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Reduction of vehicle fuel consumption from adjustment of cycle length at a signalized intersection and promotional use of environmentally friendly vehicles

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Abstract

Road transportation is the main factor affecting high greenhouse gas (GHG) emissions and poor air quality in the atmosphere. One cause is traffic congestion on urban streets due to plenty of travel demand over road network capacity and inefficient traffic management at signalized intersections. Moreover, typical vehicles consume much fuel affecting the problems mentioned above, and there is still little use of environmentally friendly vehicles, such as the hybrid car (HV). This research investigated how efficient traffic signal management could reduce vehicle fuel consumption approaching a signalized intersection in traffic congestion. In addition, the fuel consumption of HV was compared with that of conventional gasoline cars regarding how it could reduce fuel consumption in a condition of the adjustment of traffic signal management. Then, estimating fuel consumption at the intersection was assembled by traffic simulation to identify driving patterns/modes of each vehicle. The results indicated that an adjustment of traffic signal management at the intersection by optimizing cycle length calculation based on Webster's method could reduce vehicle fuel consumption by decreasing vehicle delay and stop time. If HVs replaced conventional gasoline cars by at least 5%, fuel consumption would be significantly reduced when HVs stop and run at a fluctuated speed between 1-20 km/hr (crawling) near the intersection. Therefore, this research could well detect a reduction in fuel consumption of environmentally friendly vehicles, even for vehicles traveling at a crawl.

Keywords: Traffic signal management, Cycle length, Signalized intersections, Fuel consumption, Environmentally friendly vehicles, Hybrid car

1. Introduction

Recently, high greenhouse gas (GHG) emissions such as CO_2 and air pollution from small particles, especially PM 2.5, distributed in the atmosphere are the main issue that concern Thai society. The leading cause of its emissions comes from engine combustion in the road transport sector. Due to high GHG and poor air quality in Thailand, the road transport sector has been critically affected by much fuel consumption from the combustion of various vehicle types [1], particularly personal cars, trucks, and buses in metropolitan areas, i.e., Bangkok and major cities such as Chiang Mai and Chonburi. Significant causes of much GHG and poor air pollution from road transportation consist of (1) plenty of vehicles in urban area by travel demand, (2) poor and inefficient fuel combustion of old vehicles, and (3) traffic congestion due to long waiting time (delay) of vehicles from getting the red signal at intersections [2]. In particular, a major contributor of vehicle emissions comes from needless fuel consumption at intersections when waiting for the traffic signal to turn green [3]. Thus, it would be better if vehicles use less time for stopping at intersections, which would reduce their fuel consumption.

In developing countries, there are countermeasures for mitigation of GHG emission or fuel consumption in the transport sector, such as planning urban railway extensions and promoting alternative fuel (biodiesel, ethanol-blended gasoline, or compressed natural gas (CNG)) [4]. Even though these countermeasures could lessen fuel consumption, the number of motorists in Bangkok and major cities in Thailand is still high, and traffic remains largely congested. In addition, measures related to traffic control management can be considered but are generally considered less effective than other measures [3]. Although traffic control management is not effective in fuel consumption reduction, it provides a basic solution that helps diminish fuel consumption, particularly with better traffic control management, which would be cheaper than the other measures mentioned above [4].

Regarding traffic congestion on urban streets, traffic delay and fuel consumption would decrease if it can be solved by adjusting traffic signal management because vehicle engines would not be running for a long time [3, 5]. The optimum cycle length to adjust traffic signals is the total signal time serving all signal phases, including the green time plus any change interval. It would be better if cycle length is identified based on traffic data analysis by calculation methods [6] that optimizes less delay of each vehicle. However, the traffic police typically manage most traffic signal control by their observations without delaying vehicle analysis, and the cycle

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length from their observations is longer than from traffic data analysis. Therefore, better traffic signal management based on optimum cycle length identification can be another method for mitigating fuel consumption of vehicles, GHG, and poor air pollution emissions.

Hybrid cars (HV), one of the countermeasures for promoting alternative fuel and a new generation of environmentally friendly vehicles, has been developed to save fuel. It could keep electricity energy from the internal combustion engine at the battery pack and electric machine to operate the vehicle, instead of using 100% gasoline or diesel engine, for certain driving patterns and periods [7]. Thus, HV has been an interesting issue to study the impact of vehicle fuel consumption, especially in traffic congestion on the road network over the past decade [4].

By contributions mentioned above (vehicle delay at the intersection affecting much fuel consumption, better traffic signal management, and promotional use of HV), the objective of this research is to investigate how efficient traffic signal management by optimizing cycle length could reduce vehicle fuel consumption approaching at a signalized intersection in traffic congestion in a metropolitan area, Bangkok, Thailand. In addition, fuel consumed by conventional cars, using gasoline, was compared with that by environmentally friendly vehicles, i.e., hybrid cars (HV). This comparison investigated how HV could reduce fuel consumption if there were the calculation of optimum cycle length. Estimating fuel consumption at the intersection was assembled by traffic simulation to identify driving patterns/modes of each vehicle.

2. Literature reviews and related theories

2.1 Estimating vehicle fuel consumption based on driving patterns

The driving patterns of the vehicle are the forms of the running engine, used to estimate fuel consumption or GHG emission [8]. Previous research conducted traffic data reflecting driving patterns to study their impacts on fuel consumption and GHG emission by using vehicle specific power (VSP) [9]. One study applied VSP by the delay correction model to estimate CO_2 emissions of buses at signalized intersections [5]. There was research using Virginia Tech (VT) Models to estimate fuel consumption and GHG emissions by analyzing instantaneous speed and acceleration [10, 11]. Fuel consumption and CO_2 emission impacts based on real-world data were investigated by Barth and Boriboonsomsin [12]. Real-world data were collected from probe vehicles (vehicles are installed with devices, such as GPS, indicating position, time-stamped, and speed), and fuel consumption and CO_2 emission were then measured by probe vehicles. Choudhary and Gokhale [13] studied GHG emission from different vehicle types (personal cars and rickshaws) in different traffic conditions. Finally, Pitanuwat and Sripakagorn [14] used driving pattern data to investigate driving behavior, and they found that more sensitivity driving compared to aggressive driving affected fuel consumption.

From the literature, the relationship of fuel consumption and GHG emission could be well explained, and driving patterns from test and probe vehicles could be well reflected by four basic driving patterns, which are: stopping/idling, accelerating, cruising, and decelerating. However, impact study on vehicle fuel consumption is difficult to estimate in traffic jams, while environmentally friendly vehicles has been also promoted.

Regarding estimation of fuel consumption in traffic congestion, Kumar et al. [15] and Sekhar et al. [16] studied the impact of fuel consumption when test vehicles stopped at the intersection with the engine idling. The result of estimation indicated that stopped vehicles affected much fuel loss. However, apart from stopped vehicles, which often indicate traffic congestion at the intersection, there is another condition when vehicles run at low speed before they stop in the queue and then move out from the intersection. This condition could be called crawling or stop-and-go. In addition, Srisakda et al. [17] and Fukuda et al. [18] brought 10,000 probed vehicles operated in Bangkok Metropolitan Region (BMR), Thailand. Test vehicles were separated into four basic driving modes. These driving modes are under the concept of the duration fraction defined as "Time Sharing of Driving Modes." Moreover, another driving mode called "Crawling" runs at low speed near intersections, as shown in Figure 1.

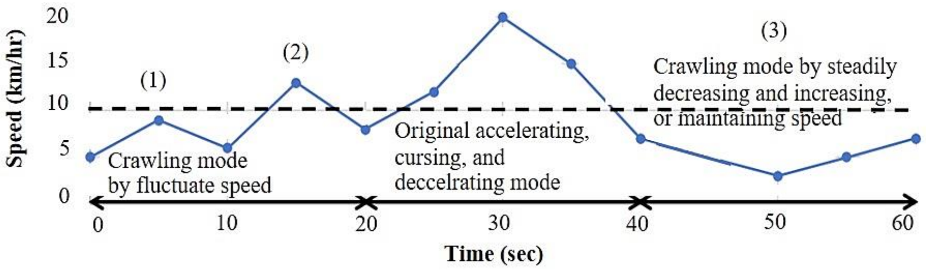


Figure 1 Examples of driving cycles of probe vehicles reflecting crawling behavior [17]

From Figure 1, vehicle crawling could be defined in 3 conditions as following:

(1) There was a fluctuation of speeds between 1 to 10 km/hr.

(2) There was only speed above 10 km/hr only once, but previous and following speeds within the period are below 10 km/hr.

(3) There were decreasing and increasing speeds or maintaining at speeds within 10 km/hr.

From the above conditions, vehicle crawling could indicate traffic jams affecting fuel consumption, not only for stopping vehicles but also for another driving pattern/mode. Therefore, environmentally friendly cars such as hybrid cars have been shown to have positive impacts when operating at a crawling mode, and their fuel consumption could be estimated more accurately.

2.2 Impacts of hybrid car operating on road network

Some studies considered promoting HV or other environmentally friendly vehicles on the road network. These studies investigated the reduction of vehicle fuel consumption in different traffic conditions (congestion or un-congestion), area (inner or outer area of metropolitan) on arterial roadways [14, 17, 18], and there was a comparison in fuel consumed between conventional gasoline and hybrid cars. These studies pointed out that conventional gasoline cars consumed much fuel consumption in the inner area, on arterial roadways in Bangkok, but hybrid cars could reduce fuel consumption in the same conditions. Raykin et al. [19] assessed the fuel consumption impact of plug-in hybrid electric vehicles (PHEVs) in different periods and road categories, and they used the traffic assignment model to explain traffic conditions by stopping percentage and average speed of this vehicle type on the road network. The results indicated that the fuel consumption of hybrid cars was the lowest on the arterial roadways. There was a study on the energy reduction among environmentally friendly vehicles consisting of hybrid electric cars (HEVs), plug-in hybrid electric cars PHEVs, and battery electric cars (BEVs). Their energy reductions were compared with ordinary cars in Beijing, China, by Wang et al. [20]. The data collected from one thousand probe vehicles to explain driving patterns in each sub-area in peak and off-peak hours and find the impact of all environmentally friendly vehicles. The results found that all vehicle types in peak hours and the inner area consumed the most fuel, and all environmentally friendly vehicles could reduce fuel consumption, particularly in peak hours. In addition, the impact of using HV in the high occupancy lanes (HOV) was investigated by Nisamani et al. [21]. The result showed that driving HVs in the HOV lanes could reduce vehicle fuel consumption and emission.

The research literature assures that environmentally friendly cars such as HV or PHEV could reduce fuel consumption, especially on arterial roadways. However, previous studies did not sufficiently focus on one of the essential components of roadways, which is the signalized intersections. If there is a well-managed traffic signal, especially by optimizing cycle length as presented in the present research, the fuel consumption of environmentally friendly cars could be decreased.

2.3 Studies on traffic management by option identification based on traffic simulation

There were previous studies regarding traffic management and its impact on arterial roadways together with signalized intersections. For example, traffic management analysis at a group of signalized intersections was investigated based on traffic simulation [22]. Ritnamkham and U-tapao [23] studied traffic impact due to opened u-turn bridge/overpass to replace conventional u-turn in the same level of the roadway, examined by traffic simulation. Also, Thamapan and Phubupphapan [24] studied traffic management on the multi-lane highway at the university entrance by finding the most suitable scenario (less delay of vehicles) in different traffic signal management strategies based on traffic simulation analysis.

From the literature, traffic simulation can identify the most suitable option in solving traffic congestion or traffic accidents on all components of arterial roadways. Traffic engineers can see the image of the forecast traffic conditions from this tool representing solution options or scenarios prior to the commencement of construction or adjustment of the road network. Traffic simulation can provide driving patterns (speed and time), which can directly calculate vehicle fuel consumption. Although fuel consumption can be also calculated in the field directly, its calculation is difficult to test on all vehicle types approaching the intersection and predict possible situations. Thus, this research utilized traffic simulation as a tool to calculate fuel consumption due to its easiness and ability to forecast results.

2.4 Traffic data for congestion assessment and optimum cycle length at intersections

There are three crucial traffic variables for congestion assessment and optimum cycle length at intersections: queue length, vehicle delay, and level of service (LOS). Notably, LOS is a measurement indicating the quality of roadway service and congestion. Highway capacity manual 2010 uses the criteria A, B, C, D, E, F to explain the difference of LOS from the lightest traffic (A) to the most congested traffic (F) [25]. To consider LOS, stop delay per vehicle measured at a signalized intersection is implemented as its control delay per vehicle indicator.

The main concept of optimum cycle length is suitable green time allocation in each direction. The targets are (1) less delay per vehicle and (2) less conflict point elimination to decrease road accidents [6, 26]. In addition, all vehicles should get equal delay if possible. Too much time on the green should not be given in some directions. The summary of green time received in all directions within one intersection is called cycle length, which is vital for allocating traffic signals.

Some methods indicate the optimum cycle length corresponding with traffic volume approaching an intersection. Every method has the same use of saturation flow and optimum cycle length. Saturation flow is a decision parameter for changing traffic signal from green, amber (yellow), to red. It can be counted at the stop-line of intersections in each direction. Then, the calculated optimum cycle length depends on the physical characteristic of the intersection and traffic volume approaching the intersection and saturation flow in each direction [6].

Webster's method is the most popular method in use [27] and was implemented to solve traffic congestion in many studies, such as Sudharshan and Hussain [28], Patel et al. [29], and Yu et al. [30]. Several studies applied this method to develop the new models for additional impact studies, excluding vehicle delay, such as fuel consumption and tailpipe emissions [31, 32], for model correlation [33], and oversaturation traffic analysis [34]. In addition, most research mentioned above indicated that this method could identify the forms of least delay occurring at signalized intersections. Therefore, Webster's method was also used for this research to obtain the least vehicle delay and fuel consumption reduction.

Webster's method considers the factor of total lost time in all directions at an intersection due to all red (red signal all directions) and yellow signals by equation 1 [35, 36].

$$C_0 = \frac{1.5L + 5}{1 - \sum_{=1}^{\phi i} Y_i} \quad (1)$$

Where C_0 = Optimum cycle length (Second)

L = Total lost time due to red signal in all directions (All red)

Y_i = Ratio of traffic volume approaching an intersection and saturation flow when vehicles move out from an intersection in each direction (i)

Φ = Number of traffic signal phase in one cycle length

Then, the calculated cycle length will be divided by green time in each direction corresponding with traffic volume approaching an intersection.

3. Research methodology

The methodology in this research is illustrated in Figure 2. Firstly, traffic volume approaching the intersection from the survey and fuel consumption from two tested cars were collected in the field. Then, these two sources of data were brought to calculate vehicle fuel consumption approaching the intersection by traffic simulation development.

For more reliable results, initial results from microscopic traffic simulation were calibrated and validated with field traffic data. Finally, simulation from each scenario was represented, and fuel consumption was also calculated.

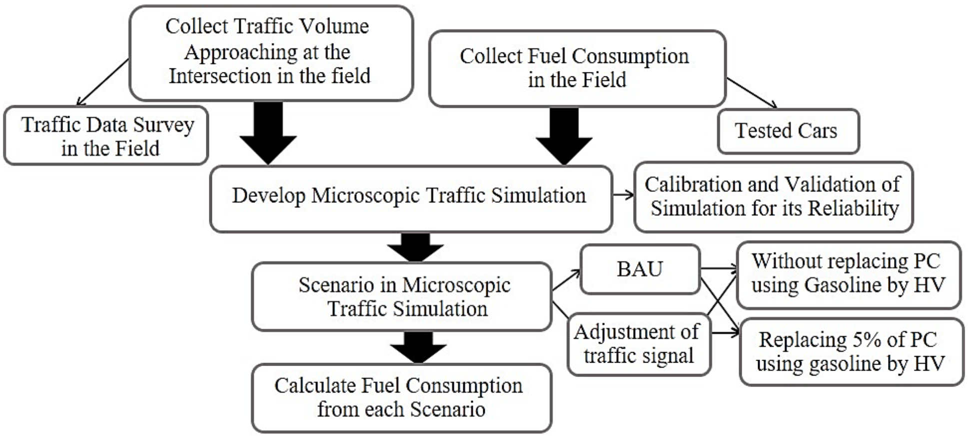


Figure 2 Research methodology

3.1 Scope of research

"Saphan Kwai," an intersection in Bangkok Metropolitan Administration (BMA), Thailand was selected as the study site, as shown in Figure 3. This intersection is a roadway crossing of Phaholyotin Road (northbound and southbound: NB and SB), Pradiphat Road (eastbound: EB), and Sutthisan Winitchai Road (westbound: WB). Phaholyotin Road and Pradiphat Road support traffic volume from the northern BMA and the Nonthaburi area, respectively. Sutthisan Winitchai Road is the connected roadway between Phaholyotin Road and Viphavadee-Rangsit Road, another main roadway from the northern BMA. Traffic volume from these roads leads to congestion almost the time on weekdays and weekends due to plentiful vehicles approaching the intersection moving into and out of the center area of BMA in all four directions.

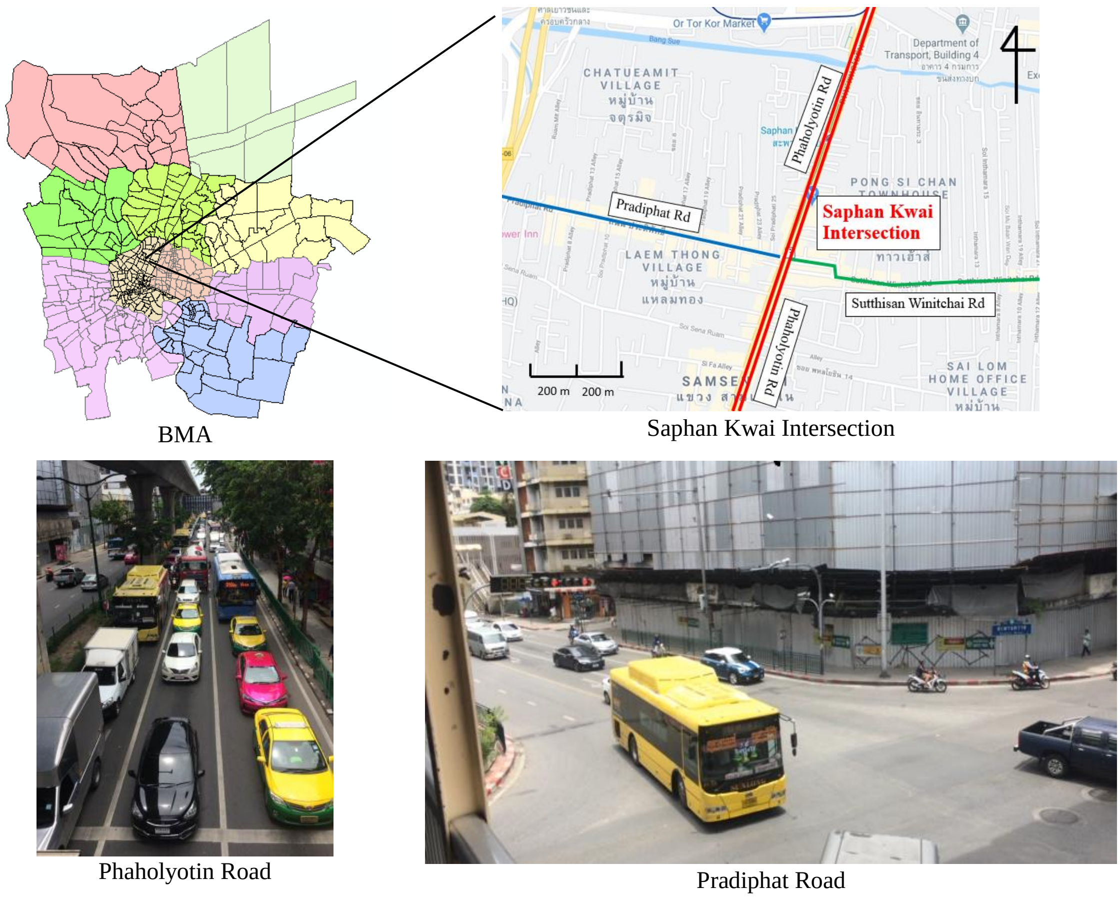


Figure 3 Study site

3.2 Traffic data survey and research assumptions

Required traffic data from the study site consisted of counted traffic volume, observed queue length in all four directions approaching the intersection, current traffic signal control, and physical characteristics: a number of lanes, lane width, and route choice for turning in each direction at the intersection.

Traffic data were collected on 11th December 2019 (weekday) for 12 hours from 7 a.m. to 7 p.m. Traffic data, including hourly traffic volume in all directions and average queue length in each approach at the intersection in 12 hours, can be shown in Figure 4.

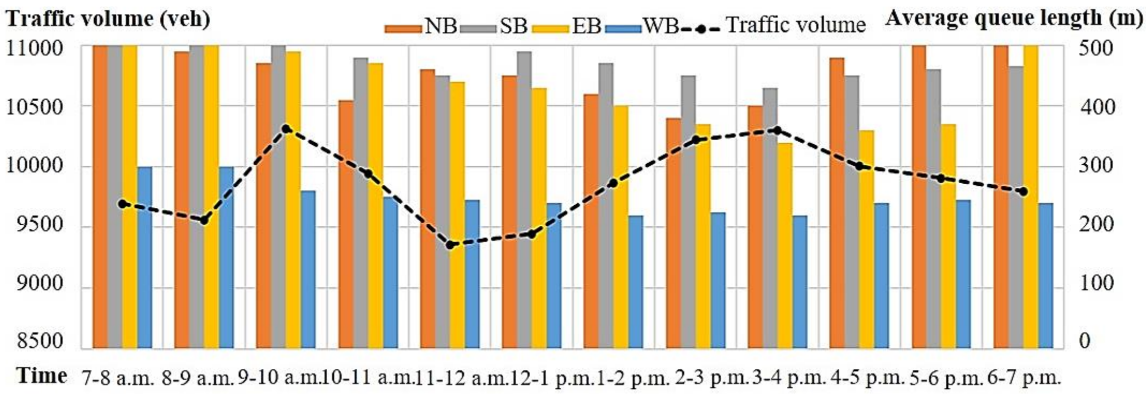
From Figure 4, hourly traffic volume data are in the range of 9,500 and 10,500 vehicles, which are not much different. These data cannot clearly explain which periods have the most traffic congestion, whereas hourly average queue length data is longer than the position detected in morning and evening peaks. Moreover, the overall average queue length in all four directions in the morning peak is longer than that in the evening peak. Consequently, traffic condition in the morning peak (7 a.m. to 8 a.m.) was selected and sufficient to calculate of vehicle fuel consumption based on traffic simulation.

Since several types of vehicles on arterial roadways, and the estimation of fuel consumption requires vehicle type, ranges of running speed, and driving modes, estimation in the field is quite difficult to obtain due to different engine sizes and driving modes. Therefore, engine size, which varies directly to fuel consumption (larger engine size, such as that of buses or trucks, consumes more fuel than the personal car), was identified as the first assumption in this research.

For a simple way to estimate fuel consumption in this research, all lengths of vehicle types were converted to passenger car unit (PCU). In the traffic engineering principle, PCU means the typical length of a personal car (PC) that equals 4.5 meters (= 1 PCU) [37]. If some vehicle types are longer than PC, such as buses or trucks, these vehicle types would be greater than 1 PC. For example, if the length of a bus equals 9 meters, it is two times that of PC's length or equals 2 PCUs. Then, traffic volume data in PCU was put into traffic simulation to estimate fuel consumption.

For example, if there are 2 PCUs, which is a bus, it is possible for fuel consumption more than a personal car (1 PCU). Consequently, PCU was the second assumption made and implemented as the unit of traffic volume in this research. PCU value in each vehicle type from the specification of the Department of Highway of Thailand [38] can be shown in Table 1.

Traffic volume of 12 vehicle types approaching all four directions of the intersection in PCU on 11th December 2019 (weekday) in the morning peak hour (from 7 a.m. to 8 a.m.) was also collected as shown in Table 1.



Remark: The maximum queue length can be detected in NB, SB, and EB = 500 meters, in WB = 300 meters. In the morning and evening peak, queue lengths are longer than the position detected.

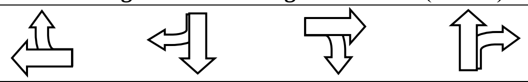
Figure 4 Traffic data including hourly traffic volume and average queue length approaching at the intersection in 12 hours

Table 1 Passenger car unit in each vehicle type and traffic volume approaching the intersection

Vehicle Types	PCU	No. of Vehicles (veh)	Traffic Volume in PCU
Bi+Tri Cycle (BC)	0.00	22	0
Motorcycle (MC)	0.33	1,785	589
Personal Car containing < 7 passengers (PC1)	1.00	5,588	5,588
Personal Car containing > 7 passengers (PC2)	1.00	1,573	1,573
Light Bus (LB)	1.50	107	161
Medium Bus (MB)	1.50	91	137
Heavy Bus (HB)	2.10	466	979
Light Truck (LT)	1.00	42	41
Medium Truck (MT)	2.10	13	27
Heavy Truck (HT)	2.50	8	20
Full Trailer (Tr)	2.50	0	0
Semi-Trailer (STr)	2.50	0	0
Total		**9,695**	**9,115**

Regarding other traffic data, the current traffic signal and physical characteristics (a number of lanes, lane width, and route choices for turning in each direction at the intersection) were collected in the field. The physical characteristics of the intersection consist of three lanes in each direction of Phaholyotin Road in northbound and southbound with 3-meter lane width, two lanes in each direction of Pradiphat and Sutthisan Winitchai Road with 3-meter lane width. Current information on traffic control management can be shown in Table 2.

Table 2 Current information of traffic control management of the intersection

Intersection	Traffic Signal Phase during Green Time (second)				Cycle Length (second)
Saphan Kwai					230
	49	73	33	75	

From Table 2, the cycle length obtained from the study site equals 230 seconds (3 minutes 50 seconds), which was quite a long duration compared with other less congested intersections. The cycle length at this intersection is set in long-duration because traffic management is operated by traffic police who believe that longer cycle length can rapidly decrease long queue length. Vehicle delay due to longer cycle length is greater than that due to shorter cycle length.

As Bangkok's climate is considerably hot throughout the entire year, the third assumption was set up that every stopped vehicle at the intersection did not switch off its engine. Although vehicles stop at the intersection for a long time, most vehicles still switch on the engine to keep the air conditioners running.

3.3 Fuel consumption collection in the field

Two PCs conventional gasoline car and hybrid car were utilized in field tests as representative for fuel consumption of all vehicles approaching the intersection. Information and properties of two tested PCs can be presented in Table 3. To reflect fuel consumption of PC containing >7 passengers and pick up, the engine size of two PCs is quite big (2,400 cc) compared with typical PC's engine size on the road network (1,500 cc). PC containing >7 passengers and pick up use large-sized engine and consume more fuel than PC containing <7 passengers. However, they are accounted as 1 PCU.

In Table 4, Fuel consumption data in the field from tested cars were collected on arterial roadways approaching the intersection during 11th-12th December 2019 (weekdays) for 12 hours from 7 a.m. to 7 p.m. In this research, however, the fuel consumption data were selected only in the morning peak hour (from 7 a.m. to 8 a.m.) to represent this Table due to the most congested period, considering traffic data in the field. Then, fuel consumption data in the field test and traffic volume converted in the unit of PCU were put into traffic simulation.

Table 3 Two tested PC information and properties

Properties	Hybrid Car	Conventional Gasoline Car
Type of PC	Toyota Camry 2.5 HV Navigator	Toyota Camry 2.5G A/T
Engine Size (cc)	2,494	
Year of Manufacture	2012	
Weight (kg)	1,600	1,475
Capacity of Battery	6.5 A-hr (3 hrs)	-

Source: Toyota Motor Thailand Company [39]

Table 4 Time-frequency of engine operation (sec) and rates of fuel consumption (cc/sec)

Weekday_Arterials_Peak_Conventional

Driving mode	Stopping/Idling				Crawing				Accelerating				Cruising				Decelerating			
Speed Range (km/h)	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec
0	0.25	298	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1-10	-	-	-	-	0.53	564	0	0	1.95	155	0	0	0.40	126	0	0	0.35	169	0	0
11-20	-	-	-	-					1.24	169	0	0	0.68	122	0	0	0.46	211	0	0
21-30	-	-	-	-	-	-	-	-	1.39	123	0	0	0.73	108	0	0	0.51	178	0	0
31-40	-	-	-	-	-	-	-	-	1.65	95	0	0	1.23	87	0	0	0.49	142	0	0
41-50	-	-	-	-	-	-	-	-	1.96	78	0	0	1.26	84	0	0	0.62	119	0	0
51-60	-	-	-	-	-	-	-	-	1.58	64	0	0	0.89	73	0	0	0.63	104	0	0
>61	-	-	-	-	-	-	-	-	1.27	21	0	0	0.54	13	0	0	0.59	24	0	0
Total time frequency (sec)	-	298	-	0	-	564	-	0	-	705	-	0	-	613	-	0	-	947	-	0
Avg. Fuel consumption (CC/sec)	0.25	-	-	-	0.53	-	-	-	1.58	-	-	-	0.82	-	-	-	0.52	-	-	-

Weekday_Arterials_Peak_Hybrid

Driving mode	Stopping/Idling				Crawing				Accelerating				Cruising				Decelerating			
Speed Range (km/h)	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec
0	0.25	18	0	286	-				-	-	-	-	-	-	-	-	-	-	-	-
1-10	-	-	-	-	0.44	283	0	269	1.09	82	0	70	0.39	63	0	72	0.21	76	0	88
11-20	-	-	-	-					0.82	101	0	74	0.51	64	0	64	0.30	98	0	116
21-30	-	-	-	-	-	-	-	-	1.12	86	0	39	0.48	57	0	61	0.30	63	0	109
31-40	-	-	-	-	-	-	-	-	1.16	70	0	35	0.52	45	0	47	0.45	59	0	79
41-50	-	-	-	-	-	-	-	-	1.16	49	0	32	0.61	42	0	38	0.29	53	0	63
51-60	-	-	-	-	-	-	-	-	1.33	33	0	33	0.55	37	0	35	0.29	47	0	58
>61	-	-	-	-	-	-	-	-	1.11	25	0	0	0.51	10	0	0	0.21	21	0	0
Total time frequency (sec)	-	18	-	286	-	283	-	269	-	446	-	283	-	318	-	317	-	417	-	513
Avg. Fuel consumption (CC/sec)	0.25	-	-	-	0.44	-	-	-	1.11	-	-	-	0.51	-	-	-	0.29	-	-	-

Rates of fuel volume consumed (cubic centimeter; cc) in 1 second (sec) on both hybrid and conventional were calculated in each speed range and driving mode. Fuel consumption rates for both gasoline engine operated (ON) and in-operated (OFF) cases represented by indicated time-frequency of engine operation (sec) are shown in this Table.

From Table 4, fuel consumption rates in the crawling mode were found at speed ranges of 1-10 and 11-20 km/h. When the conventional gasoline car is compared with the hybrid car, the gasoline car rates are greater than those in the hybrid car for all driving modes. In addition, in the gasoline engine in-operated (OFF), time-frequency cannot be discovered because it consumed fuel all the time. These field results prove that the hybrid car can save fuel on the urban street compared with the conventional gasoline car.

3.4 Microscopic traffic simulation and reliability of simulation

From traffic data set in 12 hours, the morning peak data is the most effective for calculating vehicle fuel consumption in traffic congestion based on traffic simulation. This simulation can provide the driving pattern (speed and time) for calculation. Consequently, traffic data collected in the morning peak hour (from 7 a.m. to 8 a.m.) and fuel consumption collected in the field were put into microscopic traffic simulation. The scope of the simulation is a 1-kilometer radius from the center of the intersection.

3.4.1 Reliability of the microscopic traffic simulation

The reliability of simulation can be proved by (1) GEH statistics and (2) Start-up lost time. GEH Statistics [40] is a formula used in traffic modeling to compare two sets of traffic volumes. It is computed as shown in equation 2.

$$GEH = \sqrt{\frac{2(E-V)^2}{(E+V)}} \tag{2}$$

- GEH < 5 for single link
- GEH < 4 for the summation of all link counts

Where E = volume from models or simulations
V = volume counted in the field

In this research, traffic volumes counted approaching the intersection in all four directions from simulations were compared with those from observations in the field. Traffic volumes from simulations and observations were calculated using GEH, as presented in Table 5.

Table 5 Comparison of traffic volumes approaching the intersection from simulations and observations in the field

Direction	**Traffic Volume (PCU/hr)**		**GEH**
	Simulation	**Observation**	
Northbound (NB)	2,915	2,983	1.8
Eastbound (EB)	1,984	1,864	3.8
Southbound (SB)	2,935	2,983	1.3
Westbound (WB)	1,967	1,864	3.3

The comparison of traffic volumes from simulations and observations were found that all GEH values of four directions approaching the intersection are less than 5. Thus, this research’s simulations are reliable and similar to actual traffic conditions in the GEH statistics.

Start-up lost time is the duration of each vehicle passing the intersection, counted from moving out of stop until passing through the stop-line at the intersection. From simulations, the average start-up lost time from all cycle lengths of vehicles approaching the intersection in the southbound (SB) direction in the morning peak was compared with that form observations in the field. The comparison considered vehicles stopping in the queue at every 10 meters below the stop-line (10, 20, 30, 40, and 50 meters). The results of start-up lost time comparison can be shown by graphs in Figure 5.

As from Figure 5, it was found that start-up lost time from 2 sources (simulation and observation) are not much different in each stopping position. For example, the difference between them at 10 meters below the stop-line is only 1 second. For overall comparison, root-mean-square error (RMSE), which can be calculated by the difference summation of start-up lost time from 2 sources, equals 0.8 seconds. Therefore, in case of start-up lost time, simulations of this research are reliable and similar to actual traffic conditions.
Moreover, speed and reaction time at stop of personal cars stopping at the queue and moving out from the intersection are adjusted as identical to their speed and reaction time in the field. Consequently, developed microscopic traffic simulation has already been calibrated and validated for its reliability.

3.5 Scenario identification

In this research, traffic simulations are implemented to identify the reduction in vehicle consumption and to promote hybrid car (HV) use. This research is necessary to perform several cases or scenarios of simulations to obtain more impacts.

For scenario identification in this research, Business as Usual (BAU), without doing anything, is the case for comparing with other different conditions, which are adjustment of traffic signal by optimum cycle length calculation and replacing 5% of the personal car (PC) using conventional gasoline cars by hybrid cars. 5% is implemented for this scenario because this identification was accumulated for a number of HVs in Thailand that equaled 148,688 vehicles by the end of 2019 [41]. This number was accounted for approximately 5% of all private cars in BMA.

Therefore, fuel consumption estimated at the intersection is divided into four scenarios as follows:

1) BAU
2) Adjustment of traffic signal without replacing gasoline PC by HV
3) Without adjustment of traffic signal and replacing 5% of gasoline PC by HV
4) Adjustment of traffic signal and replacing 5% of gasoline PC by HV.

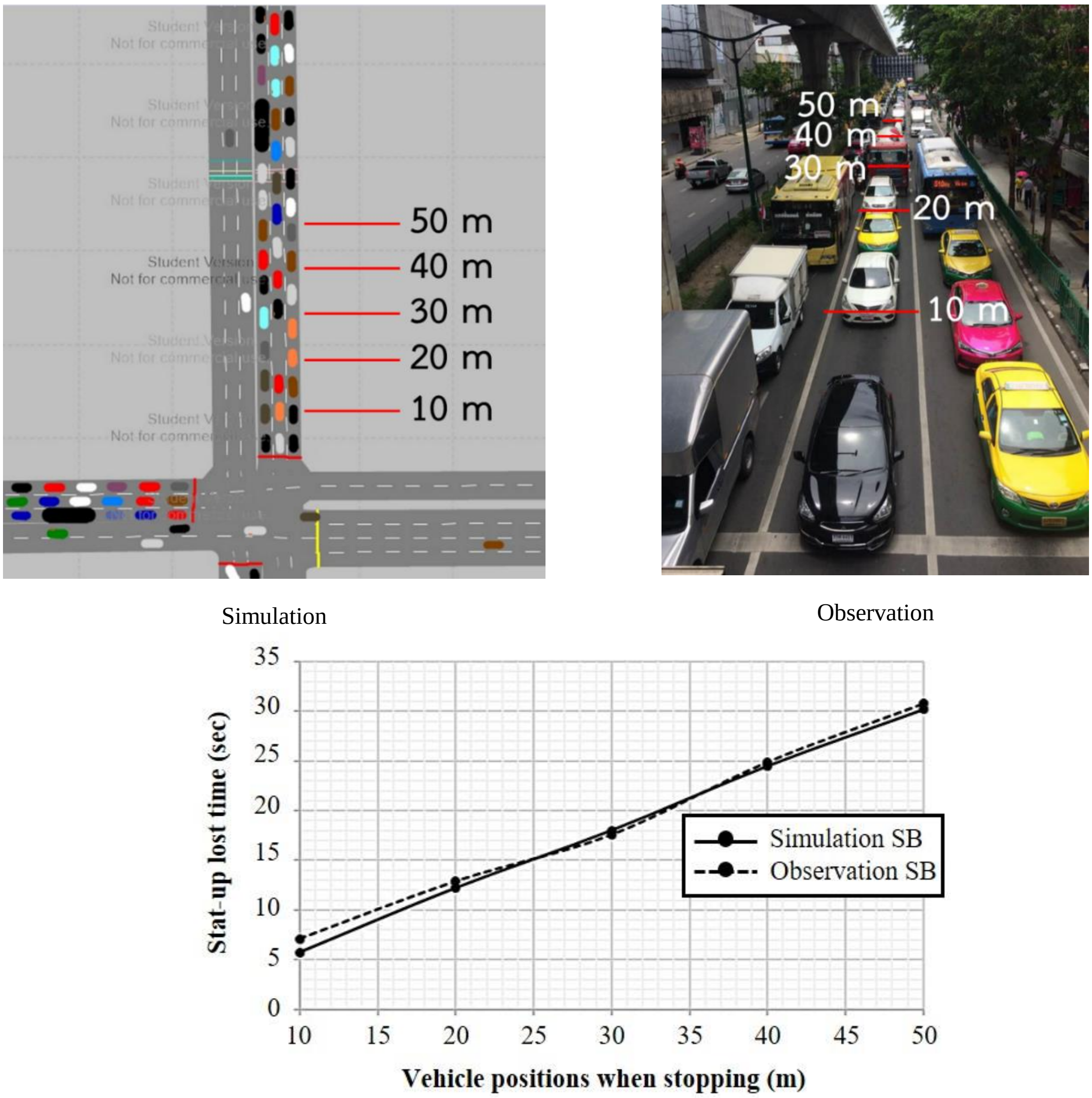


Figure 5 Comparison of start-up lost time between simulations and observations in the field

3.6 Fuel consumption calculation from simulations

Since vehicles operated with and without the hybrid system in simulations in all scenarios, fuel consumption must be calculated in these two cases of system operation. After the driving modes in each vehicle approaching the intersection was simulated, fuel consumption was measured, as shown in Table 4. Equation 3 is fuel consumption for a vehicle without using the hybrid system, while equation 4 is fuel consumption for a vehicle using the hybrid system.

$$FC_{WithoutHV} = \Sigma_{m,s}\left(FC_{m,s}^{Con} \times TS_{m,s}\right) \tag{3}$$

$$FC_{WithHV} = \Sigma_{m,s}\left(FC_{m,s}^{HV} \times TS_{m,s} \times \frac{Freq_{on,m,s}}{Freq_{on,m,s} + Freq_{off,m,s}}\right) \tag{4}$$

Where

$FC_{WithoutHV}$ = Fuel consumption for a vehicle without using the hybrid system operation (cubic centimeter; cc)

FC_{WithHV} = Fuel consumption for a vehicle using the hybrid system operation (cc)

$FC_{m,s}^{Con}$ = Measured fuel consumption rate (cc/sec) from tested gasoline car in different driving modes *m* and speed ranges *s*

$FC_{m,s}^{HV}$ = Measured fuel consumption rate (cc/sec) during the operation of the engine (ON) from the tested hybrid car in different driving modes *m* speed ranges *s*

$TS_{m,s}$ = Time sharing of driving mode *m* in different speed ranges *s* detected from simulation (sec)

$Freq_{on,m,s}$ and $Freq_{off,m,s}$ = Time-frequency (sec) of the operation (ON) and in-operation (OFF) of the engine in different driving modes *m* speed ranges *s*

Then, the calculated fuel consumption from both equations was converted to average fuel consumption in each vehicle per 1 hour (cc/veh/hr).

4. Results and discussion

4.1 Results of scenarios

The summary of simulation results is based on four parameters: average delay, level of service, queue length at the most congested direction, and average fuel consumption in each scenario in the morning peak hour (7 a.m. - 8 a.m.), which are shown in Table 6. The first three parameters show how congested the traffic is. Average fuel consumption would be determined from driving modes of vehicles in simulations and the calculation based on the field test and equations 3 and 4.

Table 6 Summary of simulation results in each scenario in the morning peak hour

Scenario	Average Delay (sec/veh)	Level of Service (LOS)	Queue Length at 95 percentile (m)	Average Fuel Consumption (cc/veh/hr)	% Reduction of Fuel Consumption from BAU
1) BAU	307	E	719	478	-
2) Traffic Signal Adjustment	292	D	393	389	19%
3) Replacing 5% of PC by HV	307	E	719	447	7%
4) 2+3	292	D	393	363	24%

From Table 6, after using Webster's method for traffic signal adjustment, it was found that cycle length at this intersection decreased from 230 seconds to 115 seconds. Therefore, adjustment of the traffic signal at the intersection with shorter cycle length in the 2nd scenario can reduce average delay, queue length (which can reduce almost a half), and LOS changing from E (almost congested level) to D (quite congested level). According to average fuel consumption, it can be reduced by 19% compared with the BAU case.

For the 3rd scenario, if HV is more promoted in BMA and is operated on the road network at least 5% of PC, average fuel consumption can be reduced at only 7%, which is less than that in the 2nd scenario compared with BAU case.

If there is a combination between the 2nd scenario and the 3rd scenario, as shown in the 4th scenario, average fuel consumption can be reduced from 478 to 363 cc/veh/hr, which was accounted for 24% reduction compared with the BAU case.

Thus, both adjustment of traffic signal by optimum cycle length calculation based on Webster's method at the intersection by shorter cycle length and more usage of HV on the road network in BMA can significantly reduce vehicle delay and fuel consumption of vehicles approaching at intersections in the urban area.

When all driving modes are analyzed in comparison between BAU case and other scenarios, as shown in Table 7, it was found that only adjustment of the traffic signal in the 2nd scenario can significantly reduce fuel consumption in stopping mode (46%). Replacing 5% of gasoline PC by HV without traffic signal adjustment in the 3rd scenario can significantly reduce in crawling mode (19%). In the 4th scenario, fuel consumption can be significantly reduced in stopping mode (49%) and crawling mode (21%).

Table 7 Average fuel consumption (cc/veh/hr) and % reduction in each driving mode in different scenario**s**

Scenario	Stopping	Crawling	Cruising	Accelerating	Decelerating	Total
1) BAU	175	95	1.28	130	77	478
2) Traffic Signal Adjustment	94 (46%)	92 (3%)	1.17 (9%)	126 (3%)	75 (3%)	389 (19%)
3) Replacing 50% of PC by HV	167 (5%)	77 (19%)	1.22 (5%)	128 (2%)	74 (4%)	447 (7%)
4) 2+3	90 (49%)	75 (21%)	1.11 (13%)	124 (5%)	73 (5%)	363 (24%)

These results indicate that adjustment of the traffic signal can significantly reduce fuel consumption because it decreased the vehicle stop time, which also consumes fuel without vehicle movement. In addition, more HV operation on the urban street can significantly reduce fuel consumption when vehicles run at low speed (crawling) because electricity mode is operated in HV mode instead of gasoline mode.

For other driving modes in all scenarios, cruising can reduce fuel consumption by around 5-15%, while accelerating and decelerating can reduce by around 2-5%. These results indicate that the HV must use gasoline operation when driving faster, but it is unnecessary when driving at cruise or a steady speed.

4.2 Comparison of results with other related research

For comparison of reduction of fuel consumption with other research, the results of this research in the 4th scenario (24%) are lower than the research of Pitanuwat and Sripakagorn [14], which indicated that using hybrid cars in BMA could reduce fuel consumption up to 47.3% for aggressive driving at signalized intersections. The high reduction percentage is that only tested hybrid cars were considered when calculating the impacts on fuel consumption.

To compare fuel consumption estimation with other models, the Vehicle Specific Power (VSP) model is chosen for comparison because it could be utilized as the explanatory variable to predict vehicle emissions expressed by the instantaneous tractive power per vehicle mass [5]. The VSP model in this research could be created by parameters consisting of the total mass of the tested car, rolling resistance coefficient, ambient air density, aerodynamic drag term coefficient, and the frontal area, as shown in equation 5.

$$VSP = v \times (a + 9.81(Grade(\%) + 0.132) + 0.000211v^3 \quad (5)$$

Where VSP = vehicle specific power (kWatt/ton)
v = vehicle speed (m/s)
a = vehicle acceleration (m/s^2)
Grade (%) = 0 considering the flat topography in Bangkok

From equation 5, instantaneous speed acceleration and deceleration could be collected to divide the driving mode/pattern into VSP bin for stopping (v = 0, a = 0), accelerating (v > 0, a > 0), decelerating (v > 0, a < 0), and cruising (v > 0, a = 0). However, it is difficult to analyze VSP binning for the driving patterns to indicate how environmentally friendly cars could reduce fuel consumption in traffic congestion when vehicles move with the fluctuated speed of 1-20 km/hr near intersections. Although Song et al. [5] tried to estimate fuel consumption of vehicles by the delay correction model applied from VSP at signalized intersections and the emission impacts could be perceived, its model is needed to consider vehicle trajectories by the impact of a number of stops.

Overall, the results of this research are consistent with the results of Pitanuwat and Sripakagorn [14], Srisakda et al. [17], Fukuda et al. [18], Alvaro et al. [31], and Li et al. [32] in that vehicle fuel consumption could be reduced if traffic was not congested and there was well-optimized cycle length. However, the results of this research are different from the research of Alvaro et al. [31] and Li et al. [32] because the optimum cycle length calculated by Webster's method was not in accordance with fuel consumption due to some factors such as traffic congestion and traffic volume variation. Although vehicle delay had the least value, fuel consumption did not have the least value. As a result, they developed the new models adapted from Webster's method to investigate the optimum point between vehicle delay and fuel consumption. This research only focused on the different results of traffic signal management between observation by the policies and calculation from traffic data. Thus, correlation models of optimum cycle length will be considered for further studies.

In this research, apart from considering speed, acceleration, deceleration, and stopping modes, it is better if crawling mode is included in the analysis. This is because crawling mode could separate fuel consumption in traffic congestion at signalized intersections rather than only identifying low speed or aggressive driving behavior, as seen from previous research. The crawling mode divided accelerating and decelerating mode at fluctuated speeds between 1-20 km/hr and provided many different fuel consumption results in the conventional gasoline car in accelerating mode. Moreover, the hybrid car could significantly reduce fuel consumption in the crawling mode. Thus, acknowledging crawling mode in this research could well detect the reduction of fuel consumption of environmentally friendly vehicles.

5. Conclusions

Adjustment of cycle length at intersections could reduce vehicle fuel consumption and vehicle delay because of stopping time reduction. If HV were better promoted and were operated at least 5% of PC, fuel consumption could be reduced more in stopping mode and crawling mode because HV would use electricity to operate the engine when it stops or runs at crawling and cruising speed. In addition, the crawling mode in this research could well reduce fuel consumption of environmentally friendly vehicles. These results could be a good example for well-organized traffic management for less vehicle delay and fuel consumption. Also, they could be extended to other intersections and metropolitans in developing countries. This research indicates that promotional use of HV could impact the goal of zero fuel consumption of electric vehicles (EV). Consequently, governments in many countries should encourage using these vehicles to reduce GHG and poor air quality emissions.

This research still has some limitations because it considered calculating fuel consumption by only personal car (PC) and assumed that more oversized vehicles would consume more fuel and have a more significant personal car unit (PCU) reflecting all vehicle types in simulation. In addition, Webster's method used in this research was not realistic, compared to previous studies, because of traffic congestion and traffic demand variation. Thus, various vehicle types (more oversized vehicles) and adjustment of Webster's method to estimate fuel consumption will be considered for further research.

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