manual. In this study, comparison of the MHCM 2006 with other manuals (i.e. HCM 2000, aaSIDRA and Arahan Teknik (Jalan) 13/87) were carried out.

Also, this research was carried out to evaluate the new manual by comparing the results estimated using the manual with the observed on-site data. In this research, data collection was carried out at several signalized intersections throughout the west coast of the Peninsular Malaysia. Besides observing traffic volume at the signalized

intersection, stopped delay was also observed using JAMAR TDC-8. In this research, the effect of motorcycles on the estimation of saturation flow was investigated

As expected, the high volume of motorcycles on Malaysian roads greatly affects the estimation of saturation flow rates and control delays. In this research, a procedure to take into consideration the effect of motorcycles in the estimation of saturation flow is proposed. Based on the results of this research, it can be concluded that the MHCM 2006 gives an accurate estimation of saturation flows and control delays as opposed to other manuals.

CHAPTER 1
INTRODUCTION

1.0 Background of study

Malaysia is moving towards becoming a developed country. With this fast pace of change so is the change in traffic conditions in this country. More and more citizens are using various types of vehicles in their everyday life, thus creating our very own typical travel behavior which is unique for this country as compared to other countries' travel behavior. This change, although seemingly a small problem to many, is a very critical change in the eyes of traffic experts.

In practice, Malaysia has been referring to other countries' capacity manual when designing our road facilities which include signalized intersections, unsignalized intersections and urban arterials. Based on previous studies (Leong, 2004), this is not an appropriate practice as we have our own unique traffic conditions as compared to other countries and this leads to the need to carry out studies based on local traffic conditions and to come up with the Malaysian manual. The findings from these researches have become an eye opener for us to realize that there are some factors contributing to the saturation flow of our roads thus affecting the intersection capacity.

Currently, engineers in Malaysia are using overseas guidelines and standards for designing road facilities. For example, engineers are using the Arahan Teknik (Jalan) 13/87 and also the Highway Capacity Manual which are based on the United States road condition in analyzing and designing traffic light junctions. However, in Malaysia, it has been found that local driving characteristics have an influence on the capacity and performance of traffic light junctions (Leong, 2004).

Because of the development of traffic engineering in Malaysia, a study about capacity analysis based on local conditions has been done. The study sponsored by the Ministry of Works has produced the Malaysian Highway Capacity Manual (MHCM 2006). This manual is the result of extensive studies carried out according to local traffic conditions.

The Malaysian Highway Capacity Manual (MHCM 2006) has been developed based on observations and researches carried out throughout Malaysia to study the local traffic situation. This manual includes procedures to carry out operational analysis on capacity analysis for signalized intersections, unsignalized intersections and urban arterials. One chapter in this manual is dedicated entirely to the signalized intersections. Signalized intersections are the most common type of junctions found in Malaysia for its practicality in distributing traffic flow to and from different approaches.

The chapter in the manual is very important as a guide for practitioners and engineers to carry out the capacity analysis of signalized intersections based on Malaysian traffic conditions. The use of current methods, i.e. the HCM 2000, aaSIDRA and Arahan Teknik (Jalan) 13/87, might result in under-designing or over-designing of a signalized intersection.

Based on Leong (2004), the ideal saturation flow and adjustment factors with respect to Malaysian traffic conditions were estimated. The study has also proposed passenger car equivalent (pce) values for the different types of vehicles found on the road network that are more suitable for Malaysian traffic behavior (MHCM 2006).

From the estimated saturation flow, users could calculate other parameter such as delay for the intersection. The delay can be used to estimate level of service (LOS) for the analyzed intersection. This is important for practitioners as they would need all this information for analyzing or designing a particular intersection.

1.1 Problem Statement

The current method adopted by the Ministry of Works is the Arahan Teknik (Jalan) 13/87. This study is based on a method developed by Webster and Cobbe from the United Kingdom in the 50s and 60s. This study, however, does not consider local traffic conditions as well as travel behavior of road users that are unique in Malaysia.

For local engineers and practitioners, the HCM 2000 and aaSIDRA are also commonly used. The HCM 2000 is the capacity analysis manual developed in the United States while the aaSIDRA is developed in Australia. These manuals are also based on their own countries and therefore, may not suitable to be used for our local road network.

To overcome this problem, a study was carried out to develop the Malaysian Highway Capacity Manual (MHCM 2006). This manual is the outcome of a study carried out based on Malaysian traffic conditions in order to make it more suitable to be used in analyzing and designing the local road network. Thus, locally based studies give more reasonable estimation of capacity for local conditions. (Hwang, et al., 2005)

The MHCM, which is based on the U.S. Highway Capacity Manual (HCM), incorporates the usage of the passenger car equivalent (pce) and adjustment factors that were calibrated based on Malaysian traffic conditions. These parameters have been derived according to local traffic observation carried out throughout the study for the manual. This ensures a reasonable comprehension of vehicles in the signalized intersection where without the knowledge gained from these local studies, precise results of analysis could not be achieved (Kim, et al., 2005).

However, a sensitivity analysis needs to be carried out to evaluate the effectiveness of the MHCM 2006. For example, there is a need to evaluate the effectiveness of saturation flow adjustment factors. This is to assess the contributions of these parameters on the estimated saturation flow as the estimated saturation flow would play an important role in capacity analysis.

Another problem that arises is about the high volume of motorcycle in the traffic flow. The high motorcycle volume will certainly affect the capacity analysis of a signalized intersection. A research in Vietnam (Nobuyuki et al., 2005) indicates the analysis of traffic conditions in Hanoi and Hochiminh city incorporating high percentage of motorcycles (the proportion of motorcycles is about 90%). The high percentage of motorcycles in the flow interferes with the performance of other vehicles. When this happens, the average speed of other vehicles are drastically reduced. This proves that a study on the effect of motorcycle on the design of signalized intersection needs to be evaluated.

From the initial observation done throughout the MHCM study, it is observed that Malaysia has a high number of motorcycles. Therefore, it can be concluded that the high motorcycle volume in a traffic flow can affect the outcome of a traffic analysis. Apart from that, we must also remember that Malaysia's travel behavior, especially the characteristics of heavy vehicles, is very unique.

The trend in number of vehicles registered in Malaysia is as shown in Table 1.1. As seen in Table 1.1, 472 116 cars were registered whereas 397 977 motorcycles were registered in 2004. This indicates the high percentage of motorcycles on Malaysian roads. Table 1.2 shows the traffic composition by types of vehicles at 15 selected stations in Malaysia. Referring to Table 1.2, motorcycles are the second highest number of vehicles on our roads with an average percentage of 20%.

Table 1.1: New Registered Motor Vehicles by Type, Malaysia, 1990 – 2004 (Source: Road Transport Department, 2005)

Year	Motorcycle	Motorcar	Bus	Taxi	Hire & Drive Car	Goods Vehicle	Others	Total
1990	188,118	152,737	1,985	2,756	941	30,757	14,926	392,220
1991	201,864	148,724	1,337	2,927	480	28,414	10,877	394,623
1992	184,171	99,867	1,506	1,710	504	20,366	9,672	317,796
1993	226,088	138,203	2,591	2,255	782	20,159	6,123	396,201
1994	283,370	180,052	2,213	3,754	2,791	27,482	20,168	519,830
1995	307,323	248,398	2,465	4,455	2,722	41,447	29,133	635,943
1996	322,145	318,765	2,620	4,358	2,545	69,234	30,844	750,511
1997	364,214	372,343	2,947	5,257	1,860	65,160	28,396	840,177
1998	237,776	159,642	797	3,569	552	11,786	6,342	420,464
1999	236,779	296,716	508	1,925	1,724	19,987	8,102	565,741
2000	238,695	344,847	544	2,635	2,883	24,316	11,949	625,869
2001	234,751	395,891	652	3,169	1,348	25,612	13,866	675,289
2002	222,685	419,713	919	4,446	1,242	25,415	16,768	691,188
2003	321,234	424,753	1,014	5,542	1,231	29,975	17,041	800,790
2004	397,977	472,116	1,290	7,746	1,797	33,169	18,268	932,363

Table 1.2: Traffic Composition (%) by Type of Vehicles at 15 Selected Stations, Malaysia, 2004 (Source: Ministry of Works, Malaysia, 2005)

No	Station	16-hour Traffic	Percentage (%) Vehicles Composition											
			April-04						October-04					
			Car / Taxi	Light Lorry	Medium Lorry	Heavy Lorry	Bus	Motor cycle	Car / Taxi	Light Lorry	Medium Lorry	Heavy Lorry	Bus	Motor cycle
Peninsular Malaysia														
1	AR 301	22,557	55.0	7.1	12.8	7.5	2.4	15.3	53.9	7.7	12.1	6.9	2.3	17.1
2	BR 805	169,97 2	73.2	4.9	4.3	0.8	1.0	15.9	77.1	4.7	3.6	0.7	0.8	13.1
3	CR 805	11,004	63.9	9.0	10.2	6.7	1.7	8.5	48.8	12.0	12.9	9.7	1.3	15.2
4	CR 902	7,031	52.8	13.3	13.0	11.7	1.2	8.1	52.6	14.1	12.9	9.8	1.4	9.2
5	DR 802	14,109	56.7	14.0	9.0	3.5	1.0	15.7	60.5	13.0	9.1	2.4	1.1	14.0
6	JR 203	44,437	61.0	12.3	9.6	5.0	2.7	9.5	58.1	10.6	10.9	7.0	1.8	11.7
7	JR 501	13,225	52.0	7.4	7.6	3.2	0.9	29.0	54.6	7.0	7.0	2.5	0.9	27.9
8	KR 501	18,156	50.4	9.3	10.0	4.9	1.1	24.3	53.1	8.8	8.9	4.6	1.1	23.5
9	NR 501	12,718	59.5	9.4	11.6	3.4	1.4	15.3	-	-	-	-	-	-
10	PR 115	33,596	50.8	7.7	9.3	4.1	1.1	27.0	50.7	7.4	10.0	3.8	1.1	27.1
11	TR 402	-	-	-	-	-	-	-	61.4	7.9	4.9	1.9	1.5	22.4
Sabah														
12	HR 201	3,078	48.6	25.2	11.8	5.9	0.7	7.8	48.5	25.0	13.4	5.2	1.3	7.1
13	HR 501	18,757	19.6	20.8	19.6	14.6	12.9	12.5	19.5	20.6	19.5	14.7	3.2	12.6
Sarawak														
14	SR 103	30,717	48.5	12.9	10.7	5.7	1.9	20.3	46.8	12.5	8.9	6.9	0.9	23.7
15	SR 402	6,041	38.2	25.4	15.8	9.7	2.5	8.4	42.0	15.8	18.5	17.1	13.2	3.5

This high number of motorcycles might cause problems when conducting the capacity analysis. In this study, the effects of motorcycles in designing signalized intersections were also investigated. From the estimated saturation flow, engineers could obtain the capacity of an intersection that would lead to the value of delay experienced by the intersection users. Delay, on the other hand, would be the measure of effectiveness (MOE) used to determine the LOS of the intersection.

As for the MHCM 2006, the precision of this manual towards the actual conditions on-site needs to be verified. The MHCM 2006 study has been carried out by analyzing on-site data. MHCM 2006 had proposed certain parameters that are more suitable for Malaysian roads. However, the accuracy of the manual as compared to on-site data has not been tested. Therefore, a study to compare the MHCM 2006 with other current practices has been proposed to find out the accuracies of the manual.

In order to measure the effectiveness of the MHCM 2006, the MOE estimated from the manual is compared to the MOE observed in the field. The values of the same MOE from the other manuals are also evaluated for comparison purposes. The MOE chosen for this study is stopped delay. The stopped delay observed on-site is compared with estimated control delay based on other manuals.

The final outcome of this study is to evaluate the accuracy of the MHCM to the actual data on-site and how it compares with other manuals.

1.2 Objectives of the study

The main objective of this study is to evaluate the capacity analysis of a signalized intersection based on local traffic conditions. The objectives of this study are as follows.

i. To carry out a sensitivity analysis on the derived saturation flow adjustment factors obtained from the MHCM.

ii. To study the effects of motorcycles on the capacity analysis of a signalized intersection and to determine the appropriate method to estimate the value of saturation flow to be used for operational analysis or for design purposes.

iii. To compare the MHCM and other manuals using appropriate measures in the field to evaluate the effectiveness of the MHCM.

1.3 Scope of the study

Traffic volume data for signalized intersections had been carried out for several sites throughout Malaysia in Central Business Districts (CBD) and non-CBD areas. The geometric parameters for the signalized intersections (e.g. lane width and gradient) as well as other related parameters such as type of turning lanes (e.g. exclusive turning lanes or shared lanes), signal phasing and cycles time were observed. The traffic volume of a signalized intersection was observed during non-peak period. Also, the actual stopped delay observed on site was measured. For the stopped delay data, random individual lanes were chosen and only one lane was observed for each stopped delay data collection. The stopped delay observed on-site will be converted to the control delay then it would be compared to the outcome obtained from the analysis by each different manual. Using this data, the signalized intersection was analyzed using all the manuals as discussed above before being compared to the values obtained on-site.

CHAPTER 2
LITERATURE REVIEW

2.0 Introduction

This chapter discusses the literature review carried out for the study. Section 2.1 discusses the basic method used for capacity analysis of signalized intersections. This section also highlights the importance of the saturation flow in the capacity analysis. Section 2.2 discusses a few methods of capacity analysis which includes the manuals involved in this study such as the HCM 2000, the Arahan Teknik (Jalan) 13/87, aaSIDRA 2.0, the MHCM as well as other studies that have been carried out previously. This is followed by a brief introduction to the Malaysian Highway Capacity Manual (MHCM) and its method of capacity analysis. This section also includes the reasons for the need to study the effect of motorcycles towards the saturation flow for our local roads. Section 2.3 emphasizes on the relationship between the stopped delay and the control delay. Finally, this chapter is concluded in Section 2.4.

2.1 Basic method for capacity analysis

This section discusses the basic methods used by all manuals to carry out their capacity analysis. There might be slight differences but that is discussed in Section 2.2 where a more detailed discussion will be given for each method.

Gilbert (1984) claimed that many years ago, somebody called the *Highway Capacity Manual* the ‘traffic engineer’s bible’. This goes to show how important capacity analysis is for traffic engineers whether in carrying out capacity analysis or in designing a particular road section.

Capacity analysis is a set of procedures used to estimate the traffic carrying capacity of transportation facilities over a range of defined operational conditions. The procedures typically result in determination of a level of service (LOS). They provide tools for the facility as well as the planning and design of future facilities (Arnold and McGhee, 1995)

Capacity analysis is carried out in order to design a signalized intersection or to carry out an operational analysis of an existing intersection. It is important as it helps to determine the suitable size of an intersection (i.e. number of lanes for each approach), cycle time and phasing that is needed to be able to accommodate the traffic volume.

Chandra et al. (1994) described the capacity analysis for a signalized intersection as more complex than carrying out capacity analysis for a road. This is because the capacity of a road is only influenced by the parameters for the road itself, whereas the capacity for a signalized intersection differs according to the parameters of all the roads that make up the intersection. This includes the geometric parameters of the individual lanes, the area type, the turning movements and other related parameters.

For an existing intersection, firstly, the traffic volume must be observed. This volume must be recorded on a direct motorway, expressway or in this case, directly at the signalized intersection itself. The volume from the point of observation should also not be limited by the capacity of the particular infrastructure (Cohen et al., 1994). Thus, the traffic volume observation is not only restricted to intersections with adequate volumes but intersection with highly saturated flows can also be included.

From this traffic volume, the peak-hour factor is determined. The percentages of left-turning and right-turning vehicles in a shared or exclusive lane could also be calculated thus left-turning and right-turning adjustment factors can be determined. As for designing a new intersection, a predicted volume is used to determine these values.

Next, the saturation flow rate of the intersection is determined. The saturation flow rate is the flow in vehicles per hour that can be accommodated by the lane group assuming that the green phase were displayed 100 percent of the time (i.e. g/C = 1.0) (TRB, 2000).

The Arahan Teknik (Jalan) 13/87 defines the saturation flow as the maximum flow, expressed as equivalent passenger cars that can cross the stop line of the approach where there is a continuous green signal indication and a continuous queue of vehicles on the approach. The MHCM 2006 describes the saturation flow as the maximum constant departure rate of a queue from the stop line of an approach lane during the green period.

However, in order to determine the saturation flow rate, the ideal saturation flow for the intersection must first be determined. Table 2.1 displays the different values of ideal saturation flow rates for different countries.

Table 2.1 : Values of Ideal Saturation Flow for Different Countries (Source: Ministry of Works Malaysia, 2006)

Country	Manual	Ideal Saturation Flow Rate (pcu/hr/lane)
Malaysia	Malaysian Highway Capacity Manual (2006)	1930
	Arahan Teknik (Jalan) 13/87	1904
U.S	Highway Capacity Manual (HCM 1985)	1800
	HCM 1994	1900
	HCM 2000	1900
Australia	aaSIDRA	1950

On-site studies have resulted in different values of saturation flow rates at different intersections. The variation in these rates are attributed to many factors which include the classification of vehicles using the facility, pedestrian activity, turning vehicles, driveway and fixed objects adjacent to lanes with less than desirable lateral clearances (McMahon et al., 1997).

The saturation flow rate is determined after the ideal saturation flow is adjusted for a variety of prevailing conditions that are not ideal (TRB, 2000). Adjustment factors are multiplication factors that adjust a parameter for a base condition to represent a prevailing condition (TRB, 2000). The values of the adjustment factors contribute to the different value of estimated saturation flow for different intersections.

Traffic signal capacity or signalized intersection capacity is usually estimated as the product of adjusted approach saturation flow rate and the effective green split (Rouphail and Akcelik, 1996). From the calculated saturation flow rate, the capacity can be determined using the basic equation used by all methods as in Equation 2.1.

$$c = Sg / C \text{ veh/hr} \qquad [2.1]$$

Where,

c = capacity of the approach (veh/hr)

g = average effective green time (sec)

C = average cycle time (sec)

S = saturation flow rate (veh/hr)

From the value of capacity, we can now determine other parameters such as the v/c ratio which will help in determining the value for delay. Delay, as defined by

HCM 2000, is the additional travel time experienced by a driver, passenger or pedestrian. It includes the uniform delay, incremental delay and initial queue delay.

When carrying out a capacity analysis, practitioners and engineers will want to come up with a signalized intersection that has appropriate values of the measures of effectiveness (MOEs). Measures of effectiveness are indices of the effectiveness of the system in improving traffic flow. Common bases of comparison include congestion, density, lane occupancy, stops, delay and queue length (Ministry of Works Malaysia, 1987).

It must be highlighted here that delays are used to determine the level of service (LOS) of a signalized intersection. This is because, the delay is the only thing that is truly perceived by the vehicles drivers at the point of location as it describes the total time drivers spend at the intersection while being unable to move their vehicles due to certain conditions such as the traffic signalization and queues. (Roess and McShane, 1987). Delays are calculated for each approach in the analysis.

However, the delay for the intersection as a whole, as well as the LOS for the entire intersection can also be determined. This is done by taking into consideration the weighted average value of control delay for all of the approaches (Marek et al., 1997).

The level of service (LOS) is used as a quantitative measure describing operational conditions in the traffic stream and their perception by drivers and passengers is linked with operational parameters, which expresses the operating quality for the signalized intersection in certain grades (Tracz and Bohatkiewicz , 1994).

It can be concluded here that basically, the method used for capacity analysis is similar from one manual to another. The differences may be in the value of the ideal saturation flow and adjustment factors that are unique to the countries' traffic behavior. However, it is important to remember that a small change in the saturation flow may result in a relatively large change in the calculated cycle time and the duration of the necessary green intervals (Ministry of Works Malaysia, 2006). It is the most important single parameter in the capacity analysis of a signalized intersection (Akcelik, 1981).

2.2 Signalized Intersection Capacity

The information obtained from the capacity analysis will help in designing the intersection, since practitioners will design the intersection so that the intersection will not be used up till its full capacity. This is to avoid long queues of traffic as well as unnecessary delays. However, different manuals have slightly different approaches in conducting the capacity analysis. This may be due to the fact that these manuals have been developed according to the respective countries' traffic behavior, therefore, in order to come up with the best procedure for the country, local studies must be conducted.

A few manuals are compared in this study. These manuals include the current practices used in Malaysia such as the Arahan Teknik (Jalan) 13/87, the HCM 2000, the aaSIDRA as well as the newly developed Malaysian Highway Capacity Manual (MHCM 2006).

2.2.1 Arahan Teknik (Jalan) 13/87

For the Arahan Teknik (Jalan) 13/87, the saturation flow is first determined according to the lane width where Equation 2.2 is used to estimate saturation flow for lane widths greater than 5.5 meters.

$$S = 525\ W \qquad [2.2]$$

Where,

S = saturation flow (pcu/hr)

W = lane width (m)

However, Table 2.2 is referred to for lane widths less than 5.5 meters.

Table 2.2: Relationship between effective lane width and saturation flow (Source: Ministry of Works Malaysia, 1987)

W (m)	3.00	3.25	3.50	3.75	4.00	4.25	4.50	4.75	5.00	5.25
S (pcu/hr)	1845	1860	1885	1915	1965	2075	2210	2375	2560	2760

After the saturation flow has been determined, it will be corrected based on actual traffic conditions using correction factors. The first correction factor is the correction factor for gradient as can be seen in Table 2.3.

Table 2.3: Correction factor for the effect of gradient (Source: Ministry of Works Malaysia, 1987)

Correction Factor, F_g	Description
0.85	For upward slope of 5%
0.88	For upward slope of 4%
0.91	For upward slope of 3%
0.94	For upward slope of 2%
0.97	For upward slope of 1%
1.00	For level grade
1.03	For downward slope of 1%
1.06	For downward slope of 2%
1.09	For downward slope of 3%
1.12	For downward slope of 4%
1.15	For downward slope of 5%

The second correction factor is for the turning radius as shown in Table 2.4.

Table 2.4: Correction factor for the effect of turning radius (Source: Ministry of Works Malaysia, 1987)

Correction Factor, F_t	Description
0.85	For turning radius R < 10m
0.90	For turning radius where 10m < R < 15m
0.96	For turning radius where 15m < R < 30m

The third correction factor is for the turning traffic as can be seen in Table 2.5. This correction factor is applicable for shared lanes.

Table 2.5: Correction factor for turning traffic (Source: Ministry of Works Malaysia, 1987)

% turning traffic	Factor for right turning, F_r	Factor for left turning, F_l
5	0.96	1.00
10	0.93	1.00
15	0.90	0.99
20	0.87	0.98
25	0.84	0.97
30	0.82	0.95
35	0.79	0.94
40	0.77	0.93
45	0.75	0.92
50	0.73	0.91
55	0.71	0.90
60	0.69	0.89

However, if a lane comprises of both left and right turning traffic, the total factor will be F_r x F_l.

After the saturation flow has been determined by multiplying the above adjustment factors, the determination of Y value is carried out. Y value is the ratio of flow to saturation flow and is determined using Equation 2.3.

$$y = q/S \qquad [2.3]$$

Where,

y = ratio of flow to saturation flow

q = actual flow on traffic-signal approach converted to pcu/hr

S = saturation flow for the approach in pcu/hr

The y value used in calculation would be the highest y value calculated from all approaches within that phase.

As for the conversion from vehicles to passenger car units (pcu), the passenger car equivalents (pce) used for this manual is as shown in Table 2.6.

Table 2.6: Conversion factors to pcu (Source: Ministry of Works Malaysia, 1987)

Type of vehicle	Passenger car equivalent
Passenger car	1.00
Motorcycles	0.33
Light Vans	1.75
Medium Lorries	1.75
Heavy Lorries	2.25
Buses	2.25

Next is the determination of lost time using the equation by Webster and Cobbe (1966) as seen in Equation 2.4 and inter-green time is calculated using Equation 2.5.

$$L = \sum_{i-1}^{n} (I - a) + \sum_{i=1}^{n} l \qquad [2.4]$$

Where,

I = the inter-green time between the phases (s)

a = the amber time, usually taken as 3 seconds

l = drivers reaction time at beginning of green per phase. In practice, this time is set to 2 seconds but 0-7 seconds can also be used

$$I = R + a \qquad [2.5]$$

Where,

I = inter-green time (s)

R = all red interval (s)

a = amber time (s)

After the lost time has been determined, the optimum cycle time is calculated. The equation used by the Arahan Teknik (Jalan) 13/87 is given in the Road Research Technical Paper No. 56 as in Equation 2.6. For practical purposes, the cycle time should be between 45 seconds to 120 seconds

$$C_o = \frac{1.5L + 5}{1 - Y} \qquad [2.6]$$

Where,

C_o = optimum cycle time (s)

L = lost time (s)

Y = ratio of flow to saturation flow

Then the signal settings are determined where green time for each phase is calculated. For each individual phase, the Y value is first calculated for the respective phases. After that, the effective green time for each signal phase is calculated using Equation 2.7.

$$g_n = \frac{Y_n}{Y}(C_o - L) \qquad [2.7]$$

Where,

g_n = effective green time of the n^{th} signal phase

Y_n = calculated Y-value of the same signal phase

C_o = optimum cycle time (s)

L = lost time (s)

The Arahan Teknik (Jalan) 13/87 uses the following equation in estimating stopped delay for each approach.

$$d = \frac{9}{10}\left[\left(\frac{C(1-\lambda)^2}{2(1-\lambda x)}\right) + \frac{x^2}{2q(1-x)}\right] \qquad [2.8]$$

Where,

d = average delay per vehicle

c = cycle time (s)

λ = proportion of the cycle that is effectively green for the phase under consideration (i.e. g/C)

q = flow (veh/hr)

x = degree of saturation, which is the ratio of actual flow to the maximum flow that can pass through the approach (i.e. $q/\lambda S$)

Finally, to determine the Level of Service (LOS) for the intersection as whole or in individual lanes, the delays obtained are used as reference. These delays are used to determine LOS based on values in Table 2.7.

Table 2.7: Level of Service for signalized intersections (Source: Ministry of Works Malaysia, 1987)

Level of Service	Stopped delay for vehicles (sec)
A	< 5.0
B	5.1 to 15.0
C	15.1 to 25.0
D	25.1 to 40.0
E	40.1 to 60.0
F	> 60.0

2.2.2 Australian Signalized Intersection Capacity Analysis

According to Miller (1968), from the Institute of Highway and Traffic Research, University of South Wales, the basic model used to estimate capacity is the one by Clayton (1940) that is then used by Wardrop (1952) and Webster (1966). Both Wardrop (1952) and Webster (1966) associate the capacity with the approach widths but in the updated study, the capacity is also associated with the number of approaches.

The basic assumptions made are as follows:

1. When the traffic light changes to green, the velocity of the traffic flow crossing the stop line will increase up to a certain value until the queue or phase ends.
2. The saturation flow does not differ from one cycle to another.

According to Underwood (1994), Miller then developed a mathematical model of traffic flow through a signalized intersection. He determined the value for the saturation flows, as well as the suitable adjustment factors needed to estimate the saturation flow by undertaking a comprehensive data collection throughout the cities in Australia. His study was then compiled into a guide for capacity analysis of a signalized intersection (Miller, 1968).

This guide was used as a model for capacity calculations, complete with details of the saturation flow as well as its adjustment factors. Procedures for signal timing calculation were also included in the guide. Miller also incorporated a method for estimating vehicle delays and probability of queues clearing at signalized intersections. His guide on capacity analysis was well received and subsequently adopted for use Australian-wide (Underwood, 1994).

For this study, the capacity is the maximum number of vehicles that can traverse the approach in certain conditions. The actual vehicle flow crossing the stop line is the capacity for the approach if it is experiencing a saturated flow. The capacity for a signalized intersection depends on the green time for the approaches. If the saturation flow for the approach is s veh/hr, then the capacity for the approach is as in Equation 2.9.

$$c = Sg / C \text{ veh/hr} \qquad [2.9]$$

Where,

c = capacity of the approach (veh/hr)

g = average effective green time (s)

C = average cycle time (s)

For the Australian method (Miller, 1968), Equation 2.10 is used to determine the delay.

$$d = \frac{c-g}{2c(1-y)} \times \left\{ \frac{2}{q} \times E(z) + (c-g) \right\} \qquad [2.10]$$

Where,

d = delay (sec/veh)

c = average cycle length (sec)

g = effective green time (sec)

y = q/s

= ratio of arrival flow to saturation flow

q = rate of arrival for vehicles (veh/hr)

E(z) = expected number of vehicles left in the queue when the signal changes to red

The guide developed by Miller became the basis of signalized intersection design in Australia during the 1960s and throughout the 1970s. However, with the gained knowledge in traffic engineering, a new guide was developed in 1981 by Akcelik. This new guide has more detailed investigation on capacity analysis in Australia. Subsequently, computer programs based on these guides were developed to aid in the capacity analysis (Underwood, 1990).

However, this study uses the software aaSIDRA (Akcelik and Associates, Traffic Signalized and Unsignalized Intersection Design and Research Aid). This software was developed by Akcelik and Associates Pty Ltd to assist engineers and practitioners in analyzing and designing signalized and unsignalized intersections.

aaSIDRA or formally known as SIDRA has been widely used by the Australian government, road and traffic authorities as well as academic and research organizations in Australia (Troutbeck and Akcelik, 1994). SIDRA was first developed by the Australian Road Research Board Ltd. aaSIDRA used in this research is aaSIDRA version 2.0.

For estimating the saturation flow, aaSIDRA separates the factors into two types:

i. Factors that are associated with the lane and applied to all traffic in the lane (lane width, gradient, parking maneuvers and busses stopping), and

ii. The factors that are related to individual vehicle classes i.e. turning vehicles and heavy vehicles.

The reason for distinguishing the factors into two groups is because, the factors in group (i) are constant throughout analysis, whereas group (ii) may change during the iterative saturation flow estimation process as the lane flow changes (Akcelik and Associates, 2000)

The adjusted saturation flow value is calculated using the adjustment factors in group (i) as well as the basic saturation flow value. For the adjusted basic saturation flow, s'_b, calculation is done using Equation 2.11.

$$s'_b = (f_w f_{gr} f_{pm} f_{bs}) s_b \qquad [2.11]$$

Where,

s'_b = adjusted basic saturation flow (veh/hr)

f_w = lane width adjustment factor

f_{gr} = gradient adjustment factor

f_{pm} = parking maneuver adjustment factor

f_{bs} = bus-stopping adjustment factor

s_b = basic saturation flow (veh/hr)

The adjustment factors for group (ii) are calculated into one adjustment factor named the vehicle composition adjustment factor, f_c. This adjustment factor is calculated to allow the effects of turning vehicles and heavy vehicles (Akcelik and Associates, 2000) and is calculated using Equation 2.12.

$$f_c = \frac{1}{\sum(p_i e_i)} \qquad [2.12]$$

Where,

f_c = traffic composition adjustment factor

e_i = through car equivalent of vehicle-turn type i

p_i = proportion of vehicles of vehicle-turn type i

The estimated saturation flow, *s*, is calculated using the adjustment factors from group (ii) with the adjusted basic saturation flow, s'_b. This can be seen in Equation 2.13.

$$s = f_c s'b = f_w f_{gr} f_{pm} f_{bs} f_c s'_b \qquad [2.13]$$

Where,

s = estimated saturation flow (pcu/hr)

s'_b = adjusted basic saturation flow (veh/hr)

f_w = lane width adjustment factor

f_{gr} = gradient adjustment factor

f_{pm} = parking maneuver adjustment factor

f_{bs} = bus-stopping adjustment factor

f_c = traffic composition factor

2.2.3 U.S. Highway Capacity Manual (HCM 2000)

The HCM 2000 was developed as a comprehensive revision of the previous highway capacity manuals in the U.S. The research carried out for this manual was funded by the Federal Highway Administration (FHWA) and the National Cooperative Highway Research Program (NCHRP), evident that these funding agencies have recognized the key role played by the HCM in the capacity analysis (Zegeer, 1994).

For the signalized intersection capacity analysis procedure, minor adjustments were made from the previous HCM. This includes a new method in calculating the estimated saturation flow which take into account the effects of pedestrian, bicycles and protected/permissive left turns from shared lanes (Kittleson et al., 2002).

As explained in Section 2.1, the first step taken in capacity analysis is to determine the saturation flow for the individual lanes in the intersection. This value is calculated using Equation 2.14 where the ideal saturation flow for this method is 1900pcu/hr/ln.