ESTIMATION OF TURNING ADJUSTMENT FACTORS AT SIGNALISED INTERSECTIONS ACCORDING TO MALAYSIAN TRAFFIC CONDITIONS

by

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To my parents

Late Quazi Mufazzel Hossain and **Mrs. Lutf-E-Jahan**

for their love, support, sacrifice, encouragement,

and most importantly, patience.

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TABLE OF CONTENTS

CHAPTER 3 - METHODOLOGY

CHAPTER 4 - ESTIMATION OF LEFT-TURN ADJUSTMENT FACTOR

CHAPTER 5 - ESTIMATION OF RIGHT-TURN ADJUSTMENT FACTOR

CHAPTER 6 - ESTIMATION OF U-TURN ADJUSTMENT FACTOR

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

S	Saturation flow rate under prevailing conditions, expressed in vehicle per hour of effective green time
S_0	Ideal saturation flow rate per lane (1930 pcu/h/lane)
N	Number of lanes in the lane group
f_{HV}	Adjustment factor for heavy vehicles in the traffic stream
f_w	Adjustment factor for lane width
f_g	Adjustment factor for approach grade
f_p	Adjustment factor for the existence of a parking lane and parking actuvuty adjacent to the lane group
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-turn traffic
f_{LT}	Adjustment factor for left-turn traffic
f_{LU}	Adjustment factor for lane utilization
f_{Lpb}	Pedestrian adjustment factor for left-turn movements
f_{Rpb}	Pedestrian adjustment factor for right-turn movements
f_c	Vehicle composition factor
K	Effect of all turning vehicles in reducing the through saturation flow rate
S_{RT}	Saturation flow rate for right-turning vehicles (pcu/h)
r	Turning radius (meter)
q	Traffic flow of opposing arm (veh/h)
S_C	Saturation flow of opposing arm (veh/h)
g	Green time (seconds)
C	Cycle time (seconds)
n_r	Flow of right-turning vehicles
n_1	Total flow of private cars plus light commercial vehicles

n_2	Total flow of medium and heavy commercial vehicles
n_3	Total flow of buses
n_4	Total flow of trams
S_{LT}	Saturation flow rate for left-turning vehicles
G	Gradient is in percentage (%);
δ_n	Lane position factor, 0 for non-nearside lane and 1 for nearside lane
δ_G	Gradient factor
w	Lane width is in meter
P_{CV}	Proportion of commercial vehicles as a per cent of total flow
q_1	Volume of the flow being studied
q_0	Volume of the opposing flow
$\bar{h}$	Average headway
$\bar{h}_c$	Average car- car headway for through car
p_{CV}	Proportion of commercial vehicles
$\bar{e}_{CV}$	Average extra headway per commercial vehicles
p_{turn}	Proportion of turning vehicles
$\bar{e}_{turn}$	Average extra headway per turning vehicle
E_{CV}	Through car equivalents for commercial vehicles
E_{turn}	Through car equivalents for turning vehicles
$\bar{e}$	Average extra headway required for turning commercial vehicle
$\bar{e}_{turn}$	Average extra headway per turning car
$\bar{h}_1$	Average through car-through car headway
P_{LTC}	Proportion of cars in lane which turned left
g	Green time (s) for the movement with opposed turns
S_u	Opposed turn saturation flow rate (veh/s) as a function of the opposing movement flow rate
g_u	Unsaturated part of the opposing movement of green (s)
$(s_u g_u)$	Number of turning vehicles (per cycle) during the period g_u

n_f	Number of turning vehicles (per cycle) after the green period from the shared lane
q_i	Flow of vehicles in class i (veh)
e_i	Through car equivalent of vehicle class i (tcu/veh)
q	Total movement = $\sum q_i$ (veh)
e_{LVr}	Through car equivalent for light vehicles subjected to a restricted turn (tcu/veh)
e_{LVn}	Through car equivalent for light vehicles subjected to a normal turn (tcu/veh)
e_{xr}	Excess headway equivalent per restricted turn (tcu/veh)
e_{LV}	Through car equivalent for light vehicles
e_{xHV}	Excess headway equivalent per heavy vehicle
h_{xHV}	Excess headway per heavy vehicle (tcu/veh)
s_b	Base saturation flow rate (tcu/h)
$e_{xHV\max}$	Maximum e_{xHV} value
P_{LT}	Proportion of left-turns (right-turn in Malaysia) in the lane group flow
P_{RT}	Proportion of right-turns (left-turn in Malaysia) in lane group
F_L	Loss of saturation flow rate due to right-turning traffic
$(PCU)_i$	Passenger car unit of vehicle type i
V_c	Turning speed of passenger car (km/h)
V_i	Turning speed of vehicle type i (km/h)
A_c, A_i	Projected rectangular area of car and vehicle type i (m^2), respectively
a_{ij}, a_{im}	Regression coefficient
n_j	Number of vehicles of type j turning right per unit time of saturated green from a lane of 3.5 meter width in vehicle per second of green per lane (vpsgpl)
$MG_{through}$	Mean gap of the vehicles in saturation flow rate, that crossed the through lane's stop line (sec)
MG_{shared}	Mean gap of the vehicles in saturation flow rate, that crossed the shared lane's stop line (sec)

$e_{TURNCAR}$	Through car equivalent for turning cars (left-turn and right-turn)
h_{LL}	Left-turn (right-turn in Malaysia) preceded by a left-turn (right-turn in Malaysia)
h_{LU}	Left-turn (right-turn in Malaysia) preceded by a U-turn
h_{UL}	U-turn preceded by a left turn (right-turn in Malaysia)
h_{UU}	U-turn preceded by a U-turn
$h_{\min}(a)$	Lower limit of average headway with a percent of U-turning vehicles
S_L	Saturation flow rate of all left-turning (right-turn in Malaysia) vehicles in pcphgpl
$S_{\max}(a)$	Upper limit of saturation flow rate with a percent of U-turning vehicles in pcphgpl
$f_{ut\max}(a)$	Upper limit of adjustment factors for U-turns, with a percent of U-turning vehicles
a	Percent of U-turning vehicles
$h_{\max}(a)$	Upper limit of average headway with a percentage of U-turning vehicles
$S_{\min}(a)$	Lower limit of saturation flow rate with percentage of U-turning vehicles (pcphgpl)
$f_{ut\min}(a)$	Lower limit of adjustment factors for U-turns, with a percentage of U-turning vehicles
S_{UT}	Saturation flow rate of mixed use lane (veh/h/l)
f_{UT}	U-turn adjustment factor
P_{UT}	U-turn percentage of mixed use lane
$RTOA$	Conflicting right-turn (left-turn in Malaysia) volume from the cross street during the U-turn phase (veh/min)
ε	Error of the mean at chosen confidence level
s	standard deviation of the sample
t_α	$(1-\alpha)^{th}$ percentile of the t-distribution with (n-1) degrees of freedom
α	1- (percent of confidence level chosen/100)
n	Sample size
d_a	Arc distance (meter)
t	Traveling time

P_{LTC}	Proportion of left-turning car
P_{LTm}	Proportion of left-turning motorcycles
P_{LTHV}	Proportion of left-turning heavy vehicles
P_{RTC}	Proportion of right-turning car
P_{LRTm}	Proportion of right-turning motorcycles
P_{RTHV}	Proportion of right-turning heavy vehicles
$d.f.$	Degrees of freedom
d	Control delay per vehicle (s/veh)
d_1	Uniform control delay (s/veh)
PF	Uniform delay progression adjustment factor
d_2	Incremental delay (s/veh)
d_3	Initial queue delay (s/veh)
X	Volume/capacity ratio known as degree of saturation
T	Duration of analysis period (hr)
k	Incremental delay factor
I	Incremental delay adjustment for the filtering or metering by upstream signal
c	Lane group capacity (veh/h)
λ	Ratio of effective green time
q	Traffic flow (veh/h)
S_{obs}	Observed saturation flow rate (pcu/h)
S_{com}	Comparison saturation flow rate (pcu/h)
R	Correlation coefficient
R^2	Coefficient of determination
o_i	Observed value
e_i	Predicted value
S_P	Predicted saturation flow
S_{AF}	Saturation flow adjustment factor

LIST OF ABBREVIATIONS

pce	Passenger car equivalents
pcu/h	Passenger car units per hour
pcphpl	Passenger car per hour per lane
pcphgpl	Passenger car per hour green per lane
Vph	Vehicle per hour
Veh/h/l	Vehicle per hour per lane
pcuphg	Passenger car unit per hour green
tcu/h	Through car equivalent per hour
cpmsvl	Conflicts per million squared vehicles per lane
s/veh	Second per vehicle
Km/h	Kilometer per hour
TRB	Transportation Research Board
ARRB	Australian Road Research Board
TRRL	Transportation and Road Research Laboratory
US HCM 2000	United State Highway Capacity Manual 2000
IHCM	Indonesian Highway Capacity Manual
MHCM 2006	Malaysian Highway Capacity Manual 2006
VDDAS	Vehicle Detector Data Acquisition System
aaSIDRA	Akcelik and Associates, Traffic Signalised and Unsignalised Intersection Design and Research Aids
TPDM	Transport Planning Design Manual
BINKOT	Directorate of Urban Road Development
CBD	Central Business District
Non-CBD	Non Central Business District
SPSS	Statistical Package for the Social Science
ATJ	Arahan Teknik (Jalan)
PTRA	proportion of right-turning vehicles to the total vehicles in the

	studied approach
PSTA	proportion of straight-ahead vehicles to the total vehicles in the studied approach
PSTO	proportion of straight-ahead through vehicle to the total vehicle in the opposite approach in each cycle
RTO	Right-turning vehicle per cycle in the opposing direction
ITE	Institute of Transportation Engineers
LOS	Level of Service
ANOVA	Analysis of Variance
EB	Eastbound
WB	Westbound
NB	Northbound
SB	Southbound
RMSE	Root Mean Square Error
RMSE (%)	Root Mean Square Error Percentages
Sig.	Observed significance value

LIST OF APPENDICES

LIST OF PUBLICATIONS & SEMINARS

Conference

1 **Hossain**, Q.S., Wan Hashim, W.I., and Leong, L.V. (2006). “Effect of turning radius for right-turning vehicles on delay at signalised intersections”. Published in the *Malaysian Universities Transportation Research Forum Conference 2006 (MUTRFC 2006),* December 4-5, Selangor, Malaysia.

2 **Hossain**, Q.S., Wan Hashim, W.I., and Leong, L.V. (2006). “Estimation of left-turn adjustment factor at signalised intersection according to Malaysian traffic conditions”. Proceedings, *International Symposium on Lowland Technology 2006 (ISLT 2006),* September 14-16, Saga, Japan.

3 **Hossain**, Q.S., Wan Hashim, W.I., and Leong, L.V. (2006). “Estimation of right-turn adjustment factor at signalised intersections according to Malaysian traffic conditions, Proceedings, *1st Civil Engineering Colloquium 2006*, Department of Civil Engineering, University Science Malaysia, May 24-25, Malaysia.

4 Wan Hashim, W.I., and **Hossain**, Q.S. (2004). “Effect of permitted right-turn on the capacity of signalised intersection.” Proceedings, *National Civil Engineering Conference (AWAM 2004)*, School of Civil Engineering, Universiti Sains Malaysia, July, Malaysia.

Other publications

1 **Hossain,**Q.S., Kabir, M.E., Hossain, M.K., Liza, R., Wan Hashim, W.I., and Leong, L.V. (2005). “Characteristics and crash involvement of speeding, violating and thrill-seeking baby-taxi drivers in Khulna Metropolitan City, Bangladesh,” Proceedings, *Sixth Eastern Asia Society for Transportation Studies (EASTS) Conference – 2005*, September, Bangkok, Thailand.

2 **Hossain,** Q.S., Adhikary, S.K., Wan Hashim, W.I., and Rezaur, R.B. (2005). “Road Traffic Accident Situation in Khulna Metropolitan City, Bangladesh.” Proceedings, *Sixth Eastern Asia Society for Transportation Studies (EASTS) Conference – 2005*, September, Bangkok, Thailand.

3 **Hossain,** Q.S., Liza, R., Uddin, M.J. and Sen, A. (2005). “Study on Effect of non-motorized transport on the performance of road in Khulna metropolitan city,” Proceedings, *Third International Conference and Annual Paper Meet of the Civil Engineering Divisions*, Institution of Engineers, Bangladesh (IEB), March, Dhaka, Bangladesh.

4 Kabir, M.E., **Hossain,** Q.S., Wan Hashim, W.I., Liza, R., Hossain, M.K. and Kalam, M.S.U. (2004). “The Role of Baby-Taxi as a Mode of Passenger Transport in Khulna Metropolitan City, Bangladesh,” *Proceedings, Malaysian Universities Transportation Engineering Forum Conference 2004 (MUTRFC-2004),* December 1-2, Shah Alam, Malaysia.

5 **Hossain,** Q.S., Liza, R., Zahedi, M.I., Zaman, M.Q., and Kiyota, M. (2004). “The Role of Double Decker Buses as a Mode of Public Transport in Khulna Metropolitan City.” *Proceedings, International Symposium on Lowland Technology (ISLT),* September 1-3, Bangkok, Thailand.

PENGANGGARAN FAKTOR-FAKTOR PELARASAN PEMUSINGAN DI PERSIMPANGAN BERLAMPU ISYARAT MENGIKUT KEADAAN LALU LINTAS DI MALAYSIA

ABSTRAK

Pergerakan memusing di persimpangan berlampu isyarat telah menjadi perkara utama oleh perancang-perancang lalu lintas dan pihak berkuasa jalan untuk berdekad lamanya. Salah satu daripada faktor-faktor terpenting mempengaruhi aliran tepu di persimpangan keutamaan ialah lalu lintas memusing (pusing-kiri, pusing-kanan dan pusingan-U). Kehadiran kenderaan-kenderaan memusing telah menurunkan aliran tepu dan kapasiti serta menyebabkan kelengahan yang melampau di suatu persimpangan. Oleh kerana itu, penganggaran faktor pelarasan memusing diperlukan untuk membuat penilaian aliran tepu dan kapasiti yang jitu di persimpangan-persimpangan berlampu isyarat.

United States Highway Capacity Manual 2000 (U.S. HCM 2000) telah digunakan secara meluas di Malaysia untuk menganggar faktor-faktor pelarasan memusing (pusing-kiri dan pusing-kanan) dan lain-lain analisis berkaitan serta rekabentuk persimpangan-persimpangan berlampu isyarat. Baru-baru ini, Malaysian Highway Capacity Manual 2006 (MHCM 2006) telah diperkenalkan untuk tujuan ini. U.S. HCM 2000 dan MHCM 2006 yang sedia ada tidak mengambil kira radius pemusingan dalam pengiraan faktor-faktor pelarasan untuk pusing-kiri dan pusing-kanan. Tambahan pula, kesan-kesan pusingan-U tidak diasingkan dalam U.S. HCM 2000 dan MHCM 2006 di mana kenderaan-kenderaan pusingan-U dikira sebagai kenderaan-kenderaan pusing-kanan (pusing-kiri dalam U.S.A). Matlamat kajian ini ialah untuk menganggar faktor-faktor pelarasan pusing-kiri dan pusing-kanan daripada lorong-lorong berkongsi dan eksklusif dengan mengambil kira radius memusing dan kadar kenderaan memusing dan untuk menganggar faktor pelarasan pusingan-U daripada lorong berkongsi pusing-kanan dan pusingan-U untuk fasa terlindung di

persimpangan berlampu isyarat untuk keadaan trafik di Malaysia. Dalam pada itu, penilaian keselamatan untuk kemudahan-kemudahan pusingan-U menggunakan kajian konflik telah dijalankan dalam kajian ini.

Untuk menjalankan analisis, data lalu lintas telah dikumpulkan di persimpangan-persimpangan berlampu isyarat di beberapa bandar yang berbeza di Malaysia. Dalam kajian ini, sebanyak lapan belas persimpangan dengan lorong berkongsi dan pusing-kiri eksklusif, tiga puluh persimpangan dengan lorong berkongsi dan pusing-kanan eksklusif, serta tiga belas persimpangan dengan lorong berkongsi (pusing-kanan dan pusingan-U) dan pusingan-U eksklusif telah dipilih. Perakam kaset audio telah digunakan dalam pengumpulan data lalu lintas. Kelebihan menggunakan perakam kaset audio adalah masa yang telibat dalam analisis adalah agak pendek dan bilangan lokasi kajian yang banyak boleh dikaji. Data yang dirakamkan dipindah dari kaset audio ke komputer menggunakan perisian BancianVer 2001.

Faktor-faktor pelarasan pusing-kiri, pusing-kanan dan pusingan-U dianggarkan menggunakan analisis regresi. Hasil yang diperolehi menunjukkan bahawa faktor-faktor pelarasan pusing-kiri dan pusing-kanan berkurang apabila kadar kenderaan memusing meningkat dan apabila radius memusing berkurang. Faktor-faktor pelarasan pusing-kiri dan pusing-kanan yang telah dianggarkan menggunakan kaedah yang dicadangkan dalam kajian ini memberikan nilai yang lebih tinggi daripada nilai dalam MHCM 2006. Hasil yang diperolehi untuk faktor pelarasan pusingan-U pula menunjukkan nilai faktor ini berkurang dengan peningkatan kadar kenderaan yang membuat pusingan-U. Hasil kajian menunjukkan pada puratanya bahawa faktor pelarasan pusingan-U menurun 2.25% untuk setiap kenaikan 10% peratusan pusingan-U. Turut didapati bahawa konflik harian pusingan-U dengan pusing-kiri yang berkonflik dari lorong-lorong bertentangan adalah 1.4 kali lebih daripada konflik-konflik pusingan-U sama arah.

Akhir sekali, penemuan-penemuan dalam kajian ini menunjukkan bahawa kaedah yang dicadangkan untuk menganggar faktor-faktor pelarasan memusing adalah lebih jitu. Tambahan pula, ianya lebih mudah difahami. Faktor-faktor pelarasan ini mampu meramal aliran-aliran tepu dengan lebih tepat yang mana mewakili keadaan jalan dan lalu lintas sebenar di Malaysia.

ESTIMATION OF TURNING ADJUSTMENT FACTORS AT SIGNALISED INTERSECTIONS ACCORDING TO MALAYSIAN TRAFFIC CONDITIONS

ABSTRACT

Turning movements at signalised intersections have been a major concern of traffic planners and road authorities for decades. One of the most important factors affecting the saturation flow at signalised intersection is turning (left-turn, right-turn and U-turn) traffic. The presence of turning vehicles tends to lower the saturation flow as well as the capacity and cause excessive delay at an intersection. Because of this the estimation of turning adjustment factor is required to make accurate assessments of the saturation flow as well as capacity of intersections.

The United States Highway Capacity Manual 2000 (US HCM 2000) has been extensively used in Malaysia to estimate the turning adjustment factors (left-turn and right-turn) and other related analysis and design at signalised intersections. Recently the Malaysian Highway Capacity Manual 2006 (MHCM 2006) has been introduced used for this purpose. The existing US HCM 2000 and the MHCM 2006 do not take into consideration the turning radius for the estimation of left-turn and right-turn adjustment factors. The effects of U-turns are not separated in both manuals (US HCM 2000 and MHCM 2006) where the U-turning vehicles are considered as right-turning vehicles (left-turn in U.S.A.) The aim of this study is to estimate the left-turn and right-turn adjustment factors from shared and exclusive lanes considering turning radius and proportion of turning vehicles and to estimate the U-turn adjustment factor from share right and U-turn lane for protected phasing at signalised intersection according to Malaysian traffic conditions.

To carry out analysis, traffic data were collected at signalised intersections in different cities in Malaysia. In this study, eighteen intersections with shared and

excusive left-turn lanes, thirty intersections with shared and exclusive right-turn lanes, and thirteen intersections with shared (exclusive right-turn with U-turn) and exclusive U-turn lanes were selected. Audio cassette recorder was used to collect the traffic data. The advantage of using audio cassette recorder is that the time involved in analysis is fairly short and large number of sites can be studied. Recorded data were transferred from audio cassette to computer using the software *BancianVer* 2001.

The left-turn, right-turn and U-turn adjustment factors are estimated using regression analysis. The results indicate that the left-turn and right-turn adjustment factors decreases as the proportion of turning vehicles increases and the turning radius decreases. The estimated left-turn and right-turn adjustment factors using the proposed method give higher value than that of the MHCM 2006. The results of the U-turn adjustment factor show that the U-turn adjustment factor decreases with an increase of proportion of U-turning vehicles. The study results show that on average the U-turn adjustment factor decreases 2.25% for every 10% increase of U-turn percentage. It is also found that the daily conflict of U-turn with conflicting left-turn from opposite lanes is 1.4 times more than the U-turn same direction conflicts.

Finally, the findings of this study indicate that the proposed method for estimating the turning adjustment factors is found more accurate. Moreover, it is simple enough to understand. These adjustment factors are able to forecast the saturation flows precisely which represents the actual traffic and roadway conditions in Malaysia.

CHAPTER 1
INTRODUCTION

1.1 Background

Turning movements at signalised intersections have been a major concern of traffic planners and road authorities for decades. An at-grade urban intersection is one of the important elements of road design and operation. The analysis of capacity for intersections differs greatly from that of roads. On straight roads, it is assumed that flow will be uninterrupted and vehicles don’t have to stop. But, in the case of intersections, vehicles are required to stop for traffic signs and signals. Moreover, the capacity of a road is influenced only by parameters for the road itself, whereas the capacity of an intersection is affected by the parameters of all the roads meeting at an intersection (Chandra et al., 1994). Thus capacity analysis for an intersection is more complex than for a road segment. Saturation flow is the most important single parameter in the capacity analysis of signalised intersections (Akcelik, 1981).

One of the most important factors affecting the capacity of a signalised intersection is turning traffic, its volume, and how it is controlled in the intersection. When the turning (left-turn and right-turn) movement is independent of through movements, saturation flow for the intersection is affected by the amount or proportion of cycle time allocated for the turning vehicles and by the provision of separate lanes for turning (left-turn and right-turn) vehicles (Chang et al., 1994). When the turning lane (left-turn and right-turn) is combined with straight movement, the turning traffic interferes with the movement of through vehicles. The saturation flow of the intersection is reduced (Chandra et al., 1994). As the saturation flow decreases due to turning vehicles, the capacity of the intersections becomes lower. Moreover, the presence of turning vehicles causes excessive delay, and increases the accident potential as traffic volume increases. According to Kimber et al. (1986), the saturation flow of the mixed traffic (turning and through) depends on the turning radius and proportion of turning vehicles. For individual lane consisting of unopposed turning traffic, saturation flow decreases for higher proportions of turning traffic and lower turning radius (Kimber et al., 1986). This indicates that the left-turn and right-turn adjustment factors must be estimated considering the proportion of turning vehicle and turning radius. However, the United States Highway Capacity Manual 2000 (US HCM 2000) (Transportation Research Board (TRB), 2000) did not take into consideration the turning radius in the estimation of left-turn and right-turn adjustment factors.

The left-turn and right-turn adjustment factors currently used in the design and analysis of signalised intersections in Malaysia are based on the factors given in the Arahan Teknik (Jalan) 13/87 (Jabatan Kerja Raya, 1987). According to the Arahan Teknik (Jalan) 13/87, the left-turn and right-turn adjustment factors for shared lanes at signalised intersections depend on the percentage of turning traffic. These factors increase as the percentage of turning vehicles decreases. In addition, the adjustment factors are included for exclusive turning traffic in order to take into consideration the effect of turning radius. Currently, the engineers and practitioners are adopting the US HCM 2000 (TRB, 2000) for analysis purposes, since the US HCM 2000 (TRB, 2000) recommends more details and flexible methods of analysis. According to TRB (2000), the left-turn (right-turn in Malaysia) and right-turn (left-turn in Malaysia) adjustment factors with protected phasing at signalised intersections for exclusive lanes is 0.95 and 0.85, respectively.

Recently, the Ministry of Works Malaysia (2006) proposed equations for left-turn and right-turn adjustment factors. According to the Ministry of Works Malaysia (2006), the left-turn and right-turn adjustment factor with protected phasing at signalised intersections for exclusive lanes is 0.84 and 0.76, respectively. For the shared lanes, the adjustment factors decrease as the proportion of turning vehicles increases.

The increase in population is accompanied by an increase in the number of vehicles and drivers on roadways. As traffic volumes continue to increase, more roads with dividers are constructed. One of the primary purposes of a median is to improve road safety by redirecting large volumes of left-turning (right-turn in Malaysia) into driveways. By dividing a road with a median, some vehicles must proceed to the next intersection and they make U-turn if want to access the other side of the road. As a result, U-turn volumes usually are expected to increase at signalised intersections where the road is divided using raised medians.

As more U-turning vehicles use a right-turn lane, the saturation flow rate for the lane may become significantly lower (Adams and Hummer, 1993). However, the US HCM 2000 (TRB, 2000) does not account for U-turns in calculating the capacity and level of service of a right-turn lane group at a signalised intersection. Due to this reason, the US HCM 2000 (TRB, 2000) does not give an adjustment factors for right-turn lanes that accommodate a large number of U-turning vehicles. In Malaysia, there are some right-turn lanes where U-turns are allowed. Different percentage of U-turning vehicles at signalised intersections might have different impact on U-turn adjustment factor as well as saturation flow estimation and therefore it should be investigated thoroughly. It is clear that the operational effects of U-turns could be a major factor in the design decision (Adams and Hummer, 1993). However, past research has not conclusively addressed this issue. This study provides the operational effects of U-turn traffic from right-turn lanes at signalised intersections according to Malaysian traffic conditions.

1.2 Problem Statement

Although much has been written about roadway capacity, the need to estimate the turning (left-turn, right-turn and U-turn) adjustment factors of the saturation flow at signalised intersections according to Malaysian traffic conditions still exist. This research deals with the estimation of turning (left-turn, right-turn and U-turn) adjustment factors at signalised intersections. In Malaysia, highway and traffic related design and analysis is based on the Arahan Teknik (Jalan) 13/87 (Jabatan Kerja Raya, 1987). This is based on the method developed by Webster and Cobbe (1966). However, relevant authorities in Malaysia have also been referring to the US HCM 2000 (TRB, 2000) in the design and analysis of signalised intersections. Nevertheless, due to certain distinct difference such as road system, vehicle composition and urban travel behaviour between traffic conditions in Malaysia and in the United States, this manual may not be representative of local traffic conditions in Malaysia (Wan Hashim et al., 2002).

Moreover, the left-turn and right-turn adjustment factors currently used in Malaysia are based on the values of the Arahan Teknik (Jalan) 13/87 (Jabatan Kerja Raya, 1987) which is slightly modified based on the Webster and Cobbe (1966) in UK. These values may not be representative of the current traffic conditions as well as travel behaviour of road users in Malaysia (Leong, 2004).

The left-turn and right-turn adjustment factors based on Malaysian traffic conditions had been considered in the Malaysian Highway Capacity Manual 2006 (MHCM 2006) (Ministry of Works Malaysia, 2006). However, the methodology developed did not take into consideration the turning radius in order to estimate the left-turn and right-turn adjustment factors.

The presence of U-turn traffic may affect the saturation flow rate as well as capacity at signalised intersection. However, no consideration is being given to U-turn adjustment factor in the design aspect of signalised intersections in Malaysia till to date. This may results in an inaccurate design of signalised intersection thus causing significant amount of traffic congestion and delay.

1.3 Objectives of the Study

The aim of this research is to estimate the turning adjustment factors at signalised intersection with respect to Malaysian traffic conditions. The objectives of this study are as follows:

a) To estimate the left-turn adjustment factor at signalised intersections.

b) To estimate the right-turn adjustment factor at signalised intersections.

c) To investigate the effect of turning radius on left-turn and right-turn adjustment factors at signalised intersections.

d) To investigate the effect of vehicle compositions on left-turn and right-turn adjustment factors at signalised intersections.

e) To estimate the U-turn adjustment factors and also study the effects of U-turn on right-turn saturation flow rates.

1.4 Scope of the Study

Vehicles headway data were collected for shared and exclusive lanes of turning traffic at signalised intersections in Central Business District (CBD) and non-CBD area throughout Malaysia. In this study, individual lanes for each type of turning traffic were considered. Geometric parameters for the intersections such as lane width, gradient, receiving lane width, and turning radius were measured. The vehicles headways were collected during peak period. The left-turn, right-turn, and U-turn adjustment factors were estimated using the regression analysis. The effects of turning radius and vehicle compositions on left-turn and right-turn adjustment factors were investigated and included the turning radius in the equation of left-turn and right-turn adjustment factors. Only the proportion of U-turning vehicles was considered in the estimation procedure of U-turn adjustment factor. The predicted saturation flow rate using the adjustment factor developed in this study and other Highway Capacity Manuals were compared with the observed saturation flow rate in the field.

1.5 Organization of the Thesis

This thesis consists of seven chapters. The contents of the following chapters are outlined here. The first chapter deals with the introduction to the problem undertaken in the thesis and its arrangement. The statement of the objectives and scope of the thesis are also presented. The second chapter discusses the relevant literature related to this study. The third chapter describes the methodologies use to achieve the objectives of the study. This chapter also describes the criteria for site selection and the procedure followed to complete data collection in an efficient and appropriate manner. The estimation of left-turn, right-turn and U-turn adjustment factors at signalised intersections are described in Chapter 4, 5 and 6, respectively. Statistical evaluation of the results for the left-turn, right-turn and U-turn adjustment factors are also included. Conclusions drawn from this research are summarised in Chapter 7. They are presented for each step of research. This chapter also provides some recommendations for future research.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

As noted in the previous chapter that the objectives of this study is to estimate the turning adjustment factors (left-turn, right-turn and U-turn) at signalised intersections for Malaysian traffic conditions. The literature review, therefore, has focused on the estimation of the left-turn, right-turn and U-turn adjustment factors which exist throughout the world. The existing published materials related to left-turn and right-turn adjustment factors in the United States Highway Capacity Manual 2000 (TRB, 2000), the Canadian Capacity Guide for Signalised Intersections (Teply et al., 1995), the Indonesian Highway Capacity Manual (IHCM) (BINKOT, 1996), the MHCM 2006 (Ministry of Works Malaysia, 2006), the Arahan Teknik (Jalan) 13/87 (Jabatan Kerja Raya, 1987), and the Transportation and Road Research Laboratory, United Kingdom (Webster and Cobbe, 1966) deal mainly with the proportion of turning vehicles. But in the Australian Road Research Board (Akcelik, 1981; 2000) uses the through car equivalents (tcu) for different types of vehicle and turn instead of proportion of turning vehicles. Moreover, Kimber et al. (1986) relate the proportion of turning vehicles and turning radius to estimate the left-turn and right-turn adjustment factors. Few researchers have looked into the relationship between the U-turn adjustment factor and proportion of U-turning vehicles. However, the U-turn adjustment factor has not yet been included in the Highway Capacity Manual anywhere in the world. The literature review will provide information needed to develop the turning adjustment factors.

Section 2.2 of this chapter discusses the concept of saturation flow to estimate the adjustment factors of turning traffic at a signalised intersection. The saturation flow prediction formulas for different Highway Capacity Manuals are described in section

2.3. Section 2.4 discusses the saturation flow rate measurement techniques. It is essential to know the concept of saturation flow, its measurement and data collection technique to estimate the left-turn, right-turn and U-turn adjustment factors. Initially, concept of saturation flow, the measurement of saturation flow rate and method of data collection are presented. The methods of data collection in the field are discussed in section 2.5. Subsequently, different methods of the left-turn and right-turn adjustment factors are presented in section 2.6. The previous studies of U-turn adjustment factors are discussed in section 2.7. Various studies that have attempted to characterize the impact of turning traffic on saturation flow rate are presented. In addition, various modelling approaches of turning traffic are presented. Finally, section 2.8 concludes this chapter.

2.2 Concept of Saturation Flow

Saturation flow is a macro performance measure of junction operation. It is an indication of the potential capacity of a junction when operating under ideal conditions (Turner and Harahap, 1993). An idealized view of saturation flow at signalised intersection is illustrated in Figure 2.1. As the traffic signal becomes green, there is a short gap between the reaction time of the two consecutive vehicle drivers. The rate of vehicles crossing the stop line then rises at an increasing rate, as vehicles accelerate to the speed determined by the cars they are following. Vehicles soon reach a state where they are following one another across the stop line at a constant gap or headway. This constant rate is represented by the area of stability of this flow profile. In a saturated junction, when the lights are red, the queues formed are usually too long to clear in the green period. Therefore, cars follow each other at constant spacing during the green period. The flow rate will only drop as the light gets amber and then stop as the light gets red. The saturation flow rate is calculated by transforming the curved profile into a rectangular one (Fig.2.1), from which the height and width of the profile can be measured. This is achieved by introducing the idea of lost time and effective green time. The lost time is the time equal to the combined green and amber periods minus the effective green time.

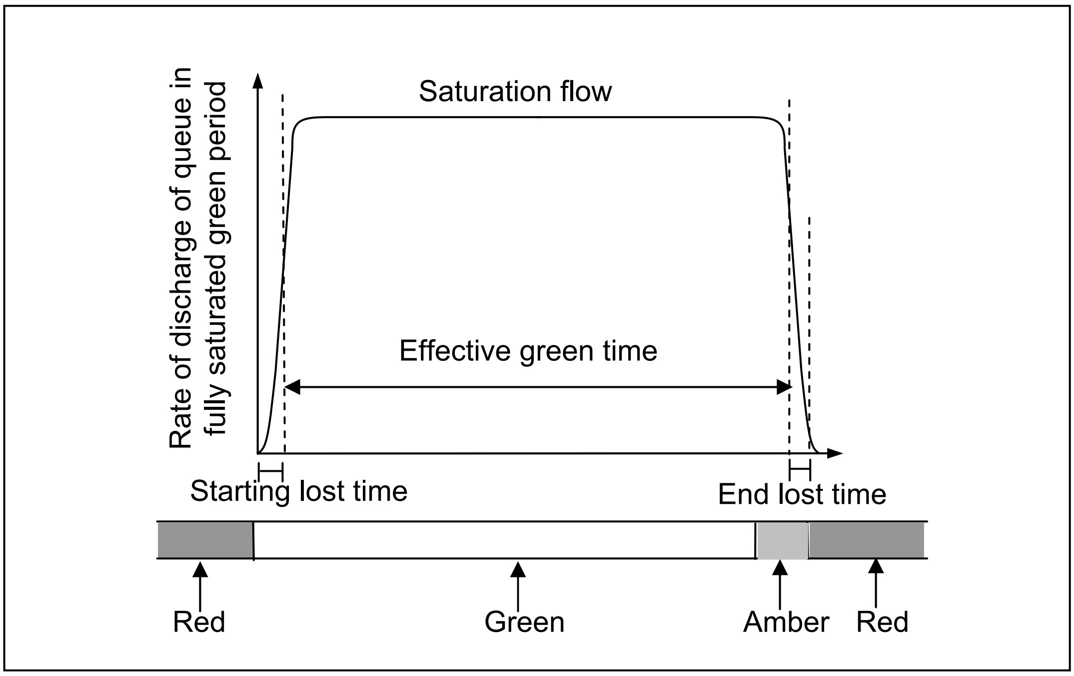

Figure 2.1: Graphical presentation of saturation flow (Kimber et al., 1986)

The US HCM 2000 (TRB, 2000) describes saturation flow rate at a signalised intersection as the maximum constant departure rate from the queue during the green period, and it remains constant until the green periods end under prevailing roadway and traffic conditions. It is expressed as vehicles per hour of effective green time (vphg).

The Transportation and Road Research Laboratory (TRRL) (1963) defines saturation flow rate as the constant rate of flow when the queue of vehicles discharges after the initial acceleration to running speed during green period. It is usually expressed in vehicles per hour of green time (vphg).

Teply et al. (1995) defines saturation flow rate as the rate at which vehicles that have been waiting in a queue during the red interval cross the stop line of a signalised intersection approach lane during the green interval. It is usually expressed in passenger car units per hour of green (pcuphg).

However, Akcelik (1981) defines saturation flow as the maximum constant departure rate from the queue during the green period. It is usually expressed in through car units per hour (tcuph).

According to Webster and Cobbe (1966), the saturation flow rate is the flow which can be obtained if there is a constant queue of vehicles when 100 percent green time is available. It is generally expressed in vehicles per hour of green (vphg).

The maximum flow, stated as equivalent passenger cars which can cross the stop line of the approach where a continuous green signal and continuous queue of vehicles on the approach are present is known as saturation flow (Jabatan Kerja Raya, 1987). Basic saturation flow is expressed in passenger car units per hour (pcuph).

The MHCM 2006 (Ministry of Works Malaysia, 2006) describes the saturation flow as the maximum constant departure rate of queue from the stop line of an approach lane during the green period.

These definitions do not indicate that there is a continuous hour of green, but involve the usual stopping and moving operation for the normally used range of cycle times and green intervals. All the definitions are based on the conventional graphical representation of saturation flow as shown in Figure 2.1. It is assumed in the traditional concept that after an initial hesitation at the beginning of the green interval, vehicle discharges at a constant rate until the queue is exhausted or shortly after the beginning of amber. The average rate of flow is lower during the first few seconds as vehicles accelerate to normal running speed and during the amber period as the flow of vehicles declines (Akcelik, 1981; Teply and Jones, 1991).

All of the above mentioned documents agree that the variability of saturation flows caused by various roadway and traffic conditions in different countries. The key difference among these documents is the treatment of traffic compositions. Teply et al. (1995), the Arahan Teknik (Jalan) 13/87 (Jabatan Kerja Raya, 1987), and the IHCM (BINKOT, 1996) suggest that it is convenient to convert all volumes of individual vehicles into passenger car units. However, for the US HCM 2000 (TRB, 2000), the ARRB (Akcelik, 1981), and the MHCM 2006 (Ministry of Works Malaysia, 2006) consider the saturation flow rate in vehicle per hour, applying different adjustment factors including the traffic composition factor. All of these documents include the turning adjustment factors in order to take into consideration the effect of turning vehicles.

2.3 Saturation Flow Prediction Formulas

Saturation flow is the key factor in the capacity analysis of signalised intersections. A number of semi-empirical equations have been proposed for estimating the saturation flow rate at signalised intersections. In estimating saturation flow rates, adjustment factors are applied to account for the effects of roadway, vehicle composition and turning percentages other than the saturation flow rates under ideal conditions. According to the US HCM 2000 (TRB, 2000), the saturation flow rate at a signalised intersection can be calculated using Equation (2.1).

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

where,

S = prevailing saturation flow rate in the lane group in vphg;

S_0 = ideal saturation flow rate per lane which is 1900 pcuphpl;

N = number of lanes in the lane group;

f_{HV} = adjustment factor for heavy vehicles

$\left(f_{HV} = \dfrac{100}{100 + \%HV(E_T - 1)} \right)$; where $E_T = 2.0 pc / HV$

f_w = adjustment factor for lane width $\left(f_w = 1 + \dfrac{w - 3.6}{9} \right)$;

f_g = adjustment factor for approach grade $\left(f_g = 1 - \dfrac{\%G}{200} \right)$;

f_p = adjustment factor for the existence of parking activities in a parking lane $\left(f_p = \dfrac{N - 0.1 - \dfrac{18 \times N_m}{3600}}{N} \right)$ where N_m is the number of parking maneuvers per hour;

f_{bb} = adjustment factor for the blocking effect of local buses stopping within the intersection area $\left(f_{bb} = \dfrac{N - \dfrac{14.4 \times N_B}{3600}}{N} \right)$ where N_B is the number of buses stopping per hour;

f_a = adjustment factor for area type ($f_a = 0.90$ in CBD and $f_a = 1.00$ in non-CBD);

f_{LU} = adjustment factor for lane utilization $\left(f_{LU} = \dfrac{V_g}{V_{g1} \times N} \right)$, where V_g is the unadjusted demand flow rate for the lane group (vph) and V_{g1} is the unadjusted demand flow rate on the single lane in the lane group with the highest volume;

f_{RT} = adjustment factor for right-turns in lane group $\left(f_{RT} = 1.0 - 0.15 \times P_{RT} \right)$ where,

P_{RT} = proportion of right-turns in lane group;

f_{LT} = adjustment factor for left-turn in lane group $\left(f_{LT} = \frac{1}{1.0 + 0.05 \times P_{LT}} \right)$ where, P_{LT} = proportion of left-turns in lane group;

f_{Lpb} = pedestrian adjustment factor for left-turn movements $\left(f_{L\,pb} = 1.0 - P_{LT}(1 - A_{pbT})(1 - P_{LTA} \right)$ where, A_{pbT} = permitted phase adjustment and P_{LTA} = proportion of left-turn protected green over total left-turn green; and

f_{Rpb} = pedestrian adjustment factor for right-turn movements $\left(f_{Rpb} = 1.0 - P_{RT}(1 - A_{pbT})(1 - P_{RTA}) \right)$ where, P_{RTA} = proportion of right-turn protected green over total right-turn green.

According to the TRRL (Kimber et al., 1986), the equation used to predict the saturation flow rate is as shown in Equation (2.2).

$$S = \frac{2080 - 140 \times \delta_n - 42 \times \delta_G \times G + 100 \times (w - 3.25)}{1 + 1.5 \frac{f}{r}} \qquad (2.2)$$

where,

S = saturation flow in pcuph;

δ_n = 0 for non-nearside lane (right-turn) and one (1.0) for nearside lane (left-turn);

δ_G = 1.0 for uphill and zero (0) for downhill gradient;

G = gradient (%);

w = lane width (meter);

f = proportion of turning (left-turn, P_{LT} or right-turn, P_{RT}) traffic; and

r = turning radius (meter).

For the Arahan Teknik (Jalan) 13/87 (Jabatan Kerja Raya, 1987), the saturation flow is estimated using Equation (2.3).

$$S = S_0 \times f_g \times f_t \times f_{LT} \times f_{RT} \qquad (2.3)$$

where,

S = estimated saturation flow in pcuph;

S_0 = $525 \times w$ for effective approach width (w) more than 5.5 m and Table 2.1 is for the effective approach width less than 5.5 m;

f_g = correction factor for the effect of gradient (Table 2.2);

f_t = correction factor for the effect of turning radius (Table 2.11) ;

f_{LT} = correction factor for left-turning traffic (Table 2.12); and

f_{RT} = correction factor for right-turning traffic (Table 2.12).

Based on the findings of the Arahan Teknik (Jalan) 13/87 (Jabatan Kerja Raya, 1987), the relationship between effective lane width and saturation flow rate and the correction factor for the effect of gradient are shown in Table 2.1 and Table 2.2, respectively.

Table 2.1: Relationship between effective lane width and saturation flow rate (Jabatan Kerja Raya, 1987)

***w* (m)**	3.00	3.25	3.50	3.75	4.00	4.25	4.50	4.75	5.00	5.25
S_0 (pcuph)	1845	1860	1885	1915	1965	2075	2210	2375	2560	2760

Table2.2: Correction factor for the effect of gradient (Jabatan Kerja Raya, 1987)

Description	**Correction factor (f_g)**
For upward slope of 5%	0.85
For upward slope of 4%	0.88
For upward slope of 3%	0.91
For upward slope of 2%	0.94
For upward slope of 1%	0.97
For level grade	1.00
For downward slope of 5%	1.03
For downward slope of 5%	1.06
For downward slope of 5%	1.09
For downward slope of 5%	0.12
For downward slope of 5%	1.15

Based on the IHCM (BINKOT, 1996), the equation adopted for protected phasing to determine the saturation flow rate is as shown in Equation (2.4).

$$S = 600 \times w \times f_{CS} \times f_{SF} \times f_g \times f_p \times f_{LT} \times f_{RT} \qquad (2.4)$$

where,

S = estimated saturation flow in pcuph;

w = effective lane width;

f_{CS} = correction factor for the effect of city size (Table 2.3);

f_{SF} = correction factor for the effect of side friction (Table 2.4);

f_g = correction factor for the effect of gradient (Table 2.5);

f_p = correction factor for the effect of parking activities $\left[f_p = \left(\frac{L_p}{3} - (W_A - 2) \times (\frac{L_p}{3} - g)/W_A \right) / g \right]$ where, L_p = distance between stop line and first parked vehicles (m), W_A = width of the approach (m), and g = green time of the approach;

f_{RT} = correction factor for right-turn $\left(f_{RT} = 1.0 + 0.26 \times P_{RT} \right)$; and

f_{LT} = correction factor for left-turn $\left(f_{LT} = 1.0 - 0.16 \times P_{LT} \right)$.

According to the IHCM (BINKOT, 1996), the correction factor for city size, side friction and gradient are shown in Table 2.3, 2.4, and 2.5 respectively.

Table 2.3: Correction factor for the effect of city size (f_{CS}) (BINKOT, 1996)

City population (Millions)	**Correction factor (f_{CS})**
> 3.0	1.05
1.0 – 3.0	1.00
0.3 – 1.0	0.94
< 0.3	0.83

Table2.4: Correction factor for side friction (f_{SF}) (BINKOT, 1996)

Road environment	**Correction factor (f_{SF})**	
	High side friction	Low side friction
Commercial	0.94	1.00
Residential	0.97	1.00
Restricted access	1.00	1.00

Table 2.5: Correction factor for the effect of gradient (BINKOT, 1996)

Description	**Correction factor (f_g)**
For upward slope of 10%	0.90
For upward slope of 8%	0.92
For upward slope of 6%	0.94
For upward slope of 4%	0.96
For upward slope of 2%	0.98
For level grade	1.00
For downward slope of 2%	1.01
For downward slope of 4%	1.02
For downward slope of 6%	1.03
For downward slope of 8%	1.04
For downward slope of 10%	1.06

According to the MHCM 2006 (Ministry of Works Malaysia, 2006), the saturation flow rate under prevailing conditions is estimated using Equation (2.5). For Malaysian traffic condition, difference in vehicles composition is taken into consideration using the correction factor, f_c.

$$S = S_0 \times N \times f_w \times f_g \times f_a \times f_{LT} \times f_{RT} \times (1/f_c) \quad (2.5)$$

where,

S = saturation flow rate under prevailing conditions, expressed in vehicle per hour of green;

S_0 = ideal saturation flow rate which is 1930 pcuphpl;

N = number of lanes in lane group;

f_w = adjustment factor for lane width $\left(f_w = 1 + \frac{w - 3.66}{3.663} \right)$;

f_g = adjustment factor for approach grade,

$\left(f_g = 1 - \frac{\%G}{26.34} \right)$ for downhill and $\left(f_g = 1 - \frac{\%G}{14.39} \right)$ for uphill;

f_a = adjustment factor for area type ($f_a = 1.0$ in Non-CBD, $f_a = 0.8454$ in CBD);

f_{RT} = adjustment factor for right-turns in lane group

$\left(f_{RT} = \frac{1}{1 + 0.195 \times P_{RT}} \right)$;

f_{LT} = adjustment factor for left-turns in lane group $\left(f_{LT} = 1 - 0.243 \times P_{LT} \right)$;

f_c = vehicle composition correction factor $\left(f_c = f_{car} + f_{HV} + f_{motor} \right)$

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

f_{car} = adjustment factor for passenger cars; and

f_{motor} = adjustment factor for motorcycles.

2.4 Saturation Flow Measurement Methods

The saturation flow rate usually achieved when the fourth to sixth passenger car crossing the stop line after the green starts (TRB, 2000). Vehicles are recorded when the front axles of the vehicles cross the stop line. The measurement of saturation flow begins when the front axle of the fourth vehicle in the queue crosses the stop line and ends when the front axle of the last queued vehicle crosses the stop line. In this method, the average headway per vehicle under saturation flow is obtained using the sum of all headways between the last and the fourth vehicle in the queue divided by the number of headways after the fourth vehicle. The time recorded for the fourth vehicle is subtracted from the time recorded for the last vehicle in the queue is the sum of all headways. The reciprocal of the average headway per vehicles will give the saturation flow rate.

The TRRL (1963) method consists in dividing the green and amber period during saturation flow into small intervals of time (0.1 minute usually). Using stop watch, the number, type and turning or straight-ahead movement of each vehicle crossing the stop line during each succession of 0.1 minute interval of green and amber period are noted. Towards the end of the amber period, there will be normally an interval of less than 0.1 minute. The length of this interval and also the number and type of vehicles crossing the stop line in this interval are noted. This interval is referred to as the last saturated interval. The vehicles discharge during the first and last saturated intervals are usually less than the remaining intervals. Therefore, the flow during the remainder of the observed periods represented the maximum discharge possible and the mean value gives the saturation flow for the approach. In the analysis, only saturated intervals are considered. The initial interval of each period is used to determine the lost time at the beginning of green. The average last interval in fully saturated green periods is similarly used to determine the lost time at the end of the green. The sum of these two components of lost times gives the total lost time for the approach. Teply et al. (1995) used the passages of the front bumper over the stop line as the time of discharge, primarily because it is consistent with the usual definition of headway. The US HCM 2000 (TRB, 2000) and the ARRB (Akcelik, 1981) reports are based on the determination of the average headways during a defined portion of the green interval. The portion of this green time starts when the fourth vehicle passes the stop line in case of the US HCM 2000 (TRB, 2000) method and after 10 seconds of green in the ARRB (Akcelik, 1981) method and the Teply et al. (1995) method includes the entire initial period of green. This study applies to the TRRL (1963) method to measure the saturation flow as the traffic is heterogeneous in character such as in UK and Malaysia.

Headway-based methods have been popular in Continental Europe, although the definitions of reference line and the part of the vehicle discharge from queue vary (Branston, 1979). Whereas, most of the British work consistently applies the TRRL (1963) method.

Practically, the exact end of saturation period is difficult to determine. According to Lam (1994), the general rule for determining the end of saturation is to note the time of last vehicle joining a queue at the approach. A fully saturated cycle is the one in which the queue has not fully discharged at the beginning of the red interval.

2.5 Data Collection Methods for Saturation Flow

There are several methods for collecting saturation flow data in the field. Video and film have been used for data collection, but extraction of the data is often performed manually or semi automatically (Sosin, 1980; Wood, 1986). Recently, Rongviriyapanich and Suppattrakul (2005) used video camera in their research to collect the discharge headway of passenger cars and motorcycles at the accuracy of 0.01 sec in north Bangkok, Thailand. Data were abstracted using an image processing technique. This method is found to be less accurate. The main error in this method is due to dark vehicles being missed. The probability of this error is a function of the quality of the video recording and the capability of the image processor. If the video image is not of top quality or if the image processor sensitivity and balance controls are not optimally set, some darker vehicles may be missed. Also, the unclear view of the video camera by a large vehicle in the adjacent lane often results in three or four vehicles, especially motorcycles being missed (Cuddon and Bennett, 1988).

Another method of collecting saturation flow data is as discussed by Miller (1968a). An audio cassette recorder was used to collect the data. The recorded event was the crossing of the stop line by the rear axle of each vehicle. This is because the first vehicle in the queue frequently stops over the stop line. Other relevant events, such as beginning and end of the green phase, and the vehicle type were also recorded. This method was said to be fast and accurate, particularly as the observer had only a single task to perform in the field. The end of saturation flow was defined as when the last vehicle which had been stopped or almost stopped in the queue had crossed the stop line. The accuracy of this method is adequate for most purposes (Miller, 1968a).

Apart from audio cassette method, pen recorder method was also used to measure the saturation flow rate. A light-sensitive resistance was attached to the lens of green signal and a tape switch was placed across each lane about six feet over the stop line. The signal received from these detectors was recorded on an Esterline-Angus 20-pen recorder. Using this method it was possible to read times of events from the chart to accuracy of about 0.1 sec. Push buttons were used to record trucks and turning vehicles on the charts, and to record interruptions. The disadvantage of this method was that it required several days work to read the information from a chart (Miller, 1968a).

However, ARRB VDDAS (Vehicle Detector Data Acquisition System) can also be used to measure saturation flow rate. The VDDAS method is the most suited to measure the saturation flow rate. Accuracy is said to be high but the problem is that the VDDAS method cannot determine the start-up lost time. In addition, this method is not suitable where few commercial vehicles are present because due to their signal profile from the detected loop, passage of two vehicles may be recorded instead of each commercial vehicle (Cuddon and Bennett, 1988). Therefore, VDDAS is probably not suitable method to be used in Malaysia because more than half of the registered vehicles in Malaysia are motorcycles and normally VDDAS is unable to detect the motorcycles as most of the time motorcyclists try to avoid crossing the detector treadle (Leong, 2004).

Audio cassette recorder method is suitable for this study. Because the time involved in analysis is fairly short and large number of sites can be studied within a short period of time. The data from a tape can be read off, analyzed and checked by one person in a few hours.

2.6 Adjustment Factor for Left-turn and Right-turn Traffic

In estimating the saturation flow rates, adjustment factors are applied to account for the effects of roadway, vehicle composition, turning proportions and other influencing factors. The adjustment factor for left-turn and right-turns are of great importance in the determination of saturation flow rate and is related to whether left-turns and right-turns are executed on a protected or a permitted phasing and whether they are accommodated in an exclusive lane or in a shared lane. This section provides an overview of methods used to estimate left-turn and right-turn adjustment factors at signalised intersections.

2.6.1 European Approaches

Archer et al. (1963) studied on the effect of turning vehicles on saturation flows on six approaches in London. Basically, two values were compared in this study:

- the observed straight-ahead saturation flow rate in pcuph

● average saturation flow rate of all traffic (including left and right turning vehicles) in pcuph

The difference in saturation flow rate between all straight-ahead and all vehicles (straight-ahead, left and right-turning) was represented using Equation (2.6).

$$P_{LT} \times \alpha + P_{RT} \times \beta = K \qquad (2.6)$$

where,

K = effect of all turning vehicles in reducing the through saturation flow rate;

P_{LT} = percentage of left-turning vehicles;

P_{RT} = percentages of right-turning vehicles;

α = the capacity ratio of one left-turning passenger car unit's (pcu) to one straight ahead pcu; and

β = the capacity ratio of one right-turning pcu to one straight ahead pcu.

The value of K was determined by the percentage of difference in saturation flow rate between observed straight-ahead and observed all traffic (including left and right turners).

Archer et al. (1963) concluded that the passenger car unit (pcu) for left-turning was 1.25 and for right-turning was 1.75. It was also indicated that an increase of 15 percent on saturation flow rate for approaches whose traffic was well disciplined by lane markings and a reduction of 12 percent for those with no lane markings.

Webster (1964) investigated the effect of right-turning vehicles in traffic signals in Crowthorne, London using a track experiment. The headway ratio method was used to observe the headway between straight-ahead and right-turning in a standard composition of 75 percent lights and 25 percent heavy vehicles. According to him, the saturation flow equation of right-turning vehicles for single lane and double lanes is as shown in Equation (2.7) and (2.8), respectively.

$$S_{RT} = \frac{1800}{\left(1 + \frac{1.5}{r}\right)} \qquad (2.7)$$

$$S_{RT} = \frac{3000}{\left(1 + \frac{1.5}{r}\right)} \qquad (2.8)$$

where,

S_{RT} = saturation flow rate for right-turning vehicles (pcuph); and

r = turning radius (meter).

If the turning radius are extrapolated to infinity, i.e. to straight path condition, the saturation flows are 1800 and 3000 pcuph for single and double lane flows, respectively.

Webster (1967) examined the three fold effects of right-turning vehicles under the circumstances of opposing flow and no exclusive right-turning lanes. Firstly, because of opposing traffic, right-turning vehicles themselves would be delayed and consequently they would delay other non-right turning vehicles in the same stream. Secondly, their presence would tend to reduce the use of the off side lane by straight-ahead vehicles due to the danger of being delayed, and thirdly, those right-turning vehicles which would remain in the intersection at the end of the green period would take a certain time to discharge and might delay the start of the opposing traffic.

Webster and Cobbe (1966) suggested that, for the first two effects, on an average each right-turning vehicle would be equivalent to 1.75 straight-ahead vehicles.

The third effect was more complicated and the following equation was obtained to give the maximum number of right-turning vehicles (n_{RT}) per cycle to take advantage of gaps in the opposing streams. The effect of right-turning vehicles can be written as in Equation (2.9).

$$n_{RT} = S_{RT} \times \left(\frac{gS_C - qC}{S_C - q} \right) \tag{2.9}$$

where,

n_{RT} = maximum number of right-turning vehicles;

q = traffic flow of opposing arm (vph);

S_C = saturation flow of opposing arm (vph);

g = green time (seconds);

C = cycle time (seconds); and

S_{RT} = effective right-turning saturation flow (vph).

Webster and Cobbe (1966) recommended that the rules regarding the effect of turning radius given by Webster (1964; 1967) for right-turning traffic can equally be applied to well-defined left-turning streams. If the left-turning vehicles are in small number (about 10 percent of the whole traffic) and intermixed with straight-ahead vehicles, it is unnecessary to make a correction as the general saturation flow include the effects of the left-turning traffic present. If the left-turning vehicles are more than 10 percent of the total traffic, a correction could be made for the additional 10 percent of