



Saturation Flow Rate Analysis at Signalized Intersections for Mixed Traffic Conditions in Motorcycle Dependent Cities

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Abstract

This article describes the results of a comprehensive saturation flow rate analysis at signalized intersections in motorcycle dependent cities. So far, available methods of capacity analysis do not consider the specific conditions of driver behavior and traffic flow which are dominant e.g. in Vietnam or other countries where motorcycles have the major share in the traffic. Consequently, there is a need to develop a proper method for such saturation flow rate analysis. The methodology of this research was developed under the specific traffic situation in Ho Chi Minh City, Vietnam, a motorcycle dependent city (MDCs). Saturation flow rate models using regression method are presented and described. The term of Motorcycle Unit (MCU) is introduced, and factors which mainly affect the saturation flow in such mixed conditions are considered. Finally, a procedure to calculate the saturation flow rate for specific traffic situations is provided. The conducted research indicates that the proposed saturation flow rate analysis model is an appropriate approach to calculate the saturation flow rate for traffic streams at signalized intersections under such mixed traffic conditions.

Keywords: Motorcycle dependent cities, motorcycles, motorcycle unit, saturation flow rate

1 Introduction of Motorcycle Dependent Cities

The term “motorcycle city” was adopted firstly by Barter (1999) [1] to define the urban transport and land use situation, but the term was used without the corresponding indicators, except some discussions on motorcycle ownership. Then, Khuat (2006) [2] proposed three main indicators: vehicle ownership, availability of alternative, and use of motorcycle to identify the motorcycle dependent level. A typical motorcycle dependent city (MDCs) should has some characteristics such as: motorcycle ownership is higher than 350 per 1000 inhabitants; private car ownership is lower than 150 per 1000 inhabitants; public transport availability is lower than 1 bus per 1000 inhabitants; modal split of

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motorcycle is higher than 40%, while modal splits of private car and public transport are lower than 20%, and modal split of non-motorized transport is about 30% to 50% [2].

2 Fundamentals of Saturation Flow Rate

2.1 Definition of Saturation Flow

According to Webster and Cobbe (1966) [3], the saturation flow rate is the flow which would be obtained if there was a constant queue of vehicles and they were given a 100 percent green time. It is generally expressed in vehicles per hour of green (vphg).

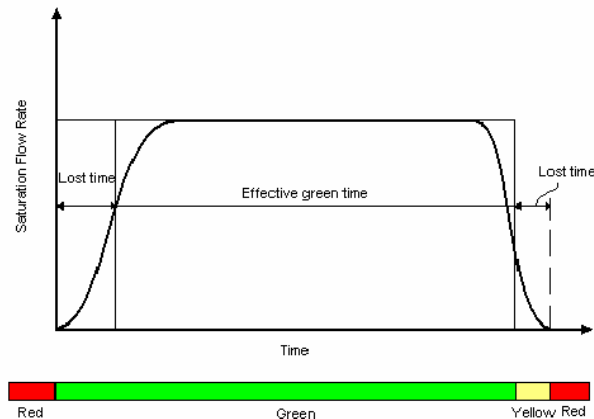


Figure 1: Variation with time of discharge rate of queue in a fully saturated green period

Source Webster and Cobbe (1966) [3]

The conventional graphical representation of the saturation flow is shown in Figure 1. The solid line in the figure shows the traditional concept, which assumes after a few seconds following the beginning of the green time, traffic discharges at a constant rate (the saturation flow rate) until the queue is discharged, when a sharp decrease in the flow occurs. The departure rate is lower during the first few seconds, while vehicles accelerate to normal running speed, and after the end of the green interval, as the flow of vehicles declines.

Through decades, the term of saturation flow was changed by different researchers. The Highway Capacity Manual (HCM) [4] describes the saturation flow rate as the flow, in vehicles per hour per lane, that can be accommodated by the lane assuming that the green phase is always available to the approach. The Canadian Capacity Guide for Signalized Intersections (CCG) [5] defines saturation flow as the rate of queue discharge from the stop line of an approach lane, expressed in passenger-car units per hour of green (pcu/hr green). Australian Road Research Board (ARRB) Report 123 [6] defines saturation flow as the maximum constant departure rate from the queue during the green period, expressed in through-car units per hour (tcu/hr).

2.2 Saturation Flow Rate Models

The Saturation flow rate at signalized intersections is computed based on the basic procedure: at first saturation flow rate in ideal condition would be determined and then affecting factors which reflect the difference between the ideal condition and the actual condition would be added. Different countries decided to put different influencing factors into their model to make the model suitable with their specific traffic conditions.

In German Highway Capacity Manual (HBS) 2015 [7], two main factors would be selected among affecting factors to calculate the saturation flow.

$$q_s = f_1 f_2 q_{s,st} \tag{1}$$

Where q_s = the saturation flow rate per lane, $q_{s,st}$ = the base saturation flow rate per lane ; f_1, f_2 = the two strongest factors among the factors: lane width, heavy vehicle, turning radius, grade, pedestrian traffic, weather conditions.

In HCM 2000 [4], the saturation flow rate for each lane group is computed according to the following equation:

$$S = S_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} \tag{2}$$

Where s = saturation flow rate for subject lane group, expressed as a total for all lanes in lane group (vehicles per hour); S_0 = base saturation flow rate per lane (passenger cars per hour per lane); N = number of lanes in lane group; f_w = adjustment factor for lane width; f_{HV} = adjustment factor for heavy vehicles in traffic stream; f_g = adjustment factor for approach grade; f_p = adjustment factor for existence of a parking lane and parking activity adjacent to lane group; f_{bb} = adjustment factor for blocking effect of local buses that stop within intersection area; f_a = adjustment factor for area type; f_{LU} = adjustment factor for lane utilization; f_{LT} = adjustment factor for left turns in lane group; f_{RT} = adjustment factor for right turns in lane group; f_{Lpb} ; f_{Rpb} = pedestrian adjustment factors.

3 Specific Characteristics of Traffic Conditions in MDCs

Figure 2 shows the performance of typical signalized intersections in Ho Chi Minh city, Vietnam. Traffic flows operated under mixed conditions in which the proportion of motorcycle is more than 90% (Figure 3), and the extreme share of motorcycles somehow affects the performance of other vehicle types.



Figure 2: Motorcycle Traffic Performance at Signalized Intersections

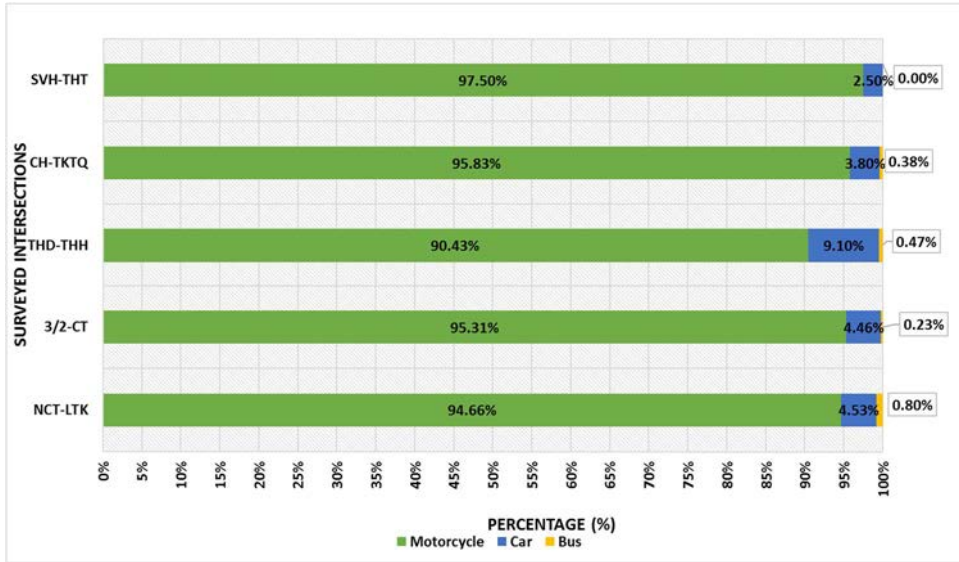


Figure 3: Traffic composition at signalized intersections in MDCs

Compared with car and other 4-wheel vehicles, motorcycles have some specific characteristic at signalized intersection. Motorcycles are considered as the smallest motorized vehicles [8], the physical dimension of a typical motorcycle using in Vietnam is (0.65m-0.8m) wide x (1.8m-2m) length x (1m-1.2m) height. Besides, the acceleration/deceleration of motorcycles are obviously higher than cars or buses. Moreover, due to the structure and shape of motorcycles, motorcyclists have a wider vision on the surrounding traffic environment and are more flexible than car drivers. This helps motorcyclists to respond faster to changes of traffic condition, and become more flexible than cars.

The traffic signal systems at intersections in Ho Chi Minh City are mostly organized by two phase signal programs. Therefore, interactions among traffic streams operating in the same phase could affect the saturation flow. Normally, there are three typical interactions among traffic flows include the interactions between the straight vehicles and the right-turn vehicles, the left-turn vehicles and the opposed left-turn vehicles. Furthermore, the traffic streams in MDCs run in groups and react to the situation with “grouping behavior” [9]. So, it is more complex to define the conflict areas and the interaction levels in order to determine the affecting degree to the capacity of traffic flows. In conclusion, there is a need to develop a model for saturation flow at signalized intersection in MDCs.

4 Saturation Flow Model at Signalized Intersection in MDCs

The following formula is recommended for estimating an appropriate saturation flow value on an approach to an intersection:

$$S = S_{0w} f_{veh} f_{turn} \tag{3}$$

Where

- S : Saturation flow rate on an approach (vehs/h)
- S_{0w} : Homogeneous motorcycle saturation flow rate according to the approach width (MCU/h)
- f_{veh} : Adjustment factor for 4-wheel vehicles in the traffic stream
- f_{turn} : Adjustment factor for turning movements including right-turn and left-turn and opposed left-turn movements

In the recommended model, all the data were collected in only one city in urban area, and the grade at all intersection is almost the same. Thus, some affecting factors such as urban type, size of urban, and grade were ignored. Moreover, due to the limitation of time and finance, the variations of saturation flow between day and night, between dry weather and wet weather were decided not to be examined. Popular influencing factors were taken into account such as approach width, vehicle composition, and turning movements include left-turn, right-turn and opposed left-turn movements.

5 Data Collection Method

Eleven signalized intersections were selected to build a database (Table 1). All of them were conducted in urban area in Ho Chi Minh City, Viet Nam. Vehicles were categorized into three types as motorcycle, car and bus. There was no truck at surveyed period in urban area due to the truck ban regulation, so truck was not considered in this study. The image processing technique was applied by using cameras installed in high positions near the intersection and recorded the traffic flows. The afternoon peak hour was chosen to ensure the saturation state of the traffic flow. Moreover, in non-lane based traffic condition, vehicles form a queue with unclear pattern and do not form a platoon, the time headway in this case is usually very difficult to collect. Thus, the counting method was applied. However, there is the fact that several motorcycles can pass the stop line at the same time, the number of vehicles were recorded in every 2 second slice to avoid errors in counting process instead of 6-second period like in the Road Note 34 method [10]. Vehicles have been considered discharged when their front wheel have passed the stopline.

No.	Intersections	Approach Width (m)	Turning Movements	Remark
1	Ton Duc Thang-Nguyen Huu Canh	4	Th	Homogeneous Motorcycle Flow
2	Xa Lo Ha Noi-Tay Hoa	6.5	Th	Mixed traffic between motorcycle and bus
3	Truong Chinh-Pham Van Bach	9.5	Th	Homogeneous Motorcycle Flow
4	Cong Hoa-Tan Ky Tan Quy	4.5	Th	Mixed traffic
5	3/2 -Le Hong Phong	12	Th,R,L	3 lane, mixed traffic
6	Dinh Bo Linh-Nguyen Xi	11	Th,R	One way street, mixed traffic condition
7	Su Van Hanh-To Hien Thanh	6.5	Th,OpL	T-junction
8	Tran Hung Dao-Nguyen Thai Hoc	12	Th,R,L,OpL	Major 4-leg intersection
9	Nguyen Chi Thanh -Ly Thuong Kiet	6.5	Th,R,L,OpL	4-leg intersection
10	Hoang Dieu-Khanh Hoi	5	Th,R,L,OpL	4-leg intersection
11	3/2 - Cao Thang	9	Th,R,L,OpL	4-leg intersection

Table 1: Main characteristics of sites surveyed

Note: Th = Through; R = Right Turn, L = Left Turn, OpL = Opposed Left Turn.

6 Model Development

6.1 Homogeneous Motorcycle Saturation Flow Rate and the Capacity Reduction Phenomenon

The saturation flow rate in homogeneous motorcycle flow should be calculated as follow:

$$S_{0wq} = \frac{\text{number of vehicles during saturated green time}}{\text{saturated green time}} \times 3600 \text{ (MCU /h)} \quad (4)$$

In the equation (4), the saturated green time is defined by the saturated green time in which traffic flow reach to the saturation state. In car traffic flow, the basic model for analyzing the saturation flow of signalized intersections is based on the hypothesis that queue discharge increases rapidly to a steady maximum when the traffic signal turns to green, commonly known as saturation flow rate ([4], [6]), so the number of vehicles remain a constant with the highest value during the saturated green time ([5], [6]). However, this hypothesis seems not correct in motorcycle traffic. The discharge rate of homogeneous motorcycle flow from three intersections is presented in Figure 4. The three graphs show that the number of motorcycles increases sharply at the former green time period and then declines in the later part of the green time. This phenomenon is called "capacity reduction phenomenon". More specifically, the green time period from the beginning to the time that the last vehicle in queue cross the stopline can be divided into three main parts, the first part from 0th-6th second green, the second part is from 6th-16th second green and the third part is from 16th-the rest of green time period for queued vehicles.

In the first period, the lost time would be occurred because vehicles need time to start and move. The situation in this case is quite complex. In the studied areas, all the traffic signals are installed with the signal countdown systems, so the drivers are very active and know exactly when green time come, they can start up even before the green begin. However, due to the unreasonable intergreen time, clearing vehicles still move inside the intersection when the green time of the entering vehicles start, this make the entering vehicles have to stop a few seconds. In the other hand, there are some cases that motorcycles stop after the stopline during the red time and they totally do not recognize when the green begin until they feel the preceding vehicles start to move. This situation would reduce the discharge rate and affect to the saturation flow rate. Thus, it is recommended that the first part of the green time should be eliminated to avoid the effect of lost time and the driving behavior's errors to the saturation flow rate.

In the second part, the discharge rate of motorcycles could reach to a peak value, and then the discharge rate reduces into a smaller value in the third period. This result could be explained that even in the queued area where the saturated state occurs, the density is not distributed equally from the beginning to the end of the queue length. Instead, the density in the closer area of the stopline is higher than the density in further area. Moreover, with the vehicles in the further area, they have more distance and time to pass the stopline and then the dispersion effect on motorcycle flow would happen. The dispersion effect make the discharge rate fluctuated up and down between successive time slices.

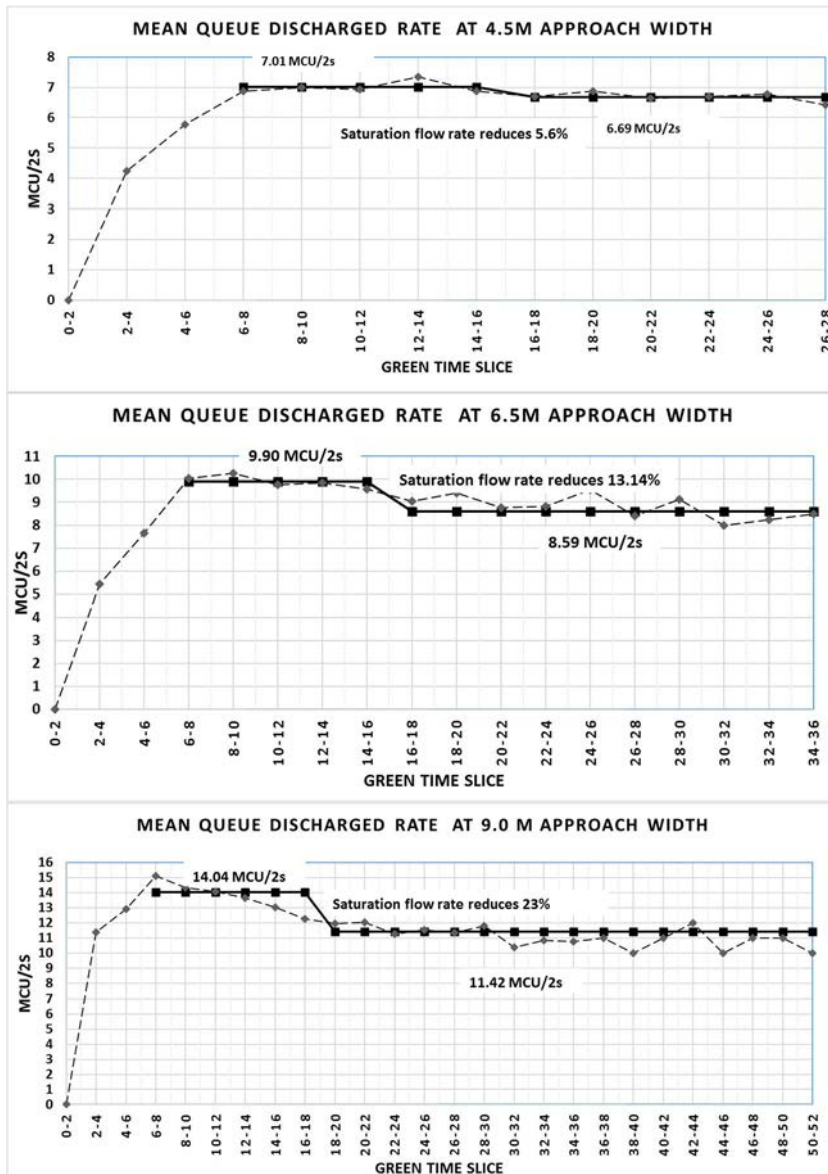


Figure 4: Queue discharge rate of homogeneous motorcycle flow at signalized intersections

Another thing should be mentioned is that the decreasing rate depends also on the approach width. For instance, at 4m approach width, the decreasing rate between second part and the third part of green is slightly around 5.6%. However, the decreasing rate at 6.5m approach width and 9m approach width are 13.14% and 23% respectively. The reason of this result could be the lateral dispersion of motorcycles. In small approach width, motorcycles stand and run close together in order to pass the stop line as fast as possible. However, in case of wider approach width, motorcycles run at further distance to the stopline have greater chances to change the direction in order to overtake the preceding vehicles. The overtaking activities require more safety areas for the motorcycles including lateral and longitudinal gaps. This dispersion phenomenon would make the lateral gaps among vehicles and form a deeper reducing trend in wider approach like in the graph.

In general, the ideal saturation flow rate depends on the approach width and fluctuate according to the expected green time interval. Thus, it is needed to separate the ideal saturation flow rate into two cases: the case with the expected green interval is lower than 16 seconds and the case with the expected green interval is higher than 16 seconds. As mention before, the observed saturated green interval would be start from the 6th second until the time that all queued vehicles discharged the stopline to eliminate the effect of the lost time and the driving behavior's errors. Based on equation (4), the saturation flow rate according to the approach width was measured. The regression model was implemented to estimate the relationship between the homogeneous motorcycle flow and the approach width. The equation for the homogenous motorcycle saturation flow rate is estimated:

$$\begin{cases} S_{ow} = 35W^3 - 509W^2 + 4590W & \text{when } t_f \leq 16s \\ S_{ow} = 42W^3 - 642W^2 + 4976W & \text{when } t_f > 16s \end{cases} \text{(MCU/h)} \quad (5)$$

Where t_f is the expected green time interval.

From the model, the saturation flow of homogeneous motorcycle flow in 3,5m approach width is computed as 11,352 MCU/h (expected green time is larger than 16s). This result is similar to the study of Hien (2007) [11] when he pointed out that the saturation flow rate of 3,5 m approach width should be 11,241 MCU/h [12].

6.2 Motorcycle Unit (MCU)

There is the fact that the heterogeneous traffic flow is more common than the homogeneous motorcycle traffic flow in urban area. The combination among motorcycles, cars, and buses with different traffic compositions would make different traffic performance and influence the saturation flow analysis. To overcome this problem, a technique converting the heterogeneous stream into homogeneous stream by using a basic vehicle equivalent unit was applied. In car dominant traffic, the passenger car was selected as the basic vehicle because it was the main mode of transport. Vehicle equivalent factors in such traffic situation were termed as passenger car unit (PCU) values. However, in motorcycle dominant traffic, obviously motorcycle is considered as the main mode with more than 90% shared rate. Thus, motorcycle should be selected as the vehicle equivalent unit in motorcycle dependent city, named as motorcycle unit (MCU).

In this study, MCU values were determined by using regression method. First, the vehicles were group into three categories: Motorcycle, Car and Bus. Then classified vehicles were counted from the 6th second of green time until the saturated state of the traffic stream was ended, that duration was called as saturated green time. It was assumed that the estimated saturated flow rate during the saturated green time T was regressed against the number of each vehicle type crossing the stopline. Moreover, only intersections that of 4-wheel vehicles not allowed to turn would be selected to avoid the turning effect of 4-wheel vehicles to the saturation flow which would also effect to the MCU values. The general form of regression model is given:

$$\frac{S_{ow}}{3600} \times T = a_0 + a_1 \times MC + a_2 \times Car + a_3 \times Bus \quad \text{(MCU/h)} \quad (6)$$

Where

- S_{ow} : Homogeneous motorcycle saturation flow rate according to the approach width (MCU/h)
- T : Saturated green time (sec)
- a_0 : Intercept
- $a_1; a_2; a_3$: Coefficient of motorcycle, car and bus

$MC; Car; Bus$: Number of motorcycles, cars and buses passing the stopline during the time T (veh)

$$\text{Motorcycle unit of vehicle type } i : \quad MCU_i = \frac{a_i}{a_1} \tag{7}$$

The numerical analysis is described:

$$\frac{S_{ow}}{3600} \times T = 8.978 + 0.798 \times MC + 4.267 \times Car + 11.022 \times Bus \tag{8}$$

The estimated MCU value is depicted in Table 4.

Parameter	Motorcycle	Car	Bus
measured MCU value	1	5.35	13.81
%vehicle	95.7	3.99	0.31

Table 2: MCU values

Model	Unstandardized Coefficients		Standardized Coefficients		Sig.
	B	Std. Error	Beta	t	
(Constant)	8.974	6.117		1.467	.157
MC	.798	.085	.773	9.398	.000
PC	4.267	1.336	.260	3.195	.004
Bus	11.022	5.038	.134	2.188	.040

Table 3: Regression result of MCU model

It is clear that the MCU values for any vehicle class is not always constant for different traffic situation. However, in this study the recommended MCU values are suggested to apply for other intersections due to the limitation of field survey. The applied MCU values for motorcycle, car and bus are 1, 5.35 and 13.81 respectively.

6.3 Effect of Vehicle Type on Saturation Flow

We could consider the number of vehicles can run during the saturated green time T is as follow:

$$Q(veh) = Q_{MC} + Q_{Car} + Q_{Bus} \tag{9}$$

Where $Q_{MC}; Q_{Car}; Q_{Bus}$ is the number of motorcycle, car and bus in the saturated green time T

In the other hand, when convert to the homogeneous motorcycle flow, the number of convert motorcycle unit could run during the saturated green time T are:

$$Q(MCU) = Q_{MC} + Q_{Car} \times E_1 + Q_{Bus} \times E_2 \tag{10}$$

Where $Q(MCU)$ the homogeneous motorcycle saturation is the flow rate during the saturated time T and $E_1; E_2$ are the MCU values of car and bus.

The effect of vehicle type on saturation flow rate could be measured by below relationship:

$$f_{veh} = \frac{Q(veh)}{Q(MCU)} = \frac{Q(veh)}{Q_{MC} + Q_{Car} \times E_1 + Q_{Bus} \times E_2} = \frac{Q(veh)}{Q(veh) \left(1 - \frac{P_{Car}}{100} - \frac{P_{Bus}}{100} \right) + Q(veh) \frac{P_{Car}}{100} \times E_1 + Q(veh) \frac{P_{Bus}}{100} \times E_2}$$

$$f_{veh} = \frac{100}{100 + P_{Car} \times (E_1 - 1) + P_{Bus} \times (E_2 - 1)} \tag{11}$$

Where P_{Car} ; P_{Bus} are the percentage of car and bus in the traffic flow

6.4 Effect of Turning Vehicles on Saturation Flow

The adjustment factors for left-turns and right-turns are important for the determination of the saturation flow rate. The effect of turning traffic (left or right) depends how they interact with the through traffic at the intersection. Although the approaches are organized by separated lanes in order to require vehicles run in their assigned lanes. However, this seems to be correct only on the link, and not correct on the approaches of signalized intersection. Vehicles mixed together in every stream. However, the distribution of the mixing level is different between shared space area (or lane). In Figure 5, for instance, motorcycles are assigned to run in the curb side lane or the right side of the approach, cars and buses are assigned to run in the left side of the approach (the off-side lane and median side lane). Due to motorcycle’s flexibility, motorcycles can change the lanes easily to choose the waiting location before discharging the stopline. Cars and buses are bigger vehicles and cannot change the lane. They have to remain and stop on their own lane (on the left side of the approach). Therefore, the figure of the queue is that right-turn and go-through motorcycles mainly stand in the right part of the approach, cars and buses including all movements stand in the left side of the approach, left-turn motorcycles stand near the median side or the left side of the approach accompany with 4-wheel vehicles. Moreover, with the two phase signal programs, unprotected opposed left-turn vehicles could run in the same phase with straight vehicles and are in conflict with them.

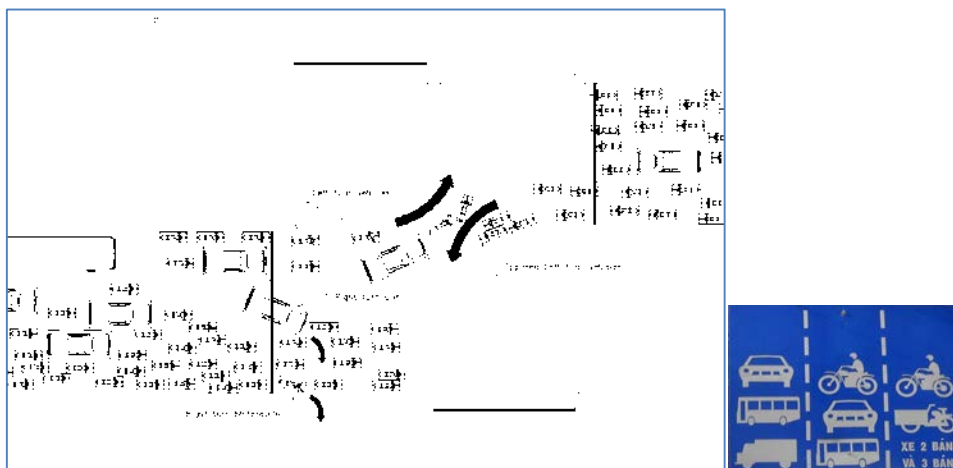


Figure 5: Turning vehicles at a typical signalized intersection in MDCs

The specific traffic situation in motorcycle dependent cities make the turning effect to the saturation flow also different with other studies. Regards to the right turn effect, motorcycles turning right do not affect the saturation flow rate due to its turning position and high flexibility behavior. However, 4-wheel vehicles turning from the left side would block the motorcycle flows running at the right side and influence the saturation flow rate of the approach. Moreover, right-turning vehicles would try to avoid the conflict with motorcycles, so the vehicle’s trajectories would not fix as curves. Thus, it is suggested that the right-turn adjustment factor depends on the percentage of 4-wheel vehicles in the total traffic and the turning radius is not considered. For the left turn effect, vehicles are not easy to discharge

because they are interfered by the opposed straight vehicles and they may have to stop inner the intersection until they could find a suitable gap from the opposed straight vehicles. The standing left-turn vehicles would interfere the straight movements and reduce the saturation flow of the approach. Therefore, it is also recommended that the left turn adjustment factor dependent on the percentage of all kind of turning vehicles in the total traffic. In the other hand, the opposed left turn traffic only conflict with straight flow when they run in the same phase, so the saturation flow rate of the straight stream is also affected by the opposed left turn adjustment factor.

Due to the complexity of turning effect to the saturation flow rate. Two cases should be clarified: The saturation flow rate of the whole approach; the saturation flow rate of the straight flow. The effect of turning movements on saturation flow rate could be measured by below relationship:

$$S_{Th} = P_{Th} S_{Approach} f_{OpL} = P_{Th} S_{0w} f_{veh} f_{R/L} f_{OpL} \tag{12}$$

$$S_{Approach} = S_{Th} + S_R + S_L = P_{Th} S_{0w} f_{veh} f_{R/L} f_{OpL} + (1 - P_{Th}) S_{0w} f_{veh} f_{R/L} = S_{0w} f_{veh} f_{R/L} [1 - P_{Th} (1 - f_{OpL})] \tag{13}$$

Where

$S_{Th}; S_R; S_L$: Saturation flow rate of through flow, right turn flow and left turn flow (MCU/h)

$S_{Approach}$: Saturation flow rate of the whole approach (MCU/h)

P_{Th} : The percentage between through discharged vehicles and the total discharged vehicles in the whole approach

$f_{R/L}$: Adjustment factor of right-turn and left-turn movements

f_{OpL} : Adjustment factor of opposed left-turn movements

Adjustment factor of right-turn and left-turn movements $f_{R/L}$ was regressed by the percentage of 4-wheel right turn vehicles and the percentage of left turn vehicles value compare with the total traffic.

$$f_{R/L} = b_0 + b_1 P_R + b_2 P_L \tag{14}$$

Where P_R is the percentage of 4-wheel right-turn vehicles (cars and buses) in the total traffic; P_L is the percentage of left-turn vehicles (motorcycles, cars and buses) in the total traffic.

In order to fulfil the boundary condition that $f_{R/L} = 1$ when there is no turning vehicle (P_R, P_L are zero). The value of b_0 must be equal to 1.

Model	Unstandardized Coefficients		Standardized Coefficients		t	Sig.
	B	Std. Error	Beta			
(Constant)	.980	.031			31.739	.000
PR	-.009	.001	-.807		-5.898	.000
PL	-.005	.002	-.470		-3.437	.005

Table 4: Regression result of turning model

To eliminate the effect of opposed left-turn traffic, green durations in which the discharged vehicles was not interfered by the opposed movements were observed. The regression model of right-turn and left-turn adjustment factors could be described as follow:

$$f_{R/L} = 1 - 0.009 P_R - 0.005 P_L \quad (15)$$

To consider the effect of opposed left-turn movements on the straight movements. The relationship between the discharged straight vehicles and the discharged left turn vehicles should be considered. Figure 6 shows the relationship between traffic volumes of the left-turn flow and straight-through flow at each cycle under the saturated flow at Cao Thang-3/2 intersection.

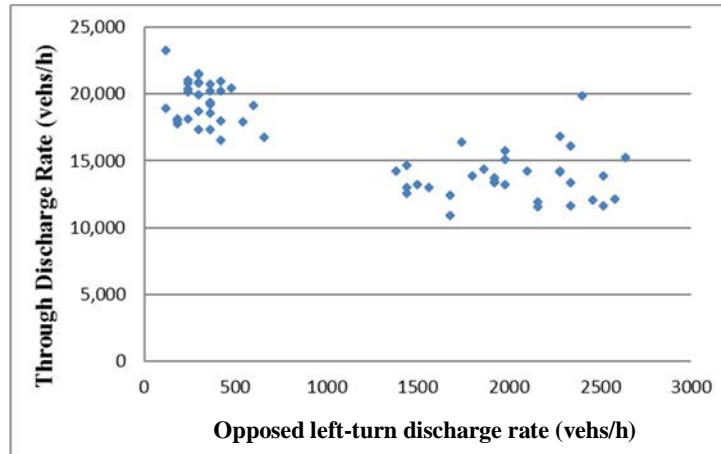


Figure 6: Relationship between through discharge rate and opposed left turn discharge rate at 3/2 Cao Thang intersection

Figure 6 shows that the higher the volume of the left-turn stream, the lower the volume of the straight-through stream, and vice versa. When the traffic light turns green, motorcycles and other vehicles from both directions on the main road start to go through and turn left in order to cross the intersection. When the straight-through traffic flow reaches to the saturation state, it is more difficult for the opposed left-turn vehicles to find an acceptable gap. However, while waiting for an acceptable gap, the left-turn vehicles are willing to make groups and then cross the intersection together. If the left-turn group becomes big enough, it is likely to accept even a very small gap, thereby reducing the volume of the straight-through flow. When vehicles entering the intersection in the main road can not fully discharge during the green time due to the hindrance of left-turn vehicles. Thus the left-turn vehicles running in the same phase with the straight-through vehicles influence the capacity of straight-through streams. The conflicts between individual vehicles actually become conflicts between the left-turn vehicle groups and the straight-through ones. Again, this is called grouping behaviour or group conflicts under the mixed traffic condition. In other words, the performance of one group may significantly affect the performance of opposed group. Figure 7 shows the adjustment factor of opposed left-turn movements to the through movements.

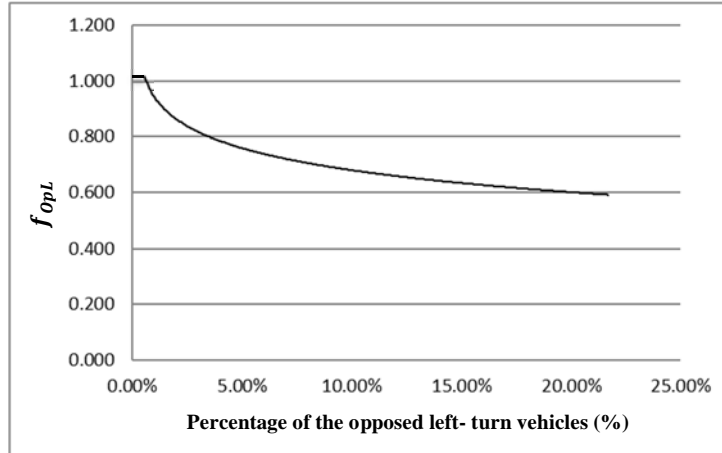


Figure 7: Adjustment factor of through stream and opposed left-turn stream

In Figure 7, we could see that if the number of opposed left-turn vehicles is quite small, lower than 1% compare with the through volume, opposed left-turn vehicles does not affect to the through saturation flow. This is because of the high flexibility and small dimension as well as the behavior of motorcycle. Opposed left-turn motorcycle runs in that low demand can not make group or platoon, they run individually and independently to the conflict area with a zigzag trajectory. Its small dimension, and the high flexibility could help to change the trajectory as a bicycle in order to pass the conflict area without interfering to the through traffic. In the other hand, through flow could also change the direction easily to cut through the tail of opposed left-turn motorcycles. Moreover, motorcycle with the dimension of (2m length x 0.7 m width), the time duration that two vehicles conflict together is so small that preceding through flow is not affected. When the percentage of opposed left-turn vehicles increases, they tend to make group to pass the conflict area. That vehicle group is not flexible and definitely slow down the discharge rate of the through traffic. Thus, the adjustment factor of opposed left-turn movements to the through flow could be estimated according to the Figure 7.

7 Procedure of Saturation Flow Rate Analysis at Signalized Intersections in MDCs

The calculation procedure of saturation flow should be conducted in the following steps:

Step 1: Calculate the homogeneous motorcycle saturation flow according to the approach width

$$\begin{cases} S_{ow} = 35W^3 - 509W^2 + 4590W & \text{when } t_f \leq 16s \\ S_{ow} = 42W^3 - 642W^2 + 4976W & \text{when } t_f > 16s \end{cases} \quad (16)$$

Step 2: Determine the effect of vehicle types

$$f_{veh} = \frac{100}{100 + P_{Car}(E_1 - 1) + P_{Bus}(E_2 - 1)} \quad (17)$$

Step 3: Determine the effect of turning movements on the saturation flow rate

$$f_{R/L} = (1 - 0.009 P_R - 0.005 P_L) \quad (18)$$

f_{opL} is estimated using the graph in Figure 7

Step 4: Combine all the adjustment factors for calculating the saturation flow rate

$$S = S_{0w} f_{veh} f_{R/L} [1 - P_{Th}(1 - f_{opL})] \quad (19)$$

8 Conclusions

The study introduced the specific traffic pattern in motorcycle dependent cities where the motorcycle rate is extremely high. On the analysis of results using both theoretical approaches and field observations, the following conclusions on the saturation flow and could be drawn:

- The observed saturated green time was conducted from the 6th second until the time that queued vehicles were fully discharged the stopline. The first 6 seconds duration was ignored in order to eliminate the influence of the lost time and the driving behavior's errors to the saturation flow.
- The homogeneous motorcycle saturation flow rate in the 3,5m approach width could reach to around 11,300 MCU/h, this figure is even higher than 5.8 time of the saturation flow rate of homogeneous car flow (1900 PCU/h). Moreover, let assumed the occupancy of motorcycles is 1.2, it is figured that homogeneous flow of motorcycles could carry around 13,000 passengers to pass through 3.5m wide approach. Thus, in term of capacity aspect, the motorcycle is much more efficient than car and even bus.
- The field observation also pointed out that there is a capacity reduction phenomenon when the saturation flow rate tends to decrease after a period with green time. Furthermore, because the high dispersion of motorcycle flow in both longitudinal and lateral direction, the decreasing level increases with the wider approach width. It is recommended that the green time should not be too long and the approach width of motorcycle flow should not be too wide in order to avoid the capacity reduction phenomenon.
- The motorcycle unit (MCU) was also introduced and estimated for car and bus. In the saturation state the MCU value for car is 5.35 and the MCU value for bus is 13.81. It is the fact that the MCU value could change depending on the traffic situation and the location. Nevertheless, this study proposed to use one set of MCU value for car and bus due to the limitation of filed observation. It is also suggested to do more survey about the variation of MCU value according to the traffic situation.
- The effect of turning movements was also analyzed. The right-turn motorcycles were proved not to influence the saturation flow, but the 4-wheel vehicles have significant influence the saturation flow rate because it would block the motorcycle flow running in the right side. The left-turning vehicles also affected the saturation flow but the affecting level is lower than the effect of right-turn vehicles.
- The effect of opposed left-turn vehicles to the movements of the through vehicles was considered. In case of low traffic volume and low relative proportion between both streams, there is no influence between them. In case of the high volume and the high proportion between them, the influence is significant.

The study also proposes a calculation procedure for the saturation flow rate at signalized intersections in motorcycle dependent cities. Only main influencing factors were considered such as approach width, vehicle type, and the turning movements. Other factors like grade, city size, weather, parking activity, pedestrian...should be taken into account in the next step.

References

1. Barter, P., *An International Comparative Perspective on Urban Transport and Urban Form in Pacific Asia: The Challenge of Rapid Motorisation in Dense Cities*. 1999, Murdoch University p. 1-407.
2. Khuat, V.H., *Traffic Management In Motorcycle Dependent Cities*, in *Transport Planning and Traffic Engineering*. 2006, Darmstadt University. p. 1-166.
3. Webster, F.V. and B.M. Cobbe, *Traffic Signals*. Road Technical Paper No. 56, 1966.
4. *Highway Capacity Manual*, ed. N.R.C. TRB, Washington, D.C. 2010.
5. Teply., S., et al., *Canadian Capacity Guide for Signalized Intersections*. 2008: Institute of Transportation Engineers, District 7 - Canada.
6. Akçelik, R., *Traffic signals: Capacity and timing analysis*. Research Report No.123, Australian Road Research Board, Victoria, 1981.
7. *Handbuch für die Bemessung von Straßenverkehrsanlagen (HBS 2015), S4 Knotenpunkte mit Lichtsignalanlage* 2015.
8. Antony, F., M. Babu, and P. Vortisch, *Modelling of motorcycle movements in mixed traffic conditions*. Transportation Research Board 94th Annual Meeting, 2015.
9. Tuan, V.A. and T. Shimizu, *An analysis of the interactions between vehicle groups at intersections under mixed traffic flow conditions*. Journal of the Eastern Asia Society for Transportation Studies, 2010: p. 1999-2017.
10. *Road Note 34: A Method of Measuring Saturation Flow at Traffic Signals*. 1963.: Road Research Laboratory, Crowthorne, UK.
11. Nguyen, H. and F. Montgomery, *Different models of saturation flow in traffic dominated by motorcycles*. Journal of the Eastern Asia Society for Transportation Studies, 2007: p. pp. 2381-2395.
12. Nguyen, H. and F. Montgomery, *Should motorcycle be blamed for traffic congestion in vietnamese cities*. Cooperation for urban mobility in the developing world (CODATU XIII), 2008.