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Article

Evaluation of Effect of Median U-Turns on Multilane Primary Highway Capacity in Thailand through Traffic Micro-Simulation Models

Wuttikrai Chaipanha[1,a], Ladda Tanwanichkul[1,b,*], and Jumrus Pitaksringkarn[2,c]

1 Department of Civil Engineering, Faculty of Engineering, KhonKaen University, KhonKaen, 40002, Thailand
2 Department of Civil Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, 10520, Thailand
E-mail: [a] w.chaipanha@gmail.com, [b]ladpit@kku.ac.th (Corresponding author), [c]jumrus@gmail.com

Abstract. This article aims to analyze the effect of median U-turns and estimate the capacity of primary highways in Thailand using a traffic micro-simulation model. Six-lane and four-lane primary highways were selected for the study. The base condition results determined that the maximum capacity of a six-lane primary highway was 2,130 passenger cars/hour/lane, while the four-lane primary highway capacity was recorded as 2,194 passenger cars/hour/lane. Both results were slightly higher than those of the HCM2010 approach. Under prevailing conditions, both sections exhibited lower capacities than the HCM results by approximately 33.7% and 19.8% for the six-lane and four-lane primary highways, respectively, causing the impact of the median U-turn and highway characteristics in Thailand to directly affect traffic and driving behavior. Using the micro-simulation results, an equation was also regressed for estimating the capacity resulting from the impact of the median U-turns and heavy vehicles. These results may be used as guidelines for the design and analysis of multilane highways in Thailand.

Keywords: Capacity, primary highway, traffic micro-simulation model, median U-turn.

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1. Introduction

Highway capacity is used for the planning, design, and operation of highways. The United States Highway Capacity Manual (US-HCM), first published in 1950, is regarded as the global standard, and has been the pioneering document in this respect as it quantifies the concept of roadway capacity for transport facilities. As such, it has been widely referenced [1, 2]. However, the manual was developed specifically for the United States and may not be relevant in other countries with unique traffic characteristics. Still, the HCM is used by researchers from several countries in their pursuit of developing indigenous methods for capacity estimation [3–7].

Thailand is a country in which differences are observed in the behavior and other factors affecting highway capacity [8, 9]. Therefore, Thailand authorities may consider the development of a highway capacity estimation method designed specifically for Thai highways. According to the Thailand Department of Highways (DOH), there exists a responsibility distance of 70,077,043 km [10]. The highways in Thailand are divided into three classes: primary, secondary, and provincial highways [11]. The most important class is the "primary highway," which supports and provides services to the largest traffic volume every day. In general, primary highways exhibit the physical appearance of a multilane highway and include the majority of multilane highways in Thailand.

The median U-turn is a unique feature of multilane highways in Thailand, which differs from the conditions used in the HCM calculations. The main use of the U-turn on multilane highways in Thailand is to facilitate the reversal of the travelling direction by vehicles. However, the functions of multilane highways in Thailand often not only allow for mobility, but also serve to provide accessibility. Therefore, it is not uncommon to observe numerous vehicles making U-turns along these routes. Vehicle conflicts in the vicinity of median U-turns have a significant impact on capacity. Considering this gap in the data, efforts have been initiated to develop enhanced capacity estimation based on the Thailand highway conditions.

The purpose of this study is the evaluation and estimation of multilane primary highway capacity regarding driving behavior based on median U-turn impact. The estimation is conducted by means of a micro-simulation model that is often used in indirect empirical methods for roadway capacity estimation [12]. These models represent reality in detail, relative to the infrastructure network, traffic demand, and driver behavior [13], as this reduces the limitations of the survey and complex phenomena that are difficult to analyze with mathematical techniques. The maximum capacity, as both a base estimation and prevailing condition, was identified, and mathematical equation models were presented to estimate the capacity of multilane primary highways.

2. Median U-Turn on Multilane Primary Highway

Driving behavior in median U-turns on Thailand multilane highways is another factor that has a significant impact on capacity. The turning and reversing of directions by vehicles at median U-turn openings results in traffic disruptions, affecting driving speed and road capacity (Fig. 1). The effect of median U-turns on capacity is an interesting topic, owing to the physical characteristics and driving behaviors being rather unique in such areas. Relatively few appearances have been observed in foreign countries, which also vary from the HCM conditions.

Fig. 1. Influence of median U-turn on the multilane highway capacity.

According to the DOH standards, the physical design of the median U-turn in Thailand is defined as the width of the median U-turn lane of 3.5 m (equivalent to a standard travel lane), taper, and pocket lane range of at least 70 and 100 m long. The opening of the median U-turn is 24 m wide with a turning radius of 19.75 m from the centerline of the road (Fig. 2).

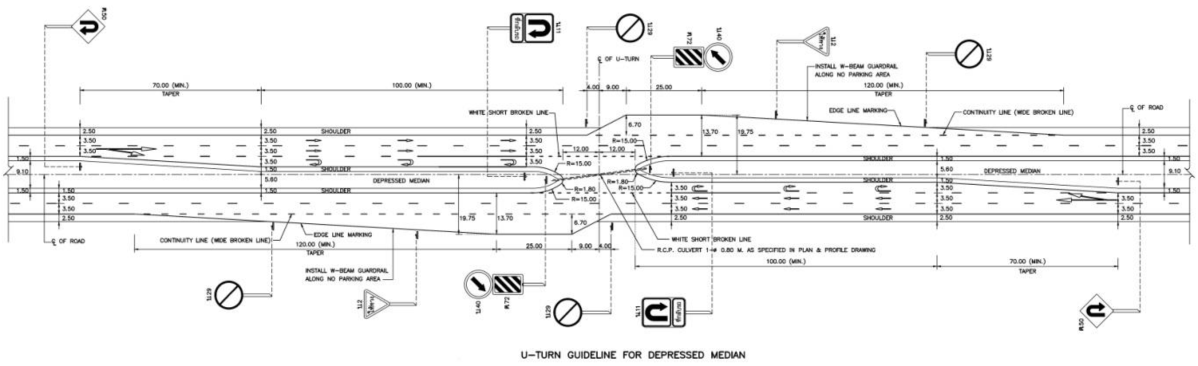

Fig. 2. DOH standard drawing for median U-turns on multilane primary highways [14].

According to the DOH (2005) [15], the appropriate distances between median U-turn openings for highways, as recommended by the Bureau of Highway Safety, DOH of Thailand, are approximately 0.80 to 1.50 km/median U-turn for community areas, 1.50 to 3.00 km/median U-turn for suburban areas, and 3.00 to 5.00 km/median U-turn in rural areas. Therefore, it is possible to design spacing between the median U-turn openings in the 1 km highway range that will be no more than two points. These data are used in the model development process and capacity estimation for highways in this study.

3. Methodology

This study forms part of the research on the application of the traffic micro-simulation model for analyzing the capacity of highways in Thailand. The micro-simulation model was developed by imitating driving behavior in each section, based on surveying and collecting relevant traffic data. The model was calibrated and validated prior to being applied to the capacity estimation. The methodology of this study can be explained as follows.

3.1. Site Selection

To investigate the impact of median U-turns on the capacity of multilane primary highways, four-lane and six-lane highways were selected as the representative sections for this study. The site selection followed the HCM 2010 base condition [16], and represents the prevailing conditions of primary highways in Thailand. The criteria for the site selections included the following:

- The selected site should be straight, without the influence of any intersections and traffic signals.
- It consists of a median U-turn that affects the capacity and is used to calibrate driving behavior in the model.
- It should be designed in accordance with the DOH standard, and the highest traffic volume will be compared to the same cross-section [14].

The representative primary highway sections were selected based on these conditions (Table 1 and Fig. 3).

Table 1. Selected sections of multilane primary highways.

Section no.	Highway no.	Section	K.M.	No. of lane
1	2	Nakhon Ratchasima- Saraburi	43+000-44+000	Six-lane
2	2	Khon Kaen - Udonthani	349+000-350+000	Four-lane

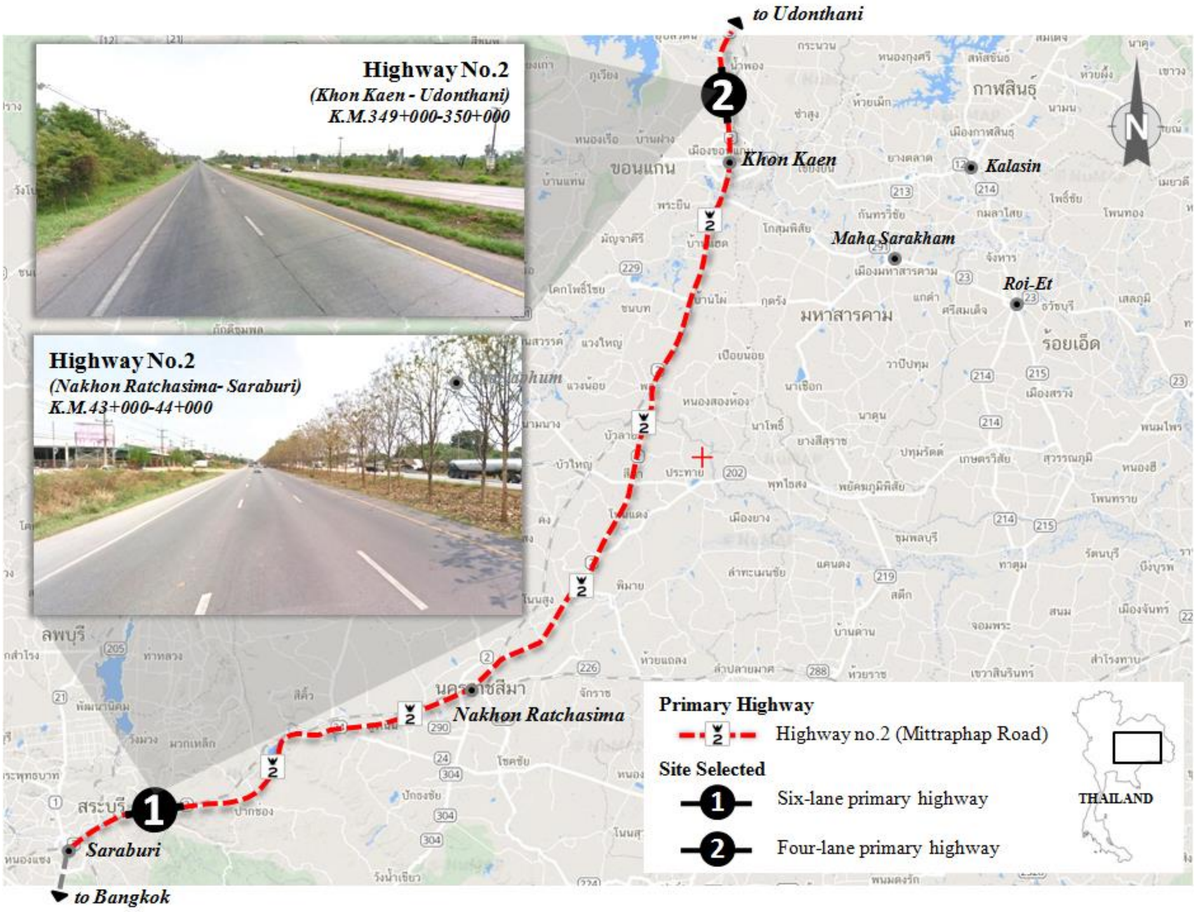

Fig. 3. Selected section site locations of primary highways.

3.2. Data Collection

The relevant data surveyed in the field were categorized into four groups:

(1) Geometric data: lane width, shoulder width, median width, median type, and aerial photos.
(2) Demand data: entry volume and traffic composition.
(3) Control data: to be used as the speed limits.
(4) Calibration data: spot speed (free-flow and median U-turn speed), travel speed, traffic count, and time gap.

Important data that directly affect capacity, such as entry volume, free-flow speed, time gap, and gap acceptance behavior of U-turning, are briefly discussed in terms of the methods, as follows:

- The entry volume was measured at two intervals, each with a duration of 1 h 30 min, during the morning and evening peak hours. Vehicles were divided into five types, namely passenger cars (PC), light and medium buses (MB), medium trucks (MT), heavy buses (HB), and heavy trucks (HT). However, only two vehicle types were analyzed: PC and Heavy Vehicles (HV). Heavy vehicles are defined as those with more than four tires in contact with the pavement [16], including MB, MT, HB, and HT (Table 2).

Table 2. Entry volume data.

Section no.	No. of lane	Period	Direction 1						Direction 2					
			PC	MB	MT	HB	HT	Total	PC	MB	MT	HB	HT	Total
1	Six-lane	A.M.	4426	6	112	96	269	4909	2273	4	119	68	271	2735
		P.M.	2458	3	114	60	266	2901	4894	7	105	85	273	5364
2	Four-lane	A.M.	1252	28	49	18	59	1406	1255	13	52	26	129	1475
		P.M.	1153	16	52	28	122	1371	1151	35	58	27	69	1340

- As part of the spot speed survey, the free-flow speed (FFS) followed the desired distributions in the micro-simulation model as a significant variable affecting the capacity [17]. Radar speed gun surveys were conducted during non-peak hours, according to vehicle type and traffic lane. Theoretically, FFS occurs when the density and flow rate in a study segment are both zero. However, in practice it is difficult to obtain such a situation on primary highways. Hence, FFS is considered as the prevailing speed at flow rates between 0 and 1,000 pc/h/ln [16], which is set to overcome this difficulty. The survey was conducted during a period with the lowest amount of traffic during daytime hours from previous surveys [18] (06.00 to 07.00 and 11.00 to 12.00) by selecting vehicles that drive in a lane without any other vehicles, or with a vehicle ahead in the lane [19] (Table 3). Based on the data, the desired speed distributions were calibrated by setting the critical control points (percentile speed) for curves (Fig. 4).

Table 3. Free-flow speed data.

Section no.	No. of lane	Vehicle type	Free-flow speed (km/h)								
			Lane 1			Lane 2			Lane 3		
			V_{15}	V_{50}	V_{85}	V_{15}	V_{50}	V_{85}	V_{15}	V_{50}	V_{85}
1	Six-lane	PC	95.0	105.0	117.2	78.0	88.0	99.0	64.7	76.0	88.0
		MB	48.9	58.0	59.4	-	-	-	-	-	-
		MT	53.4	64.0	71.0	-	-	-	-	-	-
		HB	87.4	91.0	97.7	70.1	77.0	82.9	60.7	66.5	73.7
		HT	48.0	55.0	64.3	-	-	-	-	-	-
2	Four-lane	PC	90.0	102.0	113.0	67.0	81.0	88.0			
		MB	54.0	63.0	69.7	-	-	-			
		MT	58.0	65.0	73.0	-	-	-			
		HB	80.1	85.0	94.4	59.7	66.0	78.0			
		HT	49.0	57.0	67.0	-	-	-			

** Lane numbers: the far-right lane is known as "lane 1", with each lane to the left numbered sequentially as 2 and 3.*
***Assuming only passenger cars (PC) and heavy buses (HB) are available for all traffic lanes.*

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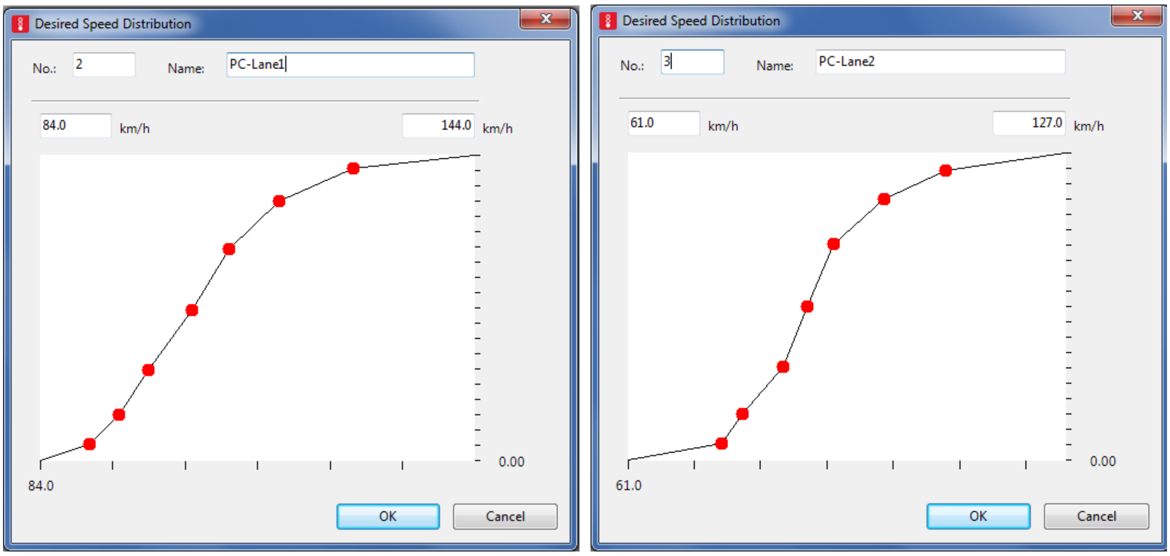


Fig. 4. Calibrated desired speed distribution in Vissim.

- In the car following model, the time gap is defined as the minimum time a driver will maintain while following another vehicle. In the case of high volumes, this distance becomes the value that has a determining influence on capacity [20, 21]. Video data were collected and used in the micro-simulation model calibration. According to the survey, the six-lane primary highway exhibited a shorter time gap than the four-lane primary highway. Owing to the physical characteristics contributing to higher speeds and driver perception of safety, the average time gaps were 1.15 and 1.17 s for sections 1 and 2, respectively.
- The gap acceptance behavior of the U-turn is an important variable affecting highway capacity. Moreover, Paonoi (2011) [22] studied the gap acceptance behavior of U-turning for the same route with a resulting recommendation of 3 to 4 s, which corresponds to the study of Ragland et al. (2006) [23] with a suggestion of gap acceptance of 4 s or less. As a result, this research uses a 3.5 s gap acceptance in the priority rule setting in the VISSIM model.

3.3. Micro-simulation Model

3.3.1. Base model development

The PTV Vissim software was applied to develop a traffic micro-simulation model, divided into five steps, as follows:

(1) The base data for the simulation include the settings for the entire network and all the basic objects for modeling vehicles; for example, distributions, functions, and behavior parameters, which further contain the vehicle types and classes.

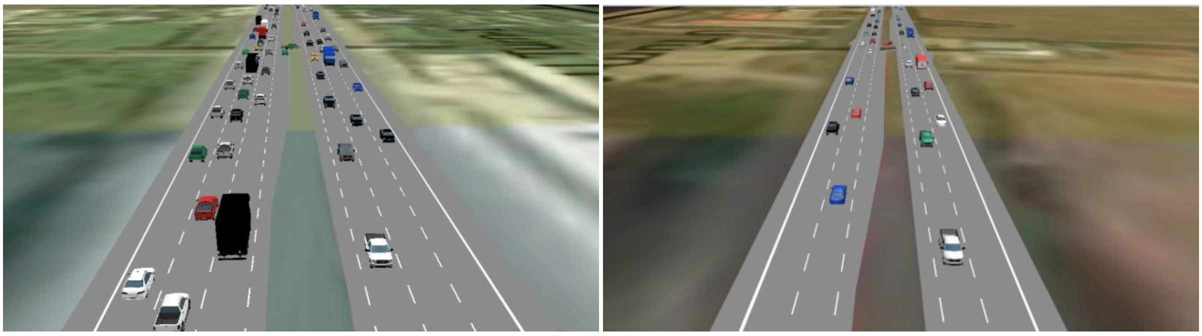
(2) Traffic networks are constructed by inserting true-to-scale digital maps as the background, with model links along which vehicles move for continuation of their journeys via connectors.

(3) Evaluation and configuration are used to select the desired evaluation results prior to starting the simulation.

(4) Simulation runs according to random number seeds are used to make numerous decisions throughout, with 20 simulation runs conducted for each test. In general, 11 runs are sufficient and the results are statistically significant [25]. The simulation run time interval in this study was set to 1 h 30 m (5,400 s); however, only a 1 h result was used for evaluation. Two additional time periods were not stably simulated, including a warm-up period (15 min after beginning the simulation runs), to ensure that the simulation did not begin with an empty network, and a cool-down period (15 min before the end of the simulation runs), which represents the flow arriving in the network. These are not included in the results evaluation.

(5) Error checking involves various reviews of the coded network, coded demands, and default parameters, and is conducted by means of input data and animation review. The base models for

the six-lane and four-lane primary highways developed by the traffic micro-simulation model are illustrated in Fig. 5.



(a) Six-lane Primary Highway (b) Four-lane Primary Highway

Fig. 5. Base models of the PTV Vissim.

3.3.2. Model calibration and validation

The calibration and validation were improved by adjusting the model parameters to maximize the ability to reproduce local driver behavior and traffic performance characteristics from the field survey. Traffic volume and travel speed were used as measures of consistency between the model and local conditions. The calibration and validation target criteria were based on the Design Manual for Roads and Bridges (DMRB) and other acceptable standards [24]. In order to calibrate and validate the model, the configuration and adjustment of the values for the VISSIM parameters CC0 (standstill distance), CC1 (headway time), and CC2 (following variation) were the most influential variables for the car following behavior model and exhibited the highest sensitivity in VISSIM [25, 26, 27]. From the model calibration and validation, the GEH statistic values were less than 0.5 for the traffic count comparison, while the percentage differences ranged from 0.1 to 4.7 for comparison of the average travel speed (Tables 4 and 5).

Table 4. Comparison of observed and simulated traffic count results.

Section	No. of lane	Direction	Observed (veh/h)	Simulated (veh/h)	GEH Statistics	Criteria Threshold	Result
Calibration result (A.M.)							
1	Six-lane	EB	3168	3168	0.0	<5	O.K.
		WB	1948	1927	0.5		O.K.
2	Four-lane	SB	1238	1250	0.3		O.K.
		NB	1178	1177	0.0		O.K.
Validation result (P.M.)							
1	Six-lane	EB	2071	2066	0.1	<5	O.K.
		WB	3407	3399	0.1		O.K.
2	Four-lane	SB	1013	1025	0.4		O.K.
		NB	1192	1184	0.2		O.K.

Table 5. Comparison of observed and simulated travel speed results.

Section	No. of lane	Direction	Observed (km/h)	Simulated (km/h)	Difference (%)	Criteria Threshold	Result
Calibration result (A.M.)							
1	Six-lane	EB	80.9	77.1	-4.7	within 5% or 1 mile, if higher	O.K.
		WB	75.5	73.4	-2.8		O.K.
2	Four-lane	SB	86.2	82.6	-4.2		O.K.
		NB	82.9	79.7	-3.9		O.K.

Validation result (P.M.)							
1	Six-lane	EB	75.1	71.9	-4.3	within 5% or 1 mile, if higher	O.K.
		WB	80.3	80.4	0.1		O.K.
2	Four-lane	SB	85.1	81.2	-4.6		O.K.
		NB	86.2	82.6	-4.2		O.K.

3.3.3. Model application

The traffic micro-simulation model was applied as a tool for estimating the primary highway capacity for each section, considering the number of median U-turns per kilometer (0, 1, and 2) and different proportions of heavy vehicles (0%, 5%, 15%, and 25%). The design volume of the median U-turn was based on a survey, with the median U-turn volume being 4% of the total two-direction traffic volume in each model. The heavy vehicle proportion coding in the models was defined as an assumption equal to the average proportions, based on the Annual Average Daily Traffic (AADT) on the primary highway [28]. The representative proportions are 5%, 25%, 10%, and 60% for the MB, MT, HB, and HT, respectively.

3.4. Capacity Estimation

The results of the capacity estimation of the primary highways form the main topic of this study. The capacity reflects the driving behavior and physical characteristics of the highways, and this information can be used to analyze, design, and conduct the planning of transportation and traffic systems for primary highways in Thailand more effectively. Estimating the capacity of a highway can be generated by using a direct empirical method, which can estimate the capacity reflecting actual data and provide high accuracy. However, a direct empirical method generally requires a survey to be conducted under capacity conditions, and it also is relatively uncommon for a capacity situation to occur on a regular weekday. As a result, micro-simulation models have been widely used for research purposes in indirect empirical analyses in order to estimate highway capacity in previous studies [8, 9, 29-34], as this reduces the survey limitations and complex phenomena that are difficult to analyze using mathematical techniques [35]. Individual driver behavior simulations can effectively reflect the traffic characteristics in each area and several studies have used traffic micro-simulation models to identify factors affecting roadway capacity.

A calibrated and validated micro-simulation model was used in this capacity estimation, and the speed data were estimated under different traffic volumes by increasing the flow rate in increments of 500 veh/h/direction from an initial value up to highway capacity. When the simulated volume reached the capacity level, increments in the input traffic volumes did not equate to an increase in the exit volume, and resulted in a decrease in the traffic flow rate [36]. The highway capacity estimation was performed using speed-volume relationships, by plotting the speed on the graph ordinate and the volume on the abscissa. The micro-simulation model replicated the traffic flow over the possible range of influencing variables, and the traffic capacity was estimated based on the simulation results [37]. The estimated capacity on the carriageway included only the traffic flow of passenger cars and heavy vehicles. In this study, the conditions were tested using a traffic micro-simulation model divided into three groups:

(1) The prevailing conditions model is a capacity estimation model for the representative section based on physical characteristics and actual field survey data.
(2) The base conditions model is the maximum capacity model in ideal conditions set, with no effects of the impact factors.
(3) The scenario conditions model is the capacity estimation model for each scenario, with varying factors affecting the capacity.

The results from the prevailing conditions model were used to estimate the capacity for the surveyed conditions as well as in comparison with HCM2010, while the base and scenario conditions were used to analyze the impact of the relevant factors and develop an equation model for primary highway capacity estimation. The estimated capacity on the carriageway included only the traffic flow of passenger cars and heavy vehicles, and did not include motorcycles, owing to the riding behavior of motorcycles on primary highways remaining in the shoulders. When the shoulder width is sufficient, motorcycles will have no impact on the carriageway capacity. Consistently with a previous study, the recommended configuration for the exclusive bike lanes per travelling direction is approximately 1.5 to 2.0 m [38] (the DOH standard shoulder width is no less than 2.5 m.). Furthermore, the proportion of motorcycles is low, at approximately 10% on average [28], and particularly on selected six-lane highways at only approximately 1%.

4. Results and Discussion

4.1. Capacity Estimation under Prevailing Conditions

In order to calculate the maximum capacity using the HCM2010 method, we begin by preparing the relevant information, particularly concerning the FFS. The researchers used the FFS measured directly from the survey, which is the average FFS of passenger cars in all traffic lanes. One of the four base speed-flow curves was selected for the base capacity in the analysis. The FFS is within the range of 84.5 to 92.5 km/h, so the capacity is 2,100 pc/h/ln. The equation below can then be used to calculate the capacity in prevailing conditions [39].

$$Capacity = BaseCap \times PHF \times f_{HV} \times f_P \quad (1)$$

where the capacity is the maximum flow rate under prevailing conditions (veh/h/ln), PHF is the peak-hour factor, f_{HV} is the adjustment factor for the presence of heavy vehicles in a traffic stream, and f_P is the adjustment factor for unfamiliar driver populations (assume that PHF and f_P are equal to 1.0). Thus, the capacity under prevailing conditions (surveyed state) is calculated for each section as 1,983 and 1,963 veh/h/ln, respectively. The traffic micro-simulation model estimated capacity under prevailing conditions for each section at 1315 and 1574 veh/hr/ln, which represent the primary highways of each type, were significantly lower than those of the HCM2010 method owing to the impact of traffic characteristics and influence of factors (median U-turns and heavy vehicles) disturbing the traffic flow (Table 6).

Table 6. Capacity estimation of primary highways under prevailing condition compared with the HCM2010 calculation.

Section no.	Highway Type	Capacity (Veh/hr/ln)		Diff. (%)
		Micro-Simulation	HCM2010	
1	Six-lane primary highway	1315	1983	-33.7%
2	Four-lane primary highway	1574	1963	-19.8%

4.2. Capacity Estimation under Base Condition

The base condition model was developed according to the driving behavior and road physical characteristics from the prevailing conditions model. This model was set to ideal conditions, and the relevant factors affecting the capacity were set to no median U-turns, with all vehicles as passenger cars in the traffic stream.

The base condition results are used to present the maximum capacity for each section and then compared with those of the HCM2010 method. The six-lane primary highway (section 1) had a maximum capacity of 2,130 pc/h/ln, while the four-lane primary highway (section 2) capacity was recorded at 2,194 pc/h/ln. However, both results were slightly higher than those of the HCM2010 approach, at 88.5 km/h FFS (for the range of 84.5 to 92.5 km/h FFS) by 0.3% to 2.9%, because they were not impacted by any factors (median U-turns and heavy vehicles), and the initial FFS from the micro-simulation model was higher than the (observed) average FFS for all traffic lanes. This was owing to the fact that, during the early stages of light traffic, vehicles in the micro-simulation model are free to choose a traffic lane; thus, most passenger cars chose to use the far-right lane, in which they could travel at a higher speed (Fig. 6).

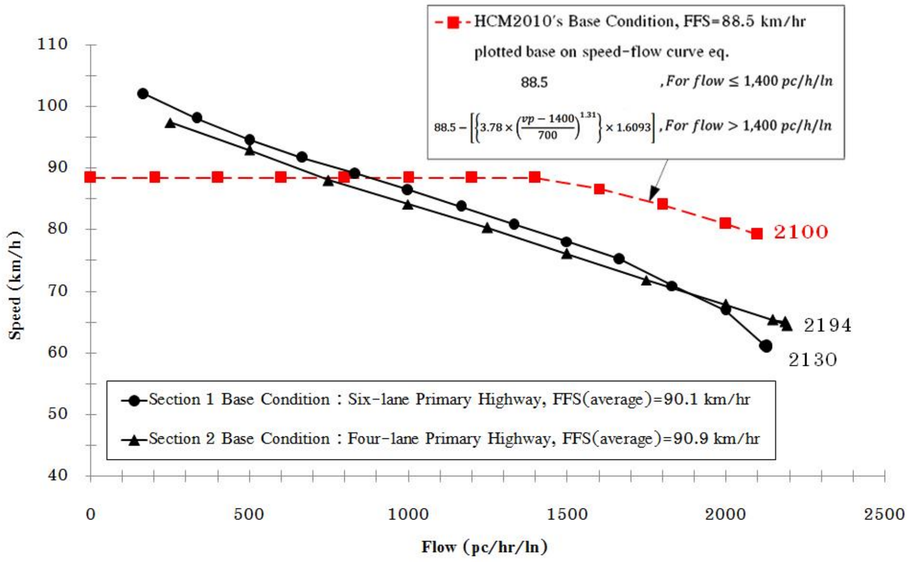


Fig. 6. Speed-flow curve under base condition.

Furthermore, it can be observed that the average capacity per lane on the six-lane primary highways is lower than that of four-lane primary highways by approximately 3.0%. The capacity decreases with the change in the number of lanes in each section, which is consistent with a common observation in numerous countries [40]. The reason for this phenomenon is that lane 1 (far-right lane) is typically dedicated as a high-speed lane, while the left lane is a lower-speed lane. Lane 3 on a six-lane primary highway is certainly often occupied by low-speed vehicles (heavy vehicles in the case of prevailing conditions). The average capacity per lane and effect of number of lanes on each primary highway section are illustrated in Fig. 7.

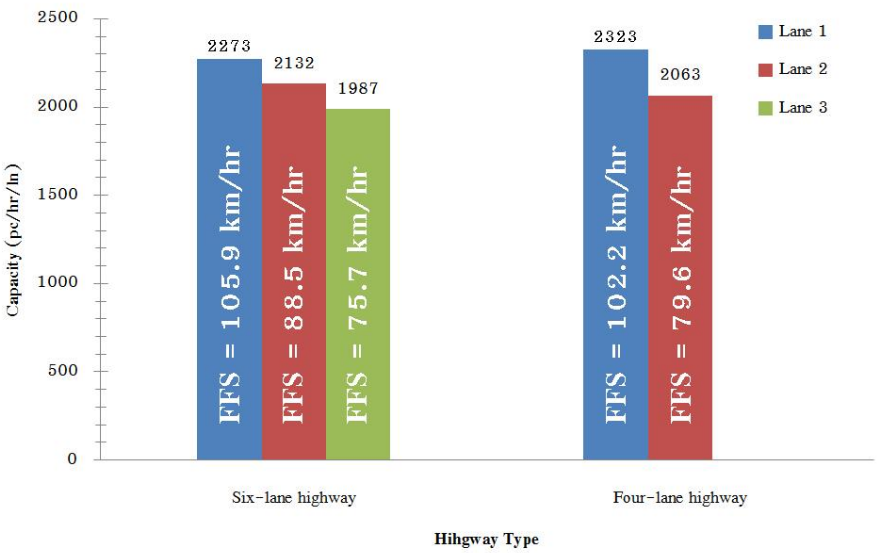


Fig. 7. Average capacity per lane for six-lane and four-lane primary highways.

4.3. Capacity Estimation under Scenario Conditions

The scenario condition model was further developed by the base model for each section, with varying factors affecting the capacity, including the median U-turn and heavy vehicles. The results demonstrate the effect of each factor on the capacity and lead to the model equation for capacity estimation.

4.3.1. Impact of median U-turn and heavy vehicles on primary highway capacity

The impact of the factors on each primary highway type capacity, as determined by the relationship between speed and traffic volume (speed-flow curve), was estimated by the micro-simulation model, as follows:

- The results for the six-lane primary highway capacity at 0 to 2 points/km with different heavy vehicle proportions (0%, 5%, 15%, and 25%) demonstrate a decrease in capacity by approximately 29.8% to 40.0% compared to the base conditions (Fig. 8).
- The results for the four-lane primary highways with the same conditions as the six-lane primary highways indicate a decrease in capacity by approximately 14.2% to 26.2% compared to the base conditions (Fig. 9).

The reduced primary highway capacity was a result of disturbance of the traffic in the opposite direction and obstruction of the traffic in the same direction as the traffic volume increased.

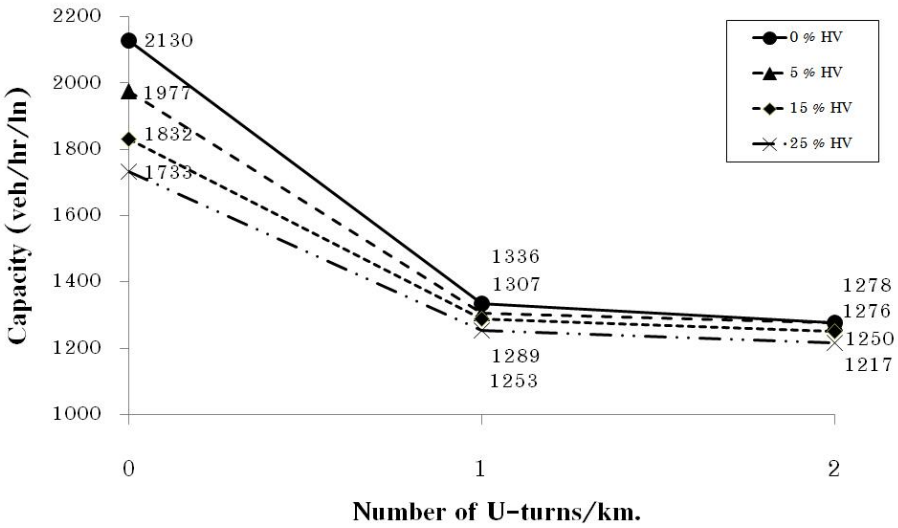


Fig. 8. Impact of median U-turn and heavy vehicles on capacity for six-lane primary highway.

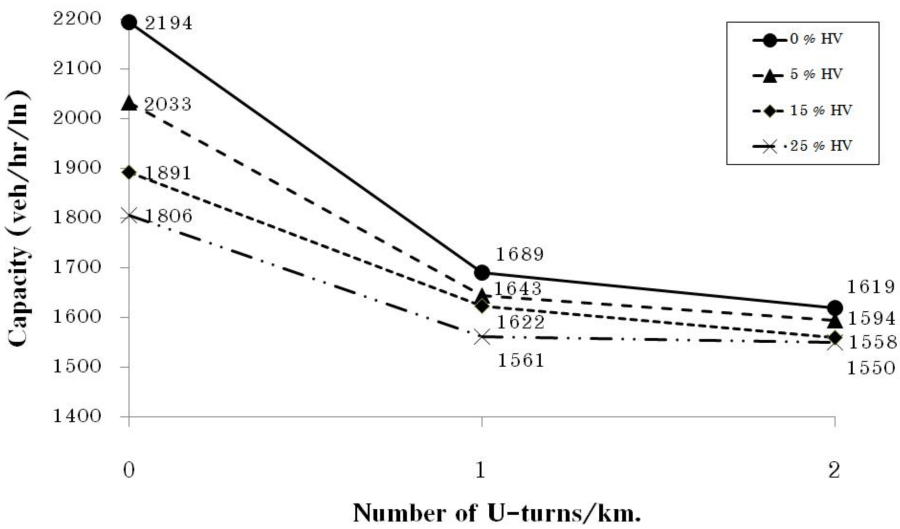


Fig. 9. Impact of median U-turn and heavy vehicles on capacity for four-lane primary highway.

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4.3.2. Capacity model

The relationships between capacity as a dependent variable and the median U-turn, and heavy vehicles as independent variables were investigated. Simple regression analysis was applied to verify the correlation coefficient (r) between the independent variables, and non-collinear variables were induced into the multiple linear regression models. The form of the multiple linear regression models is as follows:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \tag{2}$$

- Six-Lane Primary Highway Capacity Model

A multiple linear regression model was generated from the micro-simulation results, which estimated the six-lane primary highway capacity under prevailing conditions as follows:

$$C_{6\text{-}Lane} = 1899.386 - 331.375U - 6.949H \tag{3}$$

where C is the capacity for each primary highway section (veh/h/ln), U is the number of Median U-turns per kilometer (in the range of 0 to 2), and H is the percentage of heavy vehicles in the traffic stream (in the range of 0 to 25%). From the statistical analysis of the model, the coefficients of determination (R^2) reflected a high goodness of fit at 0.777, with significance at the 95% confidence level and significance of the F statistic at <0.001. The U coefficient was also significantly different from zero at the 95% confidence level, while the H coefficient was not statistically significant at the 95% confidence level. However, the heavy vehicle (H) factor concerned can be used to increase the overall model predictive, so it should be induced into the capacity model. The model provided a logical explanation for the effect of the factors on capacity. A negative sign indicated that, as the effect of the median U-turn and heavy vehicle factors increased, the capacity decreased. The standardized coefficients (β) demonstrate the influence of each variable, where the median U-turn was the most influential factor for six-lane primary highways. Details of the multiple linear regression model for capacity estimation of the six-lane primary highway are provided in Table 7.

Table 7. 95% confidence intervals for coefficient estimates of six-lane primary highway capacity model.

Independent variables	B	Std. Error	Beta	Sig.	R^2	Sig. of F
(Constant)	1899.386	97.947	-	.000		
No. of Median u-turn/km., U	-331.375	60.956	-.856	.000	0.777	0.001
%Heavy Vehicle, H	-6.949	5.184	-.211	.213		

- Four-Lane Primary Highway Capacity Model

A multiple linear regression model was generated from the micro-simulation results, which estimated the four-lane primary highway capacity under prevailing conditions, as follows:

$$C_{4\text{-}Lane} = 2013.867 - 200.375U - 7.421H \tag{4}$$

From the model statistical analysis, the coefficients of determination (R^2) were found to be 0.794, with significance at the 95% confidence level and significance of the F statistic at <0.001. The coefficients of all the independent variables were also significantly different from zero at the 95% confidence level. The model provided a logical explanation for the effect of the factors on capacity. The median U-turn had a greater impact on capacity than heavy vehicles for the four-lane primary highways. Details of the multiple linear regression model for capacity estimation of the four-lane primary highway are provided in Table 8.

Table 8. 95% confidence intervals for coefficient estimates of four-lane primary highway capacity model.

Independent variables	B	Std. Error	Beta	Sig.	R^2	Sig. of F
(Constant)	2013.867	59.567	-	.000		
No. of Median u-turn/km., U	-200.375	37.071	-.817	.000	0.794	0.001
%Heavy Vehicle, H	-7.421	3.152	-.356	.043		

The maximum capacities of the base models were 2,130 and 2,194 for the six-lane and four-lane primary highways, respectively, which were determined by using the maximum results from running the base condition in the micro-simulation model. Moreover, a statistical model was used to estimate the capacity under different scenario conditions. Twelve capacity results from running different scenarios were used to fit the curves in the statistical models. The multiple linear regression model with the influent factors including H and U were selected as the most appropriate among the different types of statistics models, because the equation model exhibited statistical significance, and reflected a high goodness of fit and logical sign explanation, indicating the effects of the factors. In fact, differences could be observed between the maximum capacity of the base model compared to that of the multiple linear regression model assigning H and U as 0, because of the different developing paths between the base model and scenario conditions.

5. Conclusion

Micro-simulation models have been increasingly used in traffic and transport applications. One capability of a micro-simulation model is the approach for estimating highway capacity. In addition to reducing the limitations of survey data, micro-simulation models can effectively emulate local traffic conditions, resulting in more accurate highway capacity estimations. In this study, a micro-simulation model was used to estimate the highway capacity of six-lane and four-lane highways as representatives of the multilane primary highways in Thailand.

A median U-turn is considered a factor affecting highway capacity, adding to the factors considered in HCM. The effects of median U-turns and capacity estimation of primary highways in Thailand were used in the traffic micro-simulation model. This study also used the prevailing conditions representing the primary highways of each type to perform the micro-simulation and compare the capacity. The micro-simulation model results were found to be significantly lower than those of the HCM2010 method. This indicates that the micro-simulation modeling from survey database conditions resulted in different highway capacities from those of HCM2010. As a result, micro-simulation models were developed to determine and estimate the maximum capacity for the base and scenario conditions by considering a median U-turn factor.

Under the base conditions, the capacity estimations of both the six-lane and four-lane primary highways results were slightly higher than those of the HCM2010 calculation, because they were not impacted by any factors. However, the prevailing conditions representing the primary highways of each type exhibited capacity results that were significantly lower than those of the HCM2010 method. This was owing to the impact of traffic characteristics and the influence of factors disturbing the traffic flow. Vehicles using median U-turns slow down and disturb the traffic flowing in the opposite direction, as well as obstruct the traffic moving in the same direction, as the traffic volume increases. Interactions and conflicts among vehicles also interfere with traffic flow on the carriageways and significantly reduce the stream speed as well as capacity.

The relationships among capacity, median U-turns, and heavy vehicles were developed into a multiple linear regression equation for capacity estimation of six-lane and four-lane primary highways. This operational efficiency, as a set of guidelines for the design and analysis of multilane highways based on the standards of Thailand's DOH, includes assumptions for level terrain. The concept can be extended in future studies by considering additional factors and different highway types. Furthermore, the observed maximum flow or other estimation methods using the empirical data should be verified and compared.

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