A STUDY ON SATURATION FLOW RATES OF THROUGH VEHICLES AT SIGNALISED INTERSECTIONS BASED ON MALAYSIAN ROAD CONDITIONS

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by

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LIST OF ABBREVAITIONS

aaSIDRA	Akcelik and Associates, Traffic Signalised and Unsignalised Intersection Design and Research Aid
ANOVA	Analysis of variance
ARRB	Australian Road Research Board
BINKOT	Directorate or Urban Road Development
CBD	Central Business District
FIFO	First-In, First-Out
Indonesian HCM	Indonesian Highway Capacity Manual
LIFO	Last-In, First-Out
Non-CBD	Non Central Business District
OLS	Ordinary least squares
pce	Passenger car equivalents
pcphgpl	Passenger car per hour green per lane
pcphpl	Passenger car per hour per lane
pcu/hr	Passenger car units per hour
QFLIERS	Motorcycles which sets off from the front of the queue before the end of the first 6 s effective green time
RRL	Road Research Laboratory
Sig.	Observed significant value
SPSS	Statistical Package for the Social Science
tcu/hr	Through-car units per hour
TPDM	Transport Planning Design Manual
TRRL	Transportation Road Research Laboratory
U.S. HCM	United States Highway Capacity Manual
VADAS	Video Analysis Data Acquisition System
VDDAS	Vehicle Detector Data Acquisition System
veh/hr	Vehicles per hour
WLS	Weighted least squares

LIST OF SYMBOLS

a_1	Estimated mean time headway for cars
a_2	Estimated mean time headway for motorcycles
a_3	Estimated mean time headway for lorries
a_4	Estimated mean time headway for trailers
a_5	Estimated mean time headway for buses
f_{HV}	Adjustment factor for heavy vehicles (any vehicle having more than four tires touching the pavement) used by the U.S. HCM
f_w	Adjustment factor for lane width
f_g	Adjustment factor for approach grade
f_p	Adjustment factor for the existence of parking activities in a parking lane
f_{bb}	Adjustment factor for the blocking effect of local buses stopping within the intersection area
f_a	Adjustment factor for area type
f_{RT}	Adjustment factor for right turns in the lane group
f_{LT}	Adjustment factor for left turns in the lane group
f_{LU}	Lane utilization factor
f_{Lpb}	Pedestrian-bicycle adjustment factor for left-turn movements
f_{Rpb}	Pedestrian-bicycle adjustment factor for right-turn movements
f_c	Traffic composition adjustment factor
f_{car}	Traffic composition factor for cars
f_{hv}	Traffic composition factor for heavy vehicles used in this study
f_m	Traffic composition factor for motorcycles
$f_{a(HRM)}$	Area type adjustment factor computed using the pce values derived by headway ratio method
$f_{a(RA)}$	Area type adjustment factor computed using the pce values derived by regression analysis
F_M	Proposed the motorcycles adjustment factor
e_{car}	pce value for cars

e_{motor}	pce value for motorcycles
e_{lorry}	pce value for lorries
$e_{trailer}$	pce value for trailers
e_{bus}	pce value for buses
$\bar{h}_{c\_c}$	Average headway of a car followed by a car
$\bar{h}_{c\_x}$	Average headway of a car followed by a type *X* vehicle
$\bar{h}_{x\_c}$	Average headway of a type *X* vehicle followed by a car
$\bar{h}_{x\_x}$	Average headway of a type *X* vehicle followed by a type *X* vehicle
$\bar{h}_{A(c\_c)}$	Adjusted mean headways for car following car
$\bar{h}_{A(x\_x)}$	Adjusted mean headways for vehicle type *X* following vehicle type *X*
h_{c_c}	Car followed by car,
h_{c_m}	Car followed by motorcycle
h_{m_c}	Motorcycle followed by car
h_{m_m}	Motorcycle followed by motorcycle
h_{c_l}	Car followed by lorry
h_{l_c}	Lorry followed by car
h_{l_l}	Lorry followed by lorry
h_{c_t}	Car followed by trailer
h_{t_c}	Trailer followed by car
h_{t_t}	Trailer followed by trailer
h_{c_b}	Car followed by bus
h_{b_c}	Bus followed by car
h_{b_b}	Bus followed by bus
δ_n	Lane position factor, 0 for non-nearside lane and 1 for nearside lane
δ_G	Gradient factor, 1 for uphill 0 for downhill
G	Gradient (%)
w	Lane width (m)
f	Proportion of turning traffic
r_t	Radius of turn
f_t	Correction factor for the effect of turning radius
f_{CS}	Correction factor for the effect of city size

f_{SF}	Correction factor for the effect of side friction
$\%HV$	Percentage of heavy vehicles in the traffic stream
E_T	Passenger car equivalents for heavy vehicle used in the U.S. HCM
S	Saturation flow rate under prevailing conditions, expressed in vehicle per hour of effective green time
S_0	Ideal saturation flow rate which is **1,900** passenger cars per hour of green time per lane
$S_{(pcu)}$	Saturation flow in tcu/hr
$S_{(veh)}$	Saturation flow in vph
$S_{(CBD)}$	Measured saturation flow in CBD areas (vph)
$S_{(Non\text{-}CBD)}$	Measured saturation flow in Non-CBD areas (vph)
N	Number of lanes in the lane group
τ	Time periods, beginning with the departure of the first vehicle and ending with the departure of last the vehicle in the platoon
n_i	Number of vehicle departures of each class
β_i	Coefficients
ε	Error term
x_1	Total number of cars in the platoon
x_2	Total number of motorcycles in the platoon
x_3	Total number of lorries in the platoon
x_4	Total number of trailers in the platoon
x_5	Total number of buses in the platoon
T	Time periods, beginning and ending at arbitrary instants
Q_g	Discharged traffic volume during green periods, expressed in pcu
M	Total flow of motorcycles per hour
MR	Hourly flow of motorcycles after 1^{st} 6 seconds of each green
$\overline{R}$	Mean effective red for movement
$\overline{g}$	Mean effective green for movement
Q	Observed number of QFLIERS (motorcycles which sets off from the front of the queue before the end of the first 6 s of effective green time) per cycle

P	Number of QFLIERS predicted per cycle from the first order macroscopic model
NL	Number of lanes
BT	Number of buses and trucks per lane per cycle
ALW	Average lane width
M_I	Motorcycles inside flow per hour
M_i	Motorcycles inside flow observed for every cycle
M_T	Total motorcycles observed per hour
M_t	Total motorcycles observed for every cycle
g	Green time
D_A	Dummy variable for area types
D_P	Dummy variable for lane positions
a	Number of headways for car following car
b	Number of headways for car following type X vehicle
c	Number of headways for type X vehicle following car
d	Number of headways for type X vehicle following type X vehicle
w	Mean headways for car following car
x	Mean headways for car following type X vehicle
y	Mean headways for type X vehicle following car
z	Mean headways for type X vehicle following type X vehicle
U	Uncorrected mean headway
C	Correction factor
s	Standard deviation of the sample
s^2	Sample variance
$s_p{}^2$	Pooled variance
t_α	$(1 - \alpha)^{th}$ percentile of the t-distribution with $(n - 1)$ degree of freedom
α	1 – (percent of confidence level choses/100)
n	Sample size
$\bar{x}$	Arithmetic mean
$s.e.(\bar{x})$	Standard error of the mean
$d.f.$	Degrees of freedom

SS_R	Regression sum of square
SS_E	Error sum of square
SS_T	Total sum of square
MS_R	Mean square of regression
MS_E	Mean square of error
r	Pearson correlation coefficient
R	Correlation coefficient
R^2	Coefficient of determination
k	Number of independent variables
y	Observed values
$\hat{y}$	Predicted values
Q	Total flow of vehicles
q_{car}	Flow of cars
$q_{trailer}$	Flow of trailers
q_{lorry}	Flow of lorries
q_{bus}	Flow of buses

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ABSTRAK

KAJIAN KE ATAS KADAR ALIRAN TEPU KENDERAAN BERGERAK TERUS DI PERSIMPANGAN BERLAMPU ISYARAT BERDASARKAN KEADAAN JALAN RAYA DI MALAYSIA

Aliran tepu merupakan satu parameter yang penting dalam analisis kapasiti persimpangan berlampu isyarat. Penentuan aliran tepu secara tepat akan mempastikan prestasi persimpangan berlampu isyarat dapat berfungsi dengan efisien. Prosedur analisis persimpangan berlampu isyarat sering menyarankan penggunaan aliran tepu yang diukur di lapangan. Walau bagaimanapun, ia adalah tidak pratikal untuk mengukur aliran tepu untuk setiap persimpangan berlampu isyarat yang ada. Tambahan pula, untuk persimpangan berlampu isyarat baru yang belum dipasang, pengukuran aliran tepu sememangnya tidak dapat dilakukan. Dengan demikian, pihak berkenaan di Malaysia seringkali merujuk kepada Manual Kapasiti Lebuhraya (edisi 1994 dan versi baru 2000) dari Amerika Syarikat dalam kebanyakan analisis dan rekabentuk jalanraya dan lebuhrayanya. Ini telah menyebabkan ketidaktepatan yang serius dalam rekabentuk persimpangan berlampu isyarat. Maka, penggunaan manual tersebut dalam keadaan jalan raya dan lebuh raya di Malaysia adalah terhad. Dengan itu, satu kajian terperinci untuk menentukur faktor pembetulan aliran tepu untuk kenderaan bergerak terus di persimpangan berlampu isyarat berdasarkan kepada keadaan lalu lintas dan jalanraya di Malaysia telah dilaksanakan. Data dicerap untuk lorong terus dengan fasa terlindung di kawasan pusat perniagaan *(Central Business District, CBD)* dan kawasan selain kawasan pusat perniagaan di seluruh Malaysia. Kawasan pusat perniagaan merupakan kawasan yang sibuk dengan aktiviti perniagaan di mana aktiviti pejalan kaki adalah

tinggi, aktiviti meletak kenderaan yang tinggi, perhentian kenderaan di persimpangan, aktiviti teksi dan bas yang tinggi, radius membelok yang kecil, penggunaan lorong membelok esklusif yang terhad dan penduduk yang padat. Nilai-nilai unit kenderaan penumpang (ukp) yang digunakan untuk mengambil kira kesan jenis kenderaan yang berbeza terhadap aliran tepu juga telah diterbitkan dengan menggunakan kaedah nisbah jarak kepala dan analisis regresi. Maka, penentukuran faktor-faktor pembetulan aliran tepu akan dilakukan berdasarkan nilai ukp yang diterbitkan melalui kedua-dua kaedah ini. Walau bagaimanapun, sepertimana yang dilaporkan oleh Jabatan Pengangkutan Jalan Malaysia, peratusan motorsikal yang didaftarkan setiap tahun (tahun 1987 hingga tahun 2001) adalah lebih kurang 50% - 60% dan sehingga masa kini, tiada pertimbangan diberikan kepada motorsikal dalam aspek rekabentuk persimpangan berlampu isyarat. Ini akan menyebabkan persimpangan berlampu isyarat yang direkabentuk tidak tepat dan akhirnya menyebabkan kesesakan lalu lintas yang agak serius berlaku. Dengan itu, kajian terperinci ke atas kesan ciri-ciri pergerakan motorsikal terhadap aliran tepu juga telah dilaksanakan dan dimasukkan ke dalam prosedur pengiraan aliran tepu. Akhir sekali, hasil daripada kajian ini telah menunjukkan model pengiraan aliran tepu yang dihasilkan dengan menggunakan nilai ukp yang diterbit menggunakan kaedah nisbah jarak kepala, setelah mengambil kira kesan ciri-ciri pergerakan motorsikal ke atas aliran tepu adalah model yang lebih baik. Model ini dapat menganggarkan aliran tepu secara tepat dan dapat mengambarkan keadaan trafik yang sebenarnya di Malaysia.

ABSTRACT

Saturation flow is an important parameter in the capacity analysis of signalised intersections. The accuracy of determining saturation flow will ensure the efficient performance of signalised intersections. Procedures for signalised intersection analysis often recommend the use of measured saturation flow rates. However, it is impractical to measure prevailing saturation flow rate for an existing site and it is impossible to measure saturation flow rate for a new signal installation which is yet to be constructed. Relevant authorities in Malaysia have been referring to the U.S., Highway Capacity Manual (version 1994 and version 2000) for many of its highway and traffic related design and analysis. It is now known that inaccuracies have prevailed to a large extent in the Malaysian design of signalised intersection and due to this fact, the applicability of this manual to Malaysian conditions was somewhat limited. As such, a detailed study to calibrate the adjustment factors for straight-through saturation flows based on local traffic and roadway conditions have been carried out. Data were collected for individual lane of through traffic with protected phasing at signalised intersections in Central Business District (CBD) and non-CBD areas throughout Malaysia. CBD areas are areas congested with business activities where there is a high concentration of pedestrian activities, frequent parking manoeuvres, vehicle blockages, high taxi and bus activities, small-radius turns, limited use of exclusive turn lanes and dense population. Passenger car equivalents (pce) values which are used to represent the varying effects of mixed vehicle types on saturation flows were also derived using the headway ratio method and regression analysis. Hence, calibrations of the adjustment factors were made based on the pce values derived by these two methods. However, as reported by the Road Transport Department of Malaysia, the percentage of motorcycles registered

annually (year 1987 to year 2001) was about 50% - 60%. Sadly, as of today, no proper considerations are given to motorcycles in the design aspect of signalised intersections. Improper consideration of motorcycles will cause inaccuracies in the design of signalised intersections thus causing significant amount of traffic congestion. Hence, a detailed examination on the effects of motorcycles behaviour on saturation flows were conducted and integrated in the saturation flow estimation procedure. Lastly, the findings of this study indicated that saturation flow prediction model established using pce values derived by headway ratio method upon taking into consideration the behaviour of motorcycles was the better model. It was able to predict saturation flows accurately and thus represent the real traffic situation in Malaysia.

CHAPTER 1: INTRODUCTION

1.1 Background

Saturation flow is the maximum constant departure rate of a queue from the stop line of an approach lane during the green period. A small change in the saturation flow value may result in a relatively large change in the calculated cycle time and the duration of the necessary green intervals. It is the most important single parameter in the capacity analysis of signalised intersections (Akcelik, 1981).

Therefore, the ability to predict saturation flow is crucial to the design of signalised intersections since it is the basis for determination of traffic signal timings and for the evaluation of intersection performance. For existing signalised intersections, saturation flow can be measured directly using standard methods. However, at the design stage for new intersection that is not possible and it is necessary to make predictions from other known factors (Kimber et. al, 1986). Therefore, a generalised predictive formula is needed for estimating saturation flow (Kimber et. al, 1986). The current practice in estimating saturation flow rates of an intersection approach under prevailing conditions is by applying adjustment factors to account for the effects of roadway, vehicle composition, proportion of turning vehicles and other related factors to the predetermined ideal saturation flow. Either measured or estimated, the determination of saturation flow involves consideration of both roadway and traffic factors (Asri Hasan et. al, 1993). Roadway conditions include basic geometric configuration of the intersection, in particular its width, grades and curvatures. Traffic conditions include volumes, vehicle movements (through, right or left) and vehicle types.

Saturation flows measured in vehicles per hour (vph) also depends very much on the proportion and type of vehicles in the traffic stream. Therefore, it is a usual practice to assign weighting factors or passenger car equivalents (pce), to the various categories of vehicle. Pce values represent the effect of changes in traffic composition on saturation flow at signalised intersections and by assigning pce values, saturation flow can be corrected to the common base of passenger car units per hour (pcu/hr) (Kimber et al., 1986). This ensures that a saturation flow value can be stated without prior knowledge of traffic composition for a particular intersection geometry and environment.

Pce values currently used in the design and analysis of signalised intersections in Malaysia were based on the values given in Arahan Teknik (Jalan) 13/87 (Public Works Department, 1987). Pce value of 1.00 is used for passenger cars (including taxis, small vans, pick-ups and 4-wheel drives), 0.33 for motorcycles, 1.75 for lorries with 2 axles and 2.25 for both trailers with 3 axles or more and buses.

Apart from that, in terms of traffic composition, Malaysia has higher number of motorcycles as compared to other western countries. The vehicles composition registered annually in Malaysia consists mainly of passenger cars, motorcycles, buses and goods vehicles as illustrated in Figure 1.1. It clearly shows that the percentage of motorcycles registered annually is about 50% - 60%.

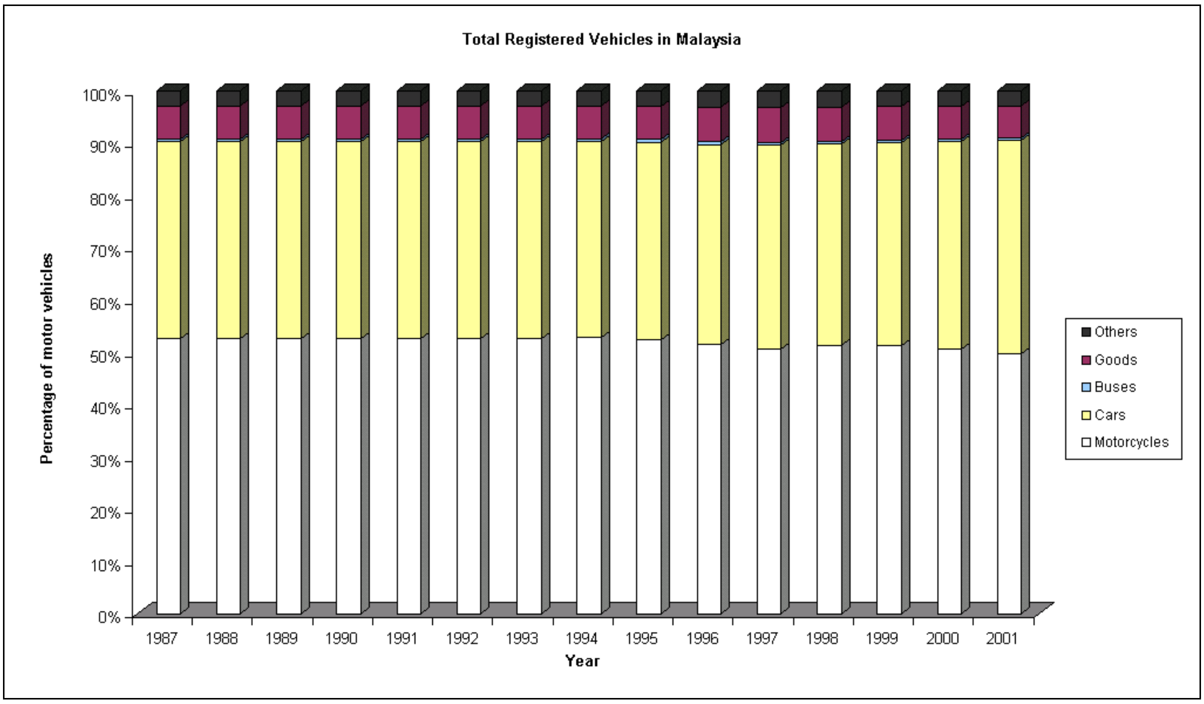

Figure 1.1: Percentage of registered vehicles in Malaysia

In Malaysia, the common type of motorcycles found on the road is that of small size motorcycles. Observation in the field indicated that motorcycles can traverse through a signalised intersection by three different ways due to its small size. During the red light, motorcycles often weave in and out of traffic stream to get as close as possible to the stop line of signalised intersection and due to the high percentage of motorcycles, most of them will stop beyond the stop line. These motorcycles are categorised as the motorcycles in front of stop line. Apart from that, most of the lane widths at traffic light junctions found in Malaysia is about 3.0 to 4.5 meters and with these lane widths, motorcyclists can travel along side other vehicles. Therefore, the second category consists of motorcycles that travel along side other vehicles (such as cars, lorries, bus, etc.) within the same traffic lane. The third category consists of motorcycles following other vehicle types in a structured discipline. Different travel pattern of motorcycles at signalised intersections might have different impact on saturation flow estimation and therefore it should be investigated thoroughly.

1.2 Problem statement

The current method in estimating saturation flow adopted by the Public Works Department of Malaysia was based on the method developed by Webster and Cobbe (1966) in United Kingdom in the 50's and 60's. Apart from that, relevant authorities in Malaysia have also been referring to the U.S., Highway Capacity Manual (U.S. HCM) (1994) and the 1997 Update as well as the new metric version, HCM (2000) in the design and analysis of signalised intersections. However, due to certain distinct differences such as road system, vehicle composition and urban travel behaviour between traffic conditions in Malaysia and in the United States, the application of this manual may not be representative of local traffic conditions in Malaysia.

Apart from that, the pce values currently used in Malaysia were also adopted with slight adjustment to the values obtained by Webster in United Kingdom in the 50's and 60's (Webster and Cobbe, 1966). And again due to certain differences such as drivers' behaviour, traffic composition and roadways characteristics; these values may not be representative of local traffic conditions in Malaysia.

In terms of vehicle composition, Malaysia clearly has a higher percentage of motorcycles as compared to the United States. In the U.S. HCM, traffic is classified into two categories only, namely light vehicles and heavy vehicles. Consequently, the high percentage of motorcycles must be taken into consideration as the presence of motorcycles will definitely affect the capacity of signalised intersections in one way or another. However, as of today there is no special consideration being given to motorcycles in the design aspect of signalised intersections. Improper consideration of motorcycles in the design of junctions results in inaccurate design of signalised intersection thus causing significant amount of traffic congestion and motorcycle accidents.

1.3 The need for the study

To date, there are several saturation flow model presented in major references throughout the world. Unfortunately, the suitability of these models for Malaysian traffic conditions is limited to some extent. Therefore, calibration or formulations of new saturation flow adjustment factors based on local standards are essential in assessing the capacity and level of service of signalised intersections in Malaysia.

Pce values of each category of vehicles have also been found to be of major significance, particularly in the estimation of saturation flow at signalised intersections. However, the pce values currently used in Malaysia have not been revised since the publication of Arahan Teknik (Jalan) 13/87 (Public Works Department, 1987) in year 1987. Therefore, more realistic pce values that reflect the present Malaysian road conditions need to be established.

Additionally, in order to incorporate the influence of different travel characteristics of motorcycles at signalised intersections, there is a need to carry out an in-depth study on the behaviour of motorcycles at signalised intersection. Therefore, apart from calibrating saturation flow adjustment factors and establishing new pce values, this thesis presents a new methodology of estimating saturation flow by incorporating a motorcycles adjustment factor in the saturation flow prediction model.

1.4 Objectives of the study

The eventual aim of this study was to derive a prediction formula for saturation flow based on Malaysian roads conditions. However, before this can be achieved, a few aspects need to be investigated so that the above-mentioned prediction formula can be developed accurately according to local conditions. Hence, the aspects that need to be examined are listed below:

a. To study on the effects of motorcycles characteristics on saturation flow and introduce a motorcycles adjustment factor in the saturation flow prediction formula and to investigate the effect of area types and lane positions on motorcycles characteristics.

b. To calibrate the saturation flow adjustment factors as presented in the U.S. HCM with respect to Malaysian conditions. Focus was given to the more significant adjustment factors for straight-through saturation flow rates. The adjustment factors that were investigated are as follows:

   - Traffic composition factor - to derive pce values for vehicles commonly found in Malaysia.
   - Ideal saturation flow rate – to determine an ideal saturation flow rate for signalised intersections in Malaysia.
   - Area type adjustment factor.
   - Lane width adjustment factor.
   - Approach grade adjustment factor.

1.5 Hypotheses of the study

The following hypotheses were examined in this study.

a. Segregation of motorcycles at signalised intersections has significant effect on saturation flow.

    i. Area type is a significant factor in the segregation of motorcycles.

    ii. Lane position is an important factor in the segregation of motorcycles.

b. Pce values have significant impact on saturation flow rates. pce values currently used in Malaysia need to be revised.

c. Ideal saturation flow rate plays a significant role in predicting saturation flow.

d. Adjustment factors namely area type, lane width and approach grade are significant factors in the development of saturation flow prediction model and should be calibrated according to local conditions

1.6 Scope of the study

Vehicles headway data and motorcycles traffic characteristics were collected for individual lane of through traffic with protected phasing at signalised intersections in Central Business Area (CBD) and non-CBD area throughout Malaysia. Geometric features of signalised intersections such as lane width, lane position, and gradient were measured. Pce values for passenger cars, motorcycles, lorries, trailers and buses were established and compared using the headway ratio method and regression analysis. Applicability of the ideal saturation flow rate of 1,900 pcphpl and adjustment factors (i.e. area type, lane width and approach grade) of the U.S. HCM were investigated and calibrated with respect to Malaysian road conditions. Motorcycles characteristics at signalised intersections were investigated and a new motorcycles adjustment factor was introduced in the saturation flow prediction formula. The effect of area types and lane positions on motorcycles characteristics were also investigated and included in the motorcycles adjustment factor.

1.7 Organisation of thesis

The structure of this thesis is as follows. The first chapter starts by giving a brief explanation on the importance of saturation flow on the capacity analysis of signalised intersections. The second chapter discusses the relevant literature related to the study. Motorcycles unique characteristics are discussed in detail in Chapter 3. Next, the study methodologies are presented in Chapter 4. Chapter 5 describes the statistical analyses carried out in this study. The results of statistical analysis for motorcycles are discussed in Chapter 6 while the estimation results for pce values by headway ratio method and regression analysis are discussed in Chapter 7. Calibration results for the adjustment factors are presented in Chapter 8. Discussions on the findings of each parameter are presented in Chapter 9. Lastly, Chapter 10 concludes the thesis and recommendations and further studies are discussed.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The relevant literatures are discussed in this chapter. Initially, this chapter begins by giving a brief overview on the concept of saturation flow, follows by a review on the different methods of saturation flow measurement and data collection. Subsequently, the ideal saturation flow rate and factors affecting saturation flow rate are examined. Focuses are given to the more prominent adjustment factors, i.e. traffic composition factor, area type adjustment factor, lane width adjustment factor and gradient adjustment factor. The relevant literatures regarding the characteristics of motorcycles at signalised intersections are discussed in Chapter 3.

2.2 Concept of saturation flow

The capacity of a traffic-signal controlled intersection is limited by the capacities of the individual critical approaches to the intersection. It is defined as the maximum rate of flow, which may move across the intersection in the existing traffic, roadway and signalisation conditions. Capacity at signalised intersections is based on the concept of saturation flow (Asri Hassan et al., 1993).

The U.S., Highway Capacity Manual describes saturation flow rate as the flow, in vehicles per hour per lane (vphpl) that can be accommodated by the lane assuming that the green phase is always available to the approach.

The Canadian Capacity Guide for Signalised Intersections defines saturation flow as the rate of queue discharges from the stop line of an approach lane, expressed in passenger-car units per hour of green (pcu/hr green) (Teply and Jones, 1991).

As for Australian Road Research Board in Research Report ARR No. 123 (Akcelik, 1981), saturation flow is defined as the maximum constant departure rate from the queue during the green period, expressed in through-car units per hour (tcu/hr).

However, Transportation Road Research Laboratory (1963) in Road Note 34/196 defines saturation flow as the constant rate a queue discharges after an initial period of acceleration to normal running speed when the green period commences at a traffic signal. It is usually expressed in vehicles per hour of green time (veh/hg).

As for Arahan Teknik (Jalan) 13/87 (Public Works Department, 1987), saturation flow is defined 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.

These definitions do not mean that there is a continuous hour of green, but imply the usual stopping and moving operation for the normally used range of cycle times and green intervals. Thus, saturation flow reflects the uniform service rate used in most applications of queuing theory for the problem of intersection capacity. All the definitions were based on the conventional graphical representation of saturation flow as shown in Figure 2.1.

This traditional concept assumed that when the signal changes to green, traffic discharged at a constant rate (saturation flow rate) until either the queue was exhausted or the green period ended. The departure rate was lower during the first few seconds as vehicles accelerate to normal running speed and similarly during the period after the end of green interval as the flow of vehicles declined (Akcelik, 1981; Teply and Jones, 1991). The basic assumption was that rate of discharge (saturation flow) does not vary from cycle to cycle (Miller, 1968).

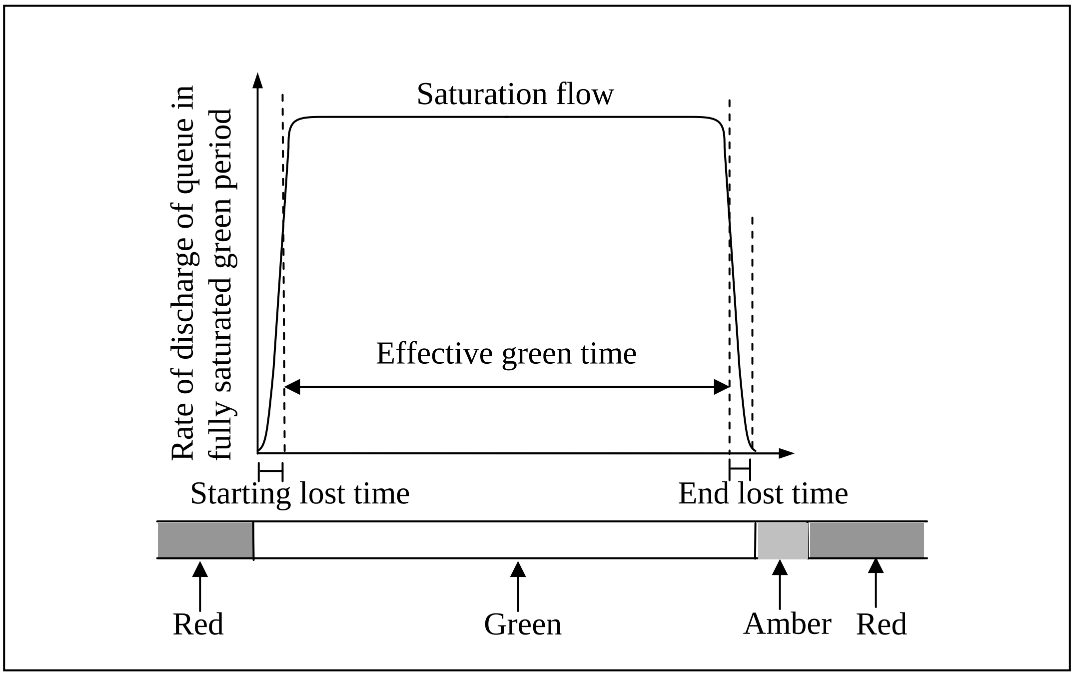

Figure 2.1: Graphical presentation of saturation flow (Kimber et al., 1986)

2.3 Saturation flow measurement methods

According to the U.S. HCM, saturation flow rate is dependent on the saturation headway, which is defined as the average headway between passenger cars in a stable moving queue as they pass through a signalised intersection, in seconds.

There were two major categories of saturation flow surveys. The first group was based on the successive times (not necessarily true headways) of vehicle discharge at a specified reference line. Stop lines, nearside crosswalk boundaries, nearside intersection boundaries or other nearside points such as the cross section at which a nearside signal was located and far side intersection boundaries or far side crosswalk lines have also been used. Vehicles are considered discharged when their front bumpers, front wheels, rear wheels, or rear bumpers have passed the reference line. As can be seen, a large number of possible combinations of reference lines and vehicle discharge criteria existed (Teply and Jones, 1991).

The second group of techniques, which count the number of vehicles passing the reference line during short portions of green interval was best represented in "A Methods for Measuring Saturation Flow at Signalised Intersections" published by the (then) Road Research Laboratory (RRL). In this method, the term "green time" which referred to the "green plus amber" period was divided into short intervals, which was 6 seconds. This method was based on recording the number of vehicles discharged from a queue in these successive short intervals of the green period. In the analysis, only saturated intervals were considered, the flow was averaged and the saturation flow and lost time were calculated. In principal, the Canadian Capacity Guide also applied this basic technique. Both the RRL and Canadian Capacity Guide methods designated the stop line as the reference line, but there was a difference in the identification of the point in time at which a vehicle was considered discharged. In the RRL report, discharge was defined as the moment when the rear wheels of vehicles crossed the stop line. The Canadian Capacity Guide used the passage of the front bumper over the stop line as the time of discharged (Teply and Jones, 1991).

The U.S. HCM and ARRB used combination of both techniques because they were based on the determination of the average headways during a specifically defined portion of the green interval. The saturation flows were calculated with the passage of the fourth vehicle in the U.S. HCM method and after 10 second of green in the ARRB technique whereas the Canadian Capacity Guide survey method included the entire initial period of flow (Teply and Jones, 1991).

According to William Lam (1991), the correct way of determining the end of saturation period was also important. According to him, the general rule for determining the end of saturation was to note the time of last vehicle joining a queue at the approach. A fully saturated cycle was the one in which the queue has not fully discharged by the beginning of the red period.

2.4 Saturation flow data collection methods

At present there were several methods for collecting saturation flow data in the field. For instance, Shou-min Tsao and Song-wei Chu (1995) used video camera in their research to collect vehicles headways data in Taipei. This method however was found to be less accurate if the video was not of top quality and the obscuring of the view of the video camera by a large vehicle in the adjacent lane often resulted in three or four vehicles, especially motorcycles being missed (Cuddon and Benneett, 1988). Hence, the location of a video camera was important and suitable sites such as overhead bridge or on top of a building were hard to acquire.

Apart from video camera, ARRB VDDAS (Vehicle Detector Data Acquisition System) can also be used to measure saturation flow. A research study carried out by Cuddon and Bennett (1988) on methods of saturation flow measurement discovered that VDDAS was a method most suited to the requirements of the saturation flow investigation as compared to video recording, ARRB VADAS (Video Analysis Data Acquisition System) and other semi-automated techniques. However, VDDAS was not a suitable method to be used in Malaysia because more than half of the registered vehicles in Malaysia were motorcycles and normally VDDAS was unable to detect the motorcycles as most of the time motorcyclists try to avoid crossing the detector treadle. Furthermore, extra vehicles were sometimes recorded due to the detector signal profile of some commercial vehicles, which actually have two peaks causing two vehicles to be counted. Thus, the use of this equipment was restricted to locations where only a few commercial vehicles were present (Cuddon and Bennett, 1988).

Another method that can be used to collect saturation flow was by using audiocassette recorder. This method was judged to be fast and accurate, particularly as the observer had only a single task to perform in the field. By using cassette recorder, events in the observed lane such as the beginning of the green interval, the passage of the rear axle of each passing vehicle over the stop line as well as the vehicle type and direction of turning (left of right turning if relevant), the end of saturation flow and the beginning of amber and red interval can be noted as they occurred (Brown and Ogden, 1988; Teply and Jones, 1991). The time involved in the analysis was also fairly short, enabling a large number of sites to be studied. The data from a tape could be read off, analysed and checked by one person in a few hours (Miller, 1968).

2.5 Ideal saturation flow

Ideal saturation flow rate is the saturation flow rate that occurs in the ideal situation. According to the U.S. HCM, the ideal conditions was defined as the characteristics for a given type of facility which were assumed to be the best possible conditions from the point of view of capacity where if the characteristics if further improved would not result in increased capacity. In U.S., the ideal situation for an approach of a signalised intersection is an approach with twelve feet lanes, through traffic, consists only of passenger car, level gradient, no adjacent parking permitted, no bus blockages and located in a non-CBD area. Based on the U.S. HCM 1985, the ideal saturation flow rate was 1,800 passenger cars per hour green per lane (pcphgpl) but based on the 1994 and 2000 versions, the ideal saturation flow rate was 1,900 pcphgpl. According to Prevedouros and Koga (1996), the choice of using 1,900 pcphgpl in U.S. HCM (1994) was to bridge the gap between places with more aggressive driving behaviour (e.g. Chicago with ideal saturation flow rate of 2,000 pcphgpl) and places with more conservative driving behaviour (e.g. Honolulu with ideal saturation flow rate of 1,800 pcphgpl).

However, in Australia, the term “base saturation flow” was used instead of ideal saturation flow rate. The base saturation flow presented in the Australian Road Research Board (ARRB), Research Report No. 123 (Akcelik, 1981) were based on environmental class and lane type as discussed further in Section 2.6.2. For a lane that consists of through traffic only with the environment of ideal or nearly ideal condition, the basic saturation flow rate was 1,850 pcu/hr. Upon obtaining the base saturation flow rate, it was adjusted to take into consideration various factors such as lane width, approach grade and traffic composition. However, the default value used in aaSIDRA

(Akcelik and Associates, Traffic Signalised and Unsignalised Intersection Design and Research Aid) (Akcelik, 2000) software developed in Australia for good environment condition was 1,950 pcu/hr (Akcelik, 2000).

Apart from that, in one of the earlier research carried out by Webster and Cobbe (1966) in United Kingdom, it was reported that the saturation flow for twelve-foot lane was 1,900 pcu/hr. However, in 1986, Kimber et al. have also carried out a study on saturation flows at signalised intersections in United Kingdom. The results of their study were presented in the Transport and Road Research Laboratory, Research Report 67 (Kimber et al., 1986). They concluded that the saturation flow for a non-nearside lane of average lane width, 3.2 m, is 2,080 pcu/hr and for nearside lanes, the value was 1,940 pcu/hr (nearside lane is the side of an approach nearest to the curb). However, in Malaysia, the value of saturation flow for lane width 3.66 m as presented in Arahan Teknik (Jalan) 13/87 was 1,904 pcu/hr. As for the value used in Indonesia Highway Capacity Manual, saturation flow for lane width 3.66 m was 2,196 pcu/hr.

2.6 Factors affecting saturation flow

In estimating saturation flows, adjustment factors were applied to account for the effects of roadway, vehicle composition, turning percentages and other influencing factors that were not ideal. According to the U.S. HCM (1994), the saturation flow rate of an approach of a signalised intersection can be calculated by using equation (2.1).

$$S = S_0 \times N \times f_{HV} \times f_w \times f_g \times f_p \times f_{bb} \times f_a \times f_{LT} \times f_{RT} \qquad (2.1)$$

where

S = Saturation flow rate under prevailing conditions, expressed in vehicle per hour of effective green time

S_0 = Ideal saturation flow rate which is **1,900** passenger cars per hour of green time per lane (pcphgpl)

N = Number of lanes in the lane group

f_{HV} = Adjustment factor for heavy vehicles (any vehicle having more than four tires touching the pavement)

f_w = Adjustment factor for lane width

f_g = Adjustment factor for approach grade

f_p = Adjustment factor for the existence of parking activities in a parking lane

f_{bb} = Adjustment factor for the blocking effect of local buses stopping within the intersection area

f_a = Adjustment factor for area type

f_{RT} = Adjustment factor for right turns in the lane group

f_{LT} = Adjustment factor for left turns in the lane group

However, the procedure for estimating saturation flow in HCM (2000) was slightly different from the U.S. HCM (1994). In the HCM (2000), the lane utilization factor, f_{LU} was included in the saturation flow prediction formula and the pedestrian-bicycle blockages in both the left-turn and right-turn adjustment factors were separated as the pedestrian-bicycle adjustment factor for left-turn movements, f_{Lpb} and pedestrian-bicycle adjustment factor for right-turn movements, f_{Rpb} respectively.

In addition to the factors considered in the U.S. HCM (1994) and HCM (2000), other factors were being applied in United Kingdom, Australia (Akcelik, 1981), Sweden, Japan, Canada (Teply and Jones, 1991) and Taiwan as shown in Table 2.1.

Table 2.1: Adjustment factors for saturation flow rate from various countries (Shou-min Tsao and Song-wei Chu, 1995 and Bang and Palgunadi, 1994)

Factors	U.S.	U.K.	Australia	Sweden	Japan	Canada	Taiwan	Indonesia
Road width		✓						
Lane width	✓		✓	✓	✓	✓	✓	✓
Grade	✓	✓	✓	✓	✓	✓	✓	✓
Heavy vehicles	✓	✓	✓	✓	✓	✓	✓	✓
Right turns	✓	✓	✓	✓	✓	✓	✓	✓
Left turns	✓	✓	✓	✓	✓	✓	✓	✓
Bus stopping	✓						✓	
Pedestrians	✓	✓				✓	✓	
Parking	✓	✓				✓	✓	✓
Site location	✓	✓					✓	
Peak hour								
Weather						✓		
Signal						✓		✓
City size								✓
Side friction								✓

In Australia (Akcelik, 1981), a traffic composition factor was included in the saturation flow prediction model as shown in equation (2.2).

$$S = \frac{f_w \times f_g}{f_c} \times S_0 \qquad (2.2)$$

where

S = Estimated saturation flow in vehicle per hour (vph)

S_0 = Basic saturation flow in through car units per hour (tcu/hr)

f_w = Adjustment factor for lane width

f_g = Adjustment factor for approach gradient

f_c = Traffic composition adjustment factor

However, in the Transport and Road Research Laboratory Research Report 67 (Kimber et al., 1986), factors that found to have a significant influence on the saturation flow in unopposed streams were as follow:

a. Condition of road surface: wet/dry
b. Proportion of turning traffic
c. Radius of turn
d. Gradient
e. Lane position (nearside or non-nearside)
f. Land width
g. Number of lanes at the stop line

Therefore, the equation used for calculating saturation flow, *S* is as shown in equation (2.3).

$$S = \frac{2080 - 140\delta_n - 42\delta_G G + 100(w - 3.25)}{1 + 1.5\, f / r_t} \quad (2.3)$$

where

S = Saturation flow (pcu/hr)

δ_n = 0 for non-nearside lane and δ_n = 1 for nearside lane

δ_G = 1 for uphill and δ_G = 0 for downhill

G = Gradient (%)

w = Lane width (m)

f = Proportion of turning traffic

r_t = Radius of turn

The Transport Planning Design Manual (TPDM) of Hong Kong Government also adopted this equation in estimating saturation flows. However, a study conducted by

William Lam (1994) to investigate the effects of radius of turning, proportion of turning vehicles and effective lane width on saturation flow at signalised intersections found out the measured saturation flows in Hong Kong are smaller than those being used in United Kingdom as the traffic flow characteristics and driver behaviour in Asian cities are different from those in the developed countries. The calibrated equations for estimating saturation flows, S in pcu/hr as reported by him are as shown in equation (2.4) for nearside lanes and equation (2.5) for non-nearside lanes.

$$S = \frac{1770 + 45(w - 3.71)}{1 + 1.5\, f/r} \qquad (2.4)$$

$$S = \frac{1895 + 45(w - 3.71)}{1 + 1.5\, f/r} \qquad (2.5)$$

where

S = Saturation flow (pcu/hr)

G = Gradient (%)

w = Lane width (m)

f = Proportion of turning traffic

r = Radius of turn

However, based on Arahan Teknik (Jalan) 13/87 (Public Works Department, 1987), factors that have to be taken into consideration in unopposed streams were similar to the factors considered by Webster and Cobbe (1966) in United Kingdom, and the saturation flow was represented by equation (2.6).

$$S = S_o \times f_g \times f_t \times f_{LT} \times f_{RT} \qquad (2.6)$$

where

S = Estimated saturation flow (pcu/hr)

S_0 = 525 × w for effective approach width, w more than 5.5 m (for approach width less than 5.5 m, saturation flow values are as shown in Table 2.8 in Section 2.6.3).

f_g = Correction factor for the effect of gradient

f_t = Correction factor for the effect of turning radius

f_{RT} = Correction factor for right-turn

f_{LT} = Correction factor for left-turn

Factors that were taken into consideration in the estimation of saturation flow based on the Indonesian Highway Capacity Manual (Indonesia HCM) (1996), are as follows:

a. Signal phasing
b. Size of the city (based on the city population)
c. Side friction
    - Type of roads – commercial, residential or restricted access
    - Level of side friction – high, medium or low
    - Ratio of non-motorised vehicles
d. Gradient
e. Parking
f. Turning traffic
    - Right turns
    - Left turns

Therefore, the equation adopted for protected phasing to determine saturation flow is as shown in equation (2.7).

$$S = 600 \times w \times f_{CS} \times f_{SF} \times f_g \times f_p \times f_{LT} \times f_{RT} \tag{2.7}$$

where

S = Estimated saturation flow (pcu/hr)

w = Effective lane width

f_{CS} = Correction factor for the effect of city size

f_{SF} = Correction factor for the effect of side friction

f_g = Correction factor for the effect of gradient

f_p = Correction factor for the effect of parking activities

f_{RT} = Correction factor for right-turn

f_{LT} = Correction factor for left-turn

Apart from that, a study on the effects of driver population on saturation flow rates has also been carried out in State College, Pennsylvania, U.S.A. (Torbic and Elefteriadou, 2000). This study analyses the difference in saturation flow rates during different times of the day and different days of the week. They concluded that there are no significant differences in the saturation flow estimated at signalised intersections during different times of the day and different days of the week. Their conclusions appeared to agree with the findings of Kimber et al. (1986) where an analysis of variance showed that day-to-day variations did not differ significantly from within-day variations. Thus there were no significant differences arising out of different driver populations on different days at the same site and saturation flow at a given site could be estimated without separating observations made on different days. All that mattered was the total number of observations (Kimber et al., 1986).

2.6.1 Traffic composition factor

Saturation flow depends on traffic composition and therefore there is a need to estimate changes in saturation flow as the traffic composition changes (Acelik, 1981). In the U.S. HCM, only two categories of vehicles were considered, that is light and heavy vehicles. Kockelman and Shabih (2001) however have conducted a study on the effect of light-duty trucks on the capacity of signalised intersections in Austin, Texas. The results of their research suggested that light-duty trucks, which include pickups, minivans and sport-utility vehicles, requires longer headways than passenger cars and have an adverse effect on the capacity of signalised intersections. Therefore, they concluded that the light-duty trucks, which occupy the place of 1.2 passenger cars in through traffic, should be considered separately from passenger cars when determining the capacity of signalised intersections.

Nevertheless, based on the U.S. HCM, the traffic composition adjustment was taken into account by deriving the percentage of heavy vehicles (defined as vehicles with more than four tires on the road) from the survey data and the corresponding heavy vehicle adjustment factors (f_{HV}) were either obtained from Table 9-6 of the U.S. HCM (1994) or calculated by using equation (2.8).

$$f_{HV} = \frac{100}{100 + \%HV(E_T - 1)} \tag{2.8}$$

where

$\%HV$ = Percentage of heavy vehicles in the traffic stream

E_T = 2.0 passenger cars per heavy vehicle for $0 \le \%HV \le 100$ but according to the U.S. HCM 1985 version, E_T of 1.5 was adopted.

The ideal saturation flow rate was then multiplied by this factor to reduce the flow, accounting for heavy vehicles in the traffic composition.

However, according to Akcelik (1981), the traffic composition factor *(f_c)* was a weighted average determined by the proportions of various vehicle types in combination with turning movements. Since only straight-through flows were surveyed, the through-car-unit (tcu) equivalent values were limited to 1 for car and 2 for all heavy vehicles but in the aaSIDRA software, the value of 1.65 was used for heavy vehicles. Heavy vehicles were defined as vehicles having more than two axles or having tandem tires on the rear axle. The average tcu/vehicle was multiplied by the basic saturation flow to convert the flow to tcu/hr green. Naturally, for the basic saturation flow that is the straight-through saturation flow, pcu and tcu were directly comparable. The traffic composition factor, f_c was calculated using equation (2.9).

$$f_c = \frac{\sum e_i q_i}{q} \tag{2.9}$$

where

q_i = Flow in vehicles for vehicle type i

q = Total flow (Σq_i)

e_i = pce of vehicle type i

However, equation (2.8) was actually derived from equation (2.9) if only two vehicle categories being considered. This can be proven by the following derivations.

$$f_c = \frac{e_{car} q_{car} + e_{HV} q_{HV}}{q} \tag{2.10}$$

$$f_c = \frac{e_{car}(q - q_{HV}) + e_{HV} q_{HV}}{q} \tag{2.11}$$

where $q = q_{car} + q_{HV}$