Development of Method to Estimate Fuel Consumption Reduction Based on Time Sharing of Driving Modes - Case of Promotion of Hybrid Cars in Bangkok -

(走行モードの時間割合に基づく燃料消費削減量推定方法の開発
- バンコクにおけるハイブリッドカー普及の例 -)

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DEVELOPMENT OF METHOD TO ESTIMATE FUEL CONSUMPTION REDUCTION BASED ON TIME SHARING OF DRIVING MODES
- CASE OF PROMOTION OF HYBRID CARS IN BANGKOK -

by

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ABSTRACT

Estimation of fuel consumption reduction in road transport sector is important to mitigate greenhouse gas (GHG) emission. Especially in developing cities which suffer from traffic congestion, the policies in road transport sector such as promoting environmentally friendly cars, alleviating traffic congestion, etc., are expected to reduce fuel consumption significantly. In order to estimate an impact on fuel consumption reduction by these policies in a city, driving state of vehicles influencing fuel consumption should be considered. However, estimation of fuel consumption is not easy due to fluctuation and unstableness of driving state in various conditions.

Recently, probe data, installed into many vehicles by Global Positioning System (GPS) devices, have been used as one of ways to reveal driving state, widely and dynamically changed in an urban area. If driving states of a vehicle can be represented by separating into driving modes travelled including stopping, accelerating, cruising, and decelerating modes, it is possible to estimate fuel consumption by considering actual driving states of a vehicle. Thus, in this study, the proportion of accumulated time in each driving mode is defined as "Time Sharing of Driving Modes" and estimate fuel consumption by applying these modes.

However, basic driving modes including stopping, accelerating, cruising, and decelerating are insufficient to explain the impacts of fuel consumption reduction by promoting environmentally friendly cars. Thus, crawling mode that occurs frequently during congestion period is not clearly evaluated on the basic four driving modes. The characteristics of fuel consumption in this driving state are considered to be significantly different from the stopped state, the cruising state and the acceleration mode. Therefore in this study, estimation method of the fuel consumption reduction reflecting the actual traffic condition was proposed by defining the crawling mode as another driving modes and adding to the determination of the time sharing of driving modes. In addition, it is possible to evaluate the policies, in which fuel consumption is changed significantly by driving modes, such as promoting environmentally friendly cars.

By the conceptual idea already explained, the specific objectives are to develop method to estimate fuel consumption of vehicle by using time sharing of driving modes with crawling as an additional mode. In order to examine the applicability of the proposed method in this study, promotion of hybrid cars which is expected to reduce fuel consumption significantly, in the Bangkok Metropolitan Area (BMR) in Thailand, where traffic congestion is quite serious and probe data are being collected and provided, was

selected as the case study.

The dissertation consists of seven chapters as follows.

Chapter 1, *Introduction*, presents background, problems, and objectives of the dissertation.

Chapter 2, *Literature Review*, presents overview of estimation of fuel consumption in road transport sector, and previous studies including estimation of fuel consumption using driving modes and fuel consumption reduction by promoting hybrid cars. Among of these studies, they considered only few test vehicles in the fields without sufficient data reflecting driving states of all roadways. There were using vehicle kilometer traveled (VKT) to estimate fuel consumption; however, VKT cannot determine and well reflect driving states although it can cover all roadways in the urban area. Some studies used probe data for estimation of fuel consumption to study the impact on promoting hybrid cars or other environmentally friendly cars, but probe data were used only as test vehicles, which could not sufficiently cover all vehicles and were used for identifying only traffic conditions. Regarding crawling of vehicles, there were some studies similar to this behavior of vehicles, called stop-and-go that lead to sharp increase or decrease in acceleration. However, probe data cannot provide more details of speed data to indicate stop-and-go, because vehicles in this situation will stop and move immediately. On the other hand, crawling of vehicles can explain traffic congestion and can define as another driving mode better than using stop-and-go, because it can explain traffic congestion although speed data obtained from probe data are rough. Thus, it is expected that crawling mode can contribute to capture traffic congestion instead of using stop-and-go. In addition, no previous studies defined about crawling behavior for estimation of fuel consumption.

Chapter 3, *Research methodology*, describes how to define driving modes for time sharing calculation and explains data collection. Four basic driving modes including stopping, accelerating, cruising, and decelerating can be defined by using speed data and its transition in every 5 seconds. Additional driving mode (crawling) can be observed by speed profiles that fluctuation of speed data are approximately between 1 to 10 km/h. For data collection in this study, two main data were collected: probe data and fuel consumption data. Probe data were obtained from the operation of 10,000 taxis in BMR to calculate time sharing of driving modes in each speed range. Data were divided into the inner and the outer area of BMR in 30 days for different days of week (weekdays and weekends), periods (morning peak, off peak, and evening peak), and road categories (highways, arterials, and minor roads). Fuel consumption data were obtained from field test of one conventional gasoline car and one hybrid car to determine fuel consumption in each driving modes and speed range. After that, two main data were used to estimate fuel consumption in BMR both in ordinary case and hybrid cars replacement case. Two cases were compared each other for estimating fuel consumption reduction. Finally, the results of estimation of fuel consumption reduction were examined for reliability confirmation.

Chapter 4, *Estimation of time sharing of driving modes*, represents the determination of time sharing of driving modes based on probe data. The results of them in all conditions indicate that decelerating mode spends the greatest time percentage in most cases (25-35%), while cruising mode is the second (20-30%), and the third is accelerating. Although time percentages of crawling mode are less than first three driving modes, crawling mode can indicate traffic congestion that is readily seen by increased time percentages of crawling mode (5-25%). If only stopping mode is considered, traffic congestion impact would not be clearly seen. Stopping and crawling percentages in the inner areas are greater than in the outer areas in all cases, and high percentages of them are readily seen only on minor roads in the inner area. In addition, time sharing of driving mode from probe data can be proved that it is reliable when compared to observe data obtained from video detection. Thus, time sharing of driving modes including four basic driving modes and additional driving mode (crawling) based on probe data can be used for estimation of fuel consumption.

Chapter 5, *Measurement of fuel consumption by field test*, shows the results of fuel consumption collected by one hybrid car and one conventional gasoline car. Two cars were operated together along the same selected roadways in the inner area of BMR for different days of week, periods, and road categories. Fuel consumption were calculated in the unit of cubic centimeters per second (cc/sec) both conventional gasoline car and hybrid car in each driving mode and speed range. In addition, time frequency during gasoline engine operated and off-operated can be also indicated. Time frequency during off-operated can be detected in hybrid car and there is also no fuel consumption because hybrid system is operated by electricity. When fuel consumption reduction in each driving mode both with and without considering crawling mode are compared, the fuel consumption in accelerating mode in with case is higher than in without case. The reason of difference is because slow acceleration is removed from original acceleration mode. Moreover, crawling mode can provide much difference results of fuel consumption in conventional gasoline car. Thus, fuel consumption on crawling mode can be significantly reduced if hybrid car replace conventional gasoline car.

Chapter 6, *Estimation of fuel consumption reduction by promoting hybrid cars*, estimates fuel consumption reduction by two defined scenarios in this study are (1) All probe cars (10,000 taxis) are replaced by hybrid cars and (2) Private cars in BMR are replaced by hybrid cars. For the first scenario, fuel consumption rates in the unit of cubic centimeters per vehicle per kilometer (cc/veh/km) and reduction percentages are summarized. From area and days of week results, the highest consumption rate is in the inner area on weekdays in without HV case. When road category is considered, the highest consumption rate is on arterials on weekdays. Regarding reduction percentages, fuel consumption reductions are clearly observed in the inner area on weekdays on arterials. For the second scenario, the aim of this scenario is to estimate fuel consumption for studying reduction impacts if amount of hybrid cars increase from the present year to 15 years later by the policy that "hybrid car sales will be 25 % in 2030 of private cars." Fuel consumption can be estiamatd by proposed equations applied from vehicle kilometer traveled (VKT) by using time sharing of driving modes, amount of detected probe cars, and average speed from probe data. As a results, with hybrid car replacement case can reduce fuel consumption by the highest redution percentages in 2026 equal to 474 kiloton of oil equivalent (ktoe), as calculated to 4.47% in comparison with all vehicles in BMR and 8.52% in comparison with only private cars.

For examination of reliability of estimation, fuel consumption rate and its reduction estimated by probe data is compared with the actual fuel consumption measured by field test and observed fuel consumption in transport sector during 2011 to 2015 obtained from energy policy of and planning office, Ministry of energy of Thailand (EPPO). The examinations found that percentage difference between estimation and observation in base year in 2011 is the highest different, accounted to 25%. After that, percentage differences can decrease until in the year of 2015, accounted for 13%. That means it can be proved that estimation of fuel consumption by proposed equations can be used for estimation of fuel consumption reduction by promoting hybrid cars. Regarding fuel consumption reduction, different percentages in most conditions are not very different from each other. That means the examination of estimation of fuel consumption reductions from probe data are confirmed in its reliability.

Chapter 7, *Conclusions*, addresses conclusion including the main contributions of the dissertation. In this dissertation, development of estimation of fuel consumption reduction in this dissertation based on time sharing of driving modes has the great advantage for the future policy implementation to reduce fuel consumption in road transport sector, and can be applied in other cities if probe data are available. Moreover, proposed additional driving mode (crawling) can provide the different results between with and without considering it by indicating traffic congestion and estimating fuel consumption in conventional gasoline car on accelerating mode. Thus, fuel consumption on crawling mode can be reduced if hybrid car replace conventional gasoline car.

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CHAPTER 1

INTRODUCTION

1.1 Background

Estimation of fuel consumption in road transport sector is important to evaluate policies for mitigation of fuel consumption and greenhouse gas (GHG) emission. However, because fluctuation and unstableness of driving patterns depends on traffic conditions, fuel consumption is difficult to estimate. Especially in traffic congestion, as indicated by low average speed and non-smooth traffic flow, fuel consumption increases and its estimation is extremely difficult [1, 2, 3].

Floating car data or probe data are one of the real-world data that can reflect driving patterns, because they are a source of high quality actual data and are available in the implementation of Intelligent Transportation Systems (ITS) [4]. Benefits of probe data are not only for being a raw data to determine congestion measures, safety measures, traffic control management, and logistics, but they are also for indicating driving patterns based on their speed and time stamped data. Thus, floating car data or probe data, well reflecting traffic conditions, can be used as data for estimation of fuel consumption.

Fuel consumption cannot be measured directly from probe cars because it is not practical to install fuel consumption measurement devices on all probe cars. In addition, devices for fuel consumption measurement require high time resolution (Less than 1 second interval), but data from probe cars cannot be obtained at this high time resolution. Thus, the method to estimate fuel consumption reduction based on probe data should be proposed.

Speed data obtained from probe data can explain driving patterns based on speed profiles, because they can differentiate driving modes of actual travel indicating stopping, accelerating, cruising, and decelerating driving periods. In this study, the proportion of accumulated time in each driving mode is applied and defined as “Time Sharing of Driving Modes.” Implementing time sharing of driving modes gives clearer explanation of driving patterns than only interpretation of average speed or acceleration data. Therefore, time sharing of driving modes based on probe data is one of applicable methodology for development of estimation of fuel consumption.

Crawling is a behavior of vehicles in traffic stream, which is the transition driving state between stopping/idling and full moving of vehicle occurring in congestion periods. Crawling behavior is very common, especially during peak hours on weekdays. Since crawling of vehicles can reflect traffic congestion not only vehicle stopping, estimation method of the fuel consumption reduction reflecting the actual traffic condition is proposed by defining the crawling mode as another driving modes and adding to the determination of the time sharing of driving modes.

1.2 Statement of Problem

Because of fluctuation and unstableness of driving conditions, fuel consumption in real-world is not easy to estimate. To estimate fuel consumption of a vehicle, a set of data representing actual driving condition is required. Probe data, installed into many vehicles, are one of the real-world data, which can provide vehicle location, speed, direction, and time stamp, and can reflect driving patterns in actual traffic conditions.

According to crawling behavior of vehicles, which is the transition state between stopping/idling and full moving of vehicle, occurs frequently during traffic congestion; however, no previous studies have considered about this behavior and include it for estimation of fuel consumption. Although there were studies about how to define the threshold speed for vehicle crawling [5, 6], crawling behavior of vehicles in different study sites and traffic conditions is probably different. These studies did not focus on congestion periods and different conditions (such as sub-area, days of week, or road category), and have not yet been analyzed to study the impacts on estimation of fuel consumption.

1.3 Purpose and Objectives

The aim of this dissertation is to propose a development method to estimate fuel consumption and exemplify the use of the method in a case of a promotion of more environmentally friendly cars. The specific objectives are as follows.

- To propose crawling mode as an additional driving mode
- To determine time sharing of driving modes collected from probe data in various traffic conditions for estimation of fuel consumption
- To study the impact of fuel consumption reduction by promoting environmentally friendly cars

1.4 Scope of Study

This dissertation proposes a development method to estimate fuel consumption based on time sharing of driving modes collected from probe data. Moreover, the estimation method is demonstrated in the case of promoting one type of environmentally friendly cars; hybrid cars in a developing city. Bangkok Metropolitan and Region area (BMR), Thailand, was selected as case study to test the estimation of fuel consumption considering vehicle crawling.

Probe data were collected from 10,000 taxis operated on roads in BMR and were analyzed in various conditions including sub-areas, days of week, periods, and road categories. Driving modes were classified to 5 modes including stopping, accelerating, cruising, decelerating, and an additional driving mode (crawling).

Impact on promoting hybrid cars can be estimated by comparison between ordinary case (without hybrid cars) and hybrid cars replacement case (with hybrid cars) in study area. Moreover, the results of estimation of fuel consumption were verified with actual fuel consumption collected by observation in field test for reliability confirmation.

1.5 Dissertation Outline

This dissertation consists of seven chapters as shown in Figure 1.1. Chapter 1 introduces the background, statement of problems, objectives, and scope of this study. Chapter 2 explains the literature review about the overview and previous studies of estimation of fuel consumption, the impacts of promoting hybrid cars and the overview of crawling behavior of vehicles. In addition, it summarizes all existing studies and points out the research gaps of existing studies. Chapter 3 describes the process of research methodology and explains the method for how to collect data. Chapter 4 determines the results of time sharing of driving modes collected from probe data in various traffic and driving conditions and also verifies these results by observed data. Chapter 5 explains descriptive data analysis of hybrid car and conventional gasoline car by field test in each condition, and indicates the results of fuel consumptions received from them. Chapter 6 determines the results of estimation of fuel consumption based on probe data, the impacts of promoting hybrid cars, and the reliability of estimation of fuel consumption and its reduction. Finally, Chapter 7 gives the conclusions and recommendations.

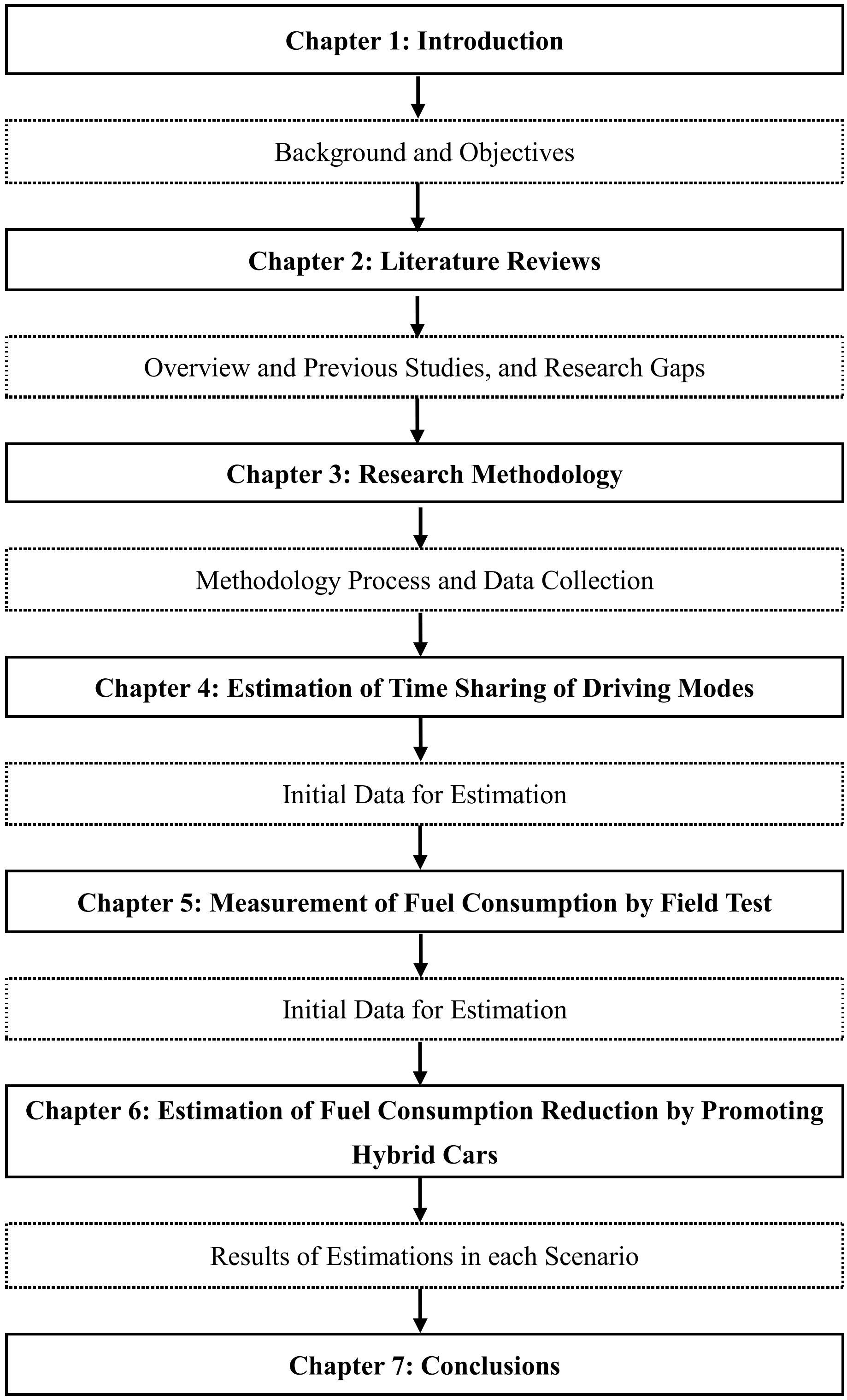

Figure 1.1 Structure of dissertation

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CHAPTER 2

LITERATURE REVIEWS

2.1 Estimation of Fuel Consumption in Road Transport Sector

2.1.1 Situations of fuel consumption in road transport sector

Globally, the transport sector has contributed to one-third of overall energy consumption and is the second largest energy consuming sector after the industrial sector. In 2009, it accounted for 29% of total energy consumption [1].

Many countries report fuel consumption in transport sector. For example, in Japan, fuel consumption in transport sector is the third largest energy consuming sector after industrial sector and residential and commercial sector that account for 24.4% and 24.6% in 1996 and 2010, respectively [2]. In European countries, transport sector can account for around a third of all energy consumption [3]. In United States, the transport sector is the second largest energy consuming sector after the industrial sector, accounting for 29% of the total energy consumption in 2009 [1].

In developing countries, like Thailand, the transport sector consumes a plenty of energy every year, in which this sector shares more than 35% of total energy consumption [1] and the consumption has increased with 4.4% average annual growth rate from 11,368 kiloton of oil equivalent (ktoe) in 1990 to 23,097 ktoe in 2008. Within this sector, approximately 75.7% of the energy is used in road transportation [4].

By comparing of fuel consumption between developed and developing countries, it was found that transport sector in developing countries proportionally consumes more energy than those in developed countries. Partly this may be due to condition of traffic (congestion) and less quality of combustion of vehicles. Thus, energy consumption in transport sector in developing countries must be concerned for environmental problems in the world.

Most of energy used in transport sector is fossil fuels [1]. The share of fossil consumption increases from 50% in 2002 to 53% in 2007 and is forecasted to reach 61% in 2035. Especially in gasoline, many developing countries still use this kind of fossil energy as the main source of fuel for vehicles. For example, it has been reported that in China nearly 50% of total Chinese gasoline consumption was in transport sector.

Moreover, fossil fuel represents 98%, 97% and 97% of total transport fuel consumption in China in 2000, 2005 and 2010, respectively. In 2008, the transport sector of USA was responsible for 70% of fossil consumption and 28% of total greenhouse gas emissions [5].

High fossil consumption emits high Green house gas (GHG) in which CO_2 is the most essential part of it. CO_2 emission from fossil fuel combustion in transport sector has received much attention [6]. Therefore, if fuel consumption can be reduced in road transport sector, CO_2 emission that is the main cause of global warming or climate change can be mitigated.

For mitigating fuel consumption, there are many countermeasures for low-carbon emission in transport sector, which can be divided into 4 categories by Dalkmann and Brannigan [7]. They consist of (1) decreasing travel demand, especially private transport mode, by travel demand management (TDM); AVOID, (2) shifting to environmentally friendly transport modes such as public or non-motorized transportation modes; SHIFT, (3) improving the energy efficiency by inventing vehicle technology; IMPROVE, and (4) increasing bio-fuels usage by blending them with fossil fuel such as gasoline or biodiesel promotion; SWITCH-FUEL.

The aims of IMPROVE countermeasures is to improve energy efficiency of automobiles in which environmentally friendly cars are examples of improving energy efficiency for reducing fossil fuel consumption. In this study, hybrid cars which is one type of environmentally friendly cars, is focused for studying the impact on fuel consumption reduction because this vehicle has been brought to the auto market in Thailand recently and it is still questionable how much driver can save their money in different driving modes as well as traffic conditions by introducing hybrid car. Meanwhile, although electric vehicles have been used or promoted in Thailand, they have been implemented only in restricted area, especially in universities, not for commercials due to insufficient electricity charge stations covered all area of a city in Thailand [8]. In addition, they can operate only in low speed range.

2.1.2 Estimation of fuel consumption

Fuel consumption is one of activity rates for estimation of GHG emission [9]. Activity rate in road transport sector can be fuel consumed (volume of fuel; liters or cubic centimeters), or distance traveled (vehicle kilometer or mile traveled; VKT or VMT). The International Energy Agency (IEA) Mobility Model (MoMo) [10] proposed basic equation in order to estimate energy consumption and GHG emissions as shown in

Equation 2.1.

$$G = \sum_i \sum_j P_{i,j} U_{i,j} C_{i,j} E_{i,j} \qquad (2.1)$$

Where G = The total energy demand (or GHG emissions) from road transport sector (calorific value used; MJ or weight of GHG; kg of CO_2)

$P_{i,j}$ = The number of vehicles interested for vehicle type i which use fuel type j (vehicles)

$U_{i,j}$ = The travel distance of vehicle type i for fuel type j (kilometers)

$C_{i,j}$ = The energy (or fuel consumption) per distance

$E_{i,j}$ = The specific energy content of fuel or emission factor of vehicle type i for fuel type j (MJ/liters or kg of CO_2/liters)

Equation (2.1) is total energy demand or GHG emission in macro scale depending on number of vehicles interested and their running distances. For reflecting traffic data of all traffic system, traveled distance of vehicles (vehicle kilometer or mile traveled; VKT or VMT) was the initial data for estimation of fuel consumption or GHG emission. VKT or VMT can be calculated by two ways. The first is odometer reading of each vehicle that can obtain distance directly. Another one is traffic volume in each road section that VKT or VMT can be calculated by traffic volume multiplied by distance in each road section. There is a lot of literature using VKT or VMT in order to estimate fuel consumption or GHG emission as follows;

Pongthanausawan [11] forecasted fuel consumption and CO_2 emission of road transport in Thailand from 2008 to the year 2030, and also access the potential and impacts of possible alternative fuels and high energy efficient vehicle technologies in road transport sector to reduce end-use energy demand and life cycle CO_2 emission. This study also used VKT from surveyed data.

Fukuda et al. [12] used surveyed VKT collected in a developing city, Khon Kaen, Thailand, by odometer reading of random vehicles in order to estimate CO_2 emission by dividing vehicle and engine types. Collected VKT was obtained as average annual VKT. Then, it was multiplied by number of register vehicles in this city, fuel usage share, and divided by average fuel efficiency to obtain fuel consumption of each fuel type. Finally, CO_2 emission could be estimated by the multiplying between fuel consumption and emission factor.

Chang et al. [13] and Li et al. [14] applied International vehicle emission (IVE) to estimate real-time traffic CO_2 emission in Beijing, China. VKT was collected from road detectors and it was used as a multiplier together with emission factor of each vehicle type and several factors (such as vehicle type percentage, driving mode percentage, speed correlation factor etc.).

Wang et al. [15] displayed a scenario analysis to estimate CO_2 reduction in China by developing strategies consisting of vehicle technology improvement, introducing BRT, and fuel switching. VKT were used as a multiplier to estimate CO_2 emission and to be also the results of its future prediction based on GDP, growth rates, and elastic factor of amount of vehicles.

Chollacoop et al. [16] estimated the impacts of fuel consumption by the policy of promoting biofuel on road transportation in Thailand. They used bottom down energy demand model to estimate its impacts based on number of vehicles, and VKT collected in this country. Also, this study forecasted the future impacts from 2010 to 2034 by using Long-range energy alternative planning system (LEAP) model that number of vehicles and VKT could be projected based on socio-economic data such as GDP or population.

Nakamichi et al. [17] conducted OD trips from interview survey data and ran them into Micro simulation model in order to estimate CO_2 emission for freight transport in Khon Kaen, Thailand. This study estimated the impacts of CO_2 emission by the scenarios of transport oriented (EV) pick up promotion in 2050. VKT could be obtained from OD, which is calculated from simulation model and the initial data for receiving traffic volume. Then, traffic volume was multiplied by distance in each road section to obtain VKT.

From literature, VKT or VMT can be used to estimate fuel consumption and CO_2 emission by the principle that more distance traveled of vehicles increases, fuel consumption and CO_2 emission also increase. However, VKT or VMT cannot determine and well reflect driving pattern, which affect fuel consumption and CO_2 emission directly. As a result, estimation of fuel consumption reduction of hybrid cars or other environmentally friendly cars by using VKT or VMT is not sufficient for accurate estimation.

Thus, estimation of fuel consumption in this study is focused in micro scale in which much or less fuel consumption depends on the factors of weight and load of vehicles, fuel types, engine efficiency, age of engine, as well as driving patterns [18]. For driving patterns in each vehicle, much or less fuel consumption depends on speed, acceleration, and amount of stops affecting revolution per minute (rpm) of engine. If rpm of the engine increases, fuel consumption as well as GHG emission increases.

2.2 Previous Study on Estimation of Fuel Consumption Using Driving Modes

According to driving pattern study for finding the impacts on fuel consumption or GHG emissions, engine dynamometer test from laboratory is original and the most simple method because it can well reflect driving activities such as different rolling situations or driving modes in on-road vehicle trips. Trips data can be defined as the standard test cycles that can provide a highly reliable baseline for comparative testing [19] such as New European Drive Cycles (Emission Test Cycles for the Certification of light duty in Europe) or US Federal Test Procedure-75 (Test Procedure for Highway and Non-road Engines). However, these standard drive cycles cannot well reflect how good representations of vehicles under real driving situations are [20, 21]. For involving this problem, real-world fuel consumption and GHG emissions are more suitable for making estimations them instead of using a dynamometer.

Probe data are one of the real-world data, as they can provide location, speed, direction, and time stamp on whole road sections in the urban area, and can reflect driving patterns that locally fluctuate depending on traffic conditions. Thus, probe data are more sufficient and appropriate for estimation of fuel consumption. In addition, they are an alternative source of high quality data and have importance in development of Intelligent Transportation Systems (ITS). They use the principle of floating car data (FCD) to collect real-time traffic data by locating the vehicle via mobile phones or GPS over the entire road network. They are performed as the sample of fixed locations by means of electronic transponders (tags) that are read as the vehicles pass the sensors [22].

Benefits of probe data are not only for being a raw data to determine congestion measures, safety measures, traffic control management, and logistics, but they are also for indicating driving patterns based on their speed and time stamped data. Moreover, probe data can be used as an alternative method for estimation of fuel consumption depended on driving patterns or modes.

The previous research regarding estimation of fuel consumption using driving modes as follows;

- Initial models for estimation of fuel consumption

The initial step for estimation of fuel consumption in road transport sector is direct measuring by test vehicles. For the most obvious examples, Rakha and Ding [23] and Rakha et al. [24, 25] applied micro scale models, Virginia Tech (VT), to predict fuel consumption and GHG emission rates based on instantaneous speed and acceleration reflecting driving pattern in each vehicle and fuel type.

Rakha and Ding [23] proposed VT-MESO model framework for modal model for fuel consumption and GHG emission rate estimation. This model was based on 3 parameters including average speed, number of stops per distance, and average stop duration for synthetic driving cycle construction for each road section. Then, the model was validated against VT-Micro that is the original models.

Rakha et al. [24] applied a framework for developing and expanding VT-Micro for estimating hot stabilized fuel consumption and GHG emission for 60 light duty vehicle types and also trucks, not only 9 vehicle types as the original models.

Rakha et al. [25] studied the impacts of stops based on VT models determined fuel consumption and GHG emission rate varied by acceleration curves. Vehicle stops could be identified by deceleration and acceleration, before and after stopping at an intersection.

Apart from VT-Models, Smit et al. [26] applied average speed received in each road section to develop speed distributions in order to predict GHG emissions instead of using single mean speed in each section. Since speed distributions could help to predict more details speed data of each vehicle, estimation of GHG emission could be more accurate.

These studies could determine fuel consumptions and GHG emission rates varied by speed in different acceleration curves that could develop for finding emission factors. Also, they tried to conduct more traffic data and some modal models to obtain more reliable estimation. However, these studies considered only test vehicles in the field for measuring fuel consumption and GHG emission without sufficient data reflecting driving patterns of all roadways in the urban area.

- Using probe information for estimation of fuel consumption and GHG emission

Song et al. [18] proposed the emission models by the relationship between emission factors and delay/number of stops at intersections on arterials. Probe data were collected by test buses for reporting driving patterns collected from speed, acceleration, delay, and number of stops. Then, vehicle specific power (VSP) was applied in this study in order to collect fuel consumption/GHG emission rates obtained from probe into the bin in each 1 KW/ton. Consumption/emission rates together with delay and number of stops could be used to estimate emission factor based on probe data from buses.

Ropkins et al. [19] estimated the impacts of fuel consumption and GHG emissions of 5% biodiesel (B5) blend compared with original diesels. Probe data, which can separate speed and acceleration in each traffic condition, was used for reporting traffic conditions and positions in only test vehicles in order to compare with fuel consumption and GHG emission results for studying the relationship between of them. Meanwhile, fuel consumption and GHG emissions could be calculated via exhaust pipe. Comparisons consisted of emission results varied by distance, and the relationships between fuel consumption/GHG emissions and speed/acceleration, as shown by map charts, both in ordinary case and introducing 5% biodiesel (B5) blend case.

Chang et al. [13] and Li et al. [14] applied International vehicle emission (IVE) to estimate real-time traffic CO_2 emission in Beijing, China. Probe data were used for collecting speed, acceleration, grade, and driving modes for separating into the bins/ranges and considering each separate case into the models, which also applied VSP study and engine stress (ES) principle into IVE that could make more details of driving patterns for estimation.

Zhang et al. [27] estimated vehicle emissions in work zones and rush hour congestion compared to emission under free flow traffic conditions along freeway segment. The comprehensive modal emission model (CHEM) was used to generate fuel consumption and GHG emission. Probe data could provide speed, acceleration, and positions every 1 second. Fuel consumption and GHG emission were predicted for different driving modes consisting of stopping, cruising, accelerating, and decelerating.

Zeng et al. [28] estimated fuel consumption in a large-scale data set, which were collected from probe and mobile fuel measurement of bus travelling. This research proposed the support vector machine (SVM) in order to study the relationship between fuel consumption and the corresponding factors including average speed, distance traveled, coverage of link speed, and engine displacement.

Choudhary and Gokhale [29] studied the impacts of different traffic conditions on GHG emission rates of personal cars and rickshaws. Traffic conditions could be identified from probe data of these vehicles. This study also found the relationship between speed/acceleration and emission rates. The results found that frequent stop-and-go occurring during interruptions and congestion are the main causes of higher emissions because stop-and-go lead to sharp increase or decrease in acceleration and deceleration. However, this study focused only arterials roadways and conducted many probe cars only reporting traffic condition.

Barth and Boriboonsomsin [30] found the impacts of fuel consumption and CO_2 emission by using real-world data, like probe data, which were collected by 626 vehicles in southern California, USA. Meanwhile, fuel consumption and CO_2 emission were measured by test vehicles. The results indicated that traffic congestion, as indicated by low average speed and non-smooth traffic flow by stopping and moving behavior of vehicles, increase fuel consumption and CO_2 emission.

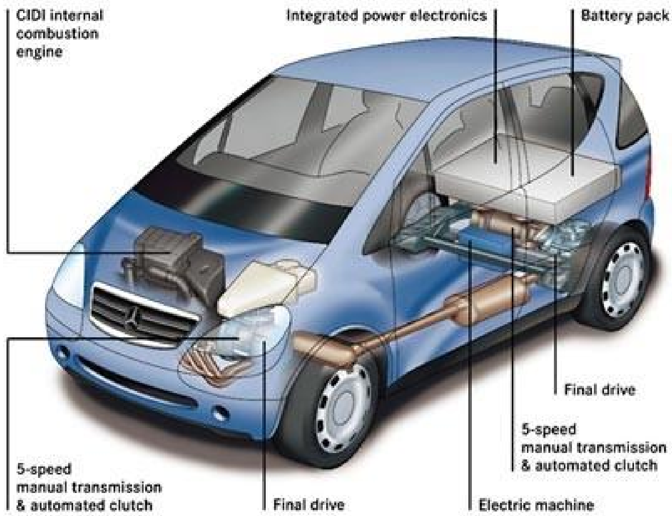
From literature, real-world data, like probe data, could well reflect driving patterns/modes and explain the relationship with fuel consumption and CO_2 emission. However, probe data were used as test vehicles, which could not sufficiently cover all vehicles on whole road sections in the urban area, and were used for identifying only driving pattern/modes [13, 14, 18], and traffic conditions [19, 27, 28, 29]. Although, Barth and Boriboonsomsin [30] conducted probe data from 626 vehicles, they still could not cover all vehicles on whole roadways in the urban area and fuel consumption and CO_2 emission have not yet estimated directly from probe cars.

2.3 Impacts of Promoting Hybrid Cars

2.3.1 Hybrid cars

Auto industry has tried to develop a new generation of fuel saving and environmentally friendly vehicles. "Hybrid Vehicle (HV)" is one such vehicle and it has been brought to the auto market in Thailand. HV is a new private car technology with the best efficiency among vehicles running during highly traffic congestion. The advantage of HV is significant fuel consumption and GHG emissions reduction compared with conventional combustion engine vehicles in similar weight class. In addition, it is already widely used in many countries such as the USA, European Countries, and Japan, especially in urban areas [31].

The concept of HV is to use the energy transformation system rather than energy storage system. The most common option is the combination of an internal combustion engine and an electric power source (battery pack and electric machine), as shown in Figure 2.1. Using the electrical energy, which supplement the power of the internal combustion engine, can improve the efficiency of the fuel use of HV.



Source: (How Stuff Work, 2016) [31]

Figure 2.1 The mechanism of hybrid car

There are three benefits of HV in order to improve the efficiency of the fuel use as follows:

(1) The conventional combustion engine can be turned off to save fuel consumption when vehicle stops or starts moving by using electric motor, which has more efficiency at low speeds.

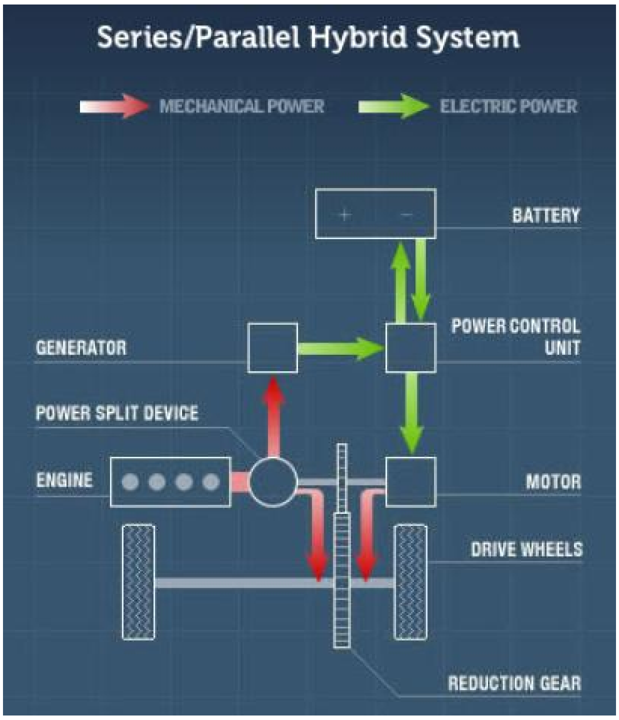
(2) The kinetic energy parts, which normally lose by heat, can be captured by electric motor and kept back into the battery during deceleration.

(3) When less power is needed, the excessive energy which generally loses will be kept in batteries. In contrast, when more power is needed, the supplementary power from batteries will be supplied to the electric motor to power the vehicle. Therefore, hybrid system can increase efficiency and reduce emissions.

HV has benefit from the efficiency improvements both in gasoline and diesel vehicles. Currently, HV technology could reduce fuel consumption about 45% compared with the conventional combustion engine in similar vehicle type [32]. This study selects HV in private car sector which consume gasoline for the conventional combustion engine to investigate how much drivers can save fuel during hybrid system operated.

On the current market, three major types of hybrid systems being used in the HV consist of series, parallel, and series/parallel system or full hybrid system. In fact, most

HV in the auto market have been developed based on the “series/parallel system” or “full hybrid system” [33]. This system leads the benefit of the series and the parallel hybrid system. In series/parallel hybrid system, the power split device and its control unit are the crucial components of this system. In Figure 2.2, the power split device transfers a part of the power produced by the gasoline engine to drive the wheel and also the generator, which is another part providing electric power for the electric motors or recharging the battery. This system can provide benefit of the energy-efficient electric motors by using the power of electric motor and gasoline engine, or the electric motor only, depending on the driving patterns.



Source: (Toyota Motor Operation, 2014) [34]

Figure 2.2 Series and parallel hybrid system

HV uses the electric energy kept in its battery to run the car by the electric motor at low speed driving. The gasoline engine is the main power source for wheels driving in cruising mode. Also, it provides the power to the generator in order to supply electricity to the electric motor when the battery charge level is low. During the full acceleration or climbing a steep slope, the dual power both direct gasoline and electric motor is operated. When the accelerator is lifted, hybrid system operates the kinetic energy by letting gasoline power to the wheels system turn to the electric power only.

Apart from HV, the newer vehicle technology called Plug-in hybrid electric vehicles (PHEVs) has been promoted recently. PHEV combines the vehicle efficiency benefits of hybridization with the opportunity to travel part-time on electricity provided by the external charger, rather than the vehicle's internal recharging system by HV [35]. Therefore, PHEV is more potential for the reduction of fossil fuel use and CO_2 emissions.

2.3.2 Previous study on impact of promoting hybrid cars

Pitanuwat and Sripakagorn [36] investigated fuel economy benefit by using hybrid cars under field driving test in Bangkok. This study analyzed the results by separating traffic conditions consisting of arterials in inner area, arterials in outer area, and highways in outer area. Moreover, this study separated the behavior of drivers into aggressive and normal calm that have different acceleration. Average speed, divided into 9 ranges, was employed to quantify as parameters for finding the impacts of fuel consumption. The results indicated that both conventional gasoline and hybrid cars had the greatest fuel consumed on arterials in inner area, and hybrid cars also achieved the greatest fuel consumption reduction in the same conditions. Meanwhile, highways had the fewest reductions. Aggressive driving was the cause of 100% increase for conventional cars and 200% increase for hybrid cars. In addition, normal-calm driving could reduce fuel consumption rather than aggressive driving. For driving patterns/modes, hybrid cars seem to be more sensitive to aggressive driving, as shown by more fuel consumption percentages compared with conventional cars.

Raykin et al. [37] evaluated the impacts on fuel consumption of plug-in hybrid cars in evening-peak on different road categories including arterials and highways. In addition, this study also analyzed energy use in each of electricity and fossil fuel. They simulated traffic assignment to demonstrate traffic situations by average speed and stopping percentage. Then, movement data of hybrid cars on each road category were put into simulation and fuel consumption was calculated when test vehicles ran along selected roadways. The results indicated that fuel consumption of hybrid cars was lower in all road categories that the lowest was on the arterials. Moreover, hybrid car, which is series system installation, was the best fuel saving.

Wang et al. [38] studied the energy reduction together with hybrid electric cars (HVs), plug-in hybrid cars (PHEVs), and battery electric cars (BEVs), compared with conventional cars (CVs) in Beijing, China. They also collected traffic data based on 1,000 probe cars to demonstrate driving cycles in each sub-area in peak and off-peak hours for finding the impacts. The results indicated that all vehicle types in downtown area in peak hours consumed the most fossil fuel. All vehicles in Beijing yield more fuel reduction benefits than in US, and the most fuel reduction was PHEVs.

Nisamani et al. [39] studied the impacts of incorporating hybrid cars into high occupancy lanes (HOV) by introducing scenarios which were different share of demand of hybrid cars. The results indicated that allowing hybrid cars into HOV lanes could reduce vehicle emission. However, if demand of hybrid cars was higher, traffic indicators were in case of congestion such as worse level of service, lower average speed. The maximum number of hybrid cars, using HOV could absorb significant relegation, was about 50,000.

From literature, promotion of hybrid cars achieved the greatest fuel consumption reduction on arterials in the inner area, especially in peak hours. However, these defined studies conducted only test hybrid cars to calculate the impacts on fuel consumption [36, 37], and did not consider minor roads [36, 37, 38, 39], in which metropolitans as above consist of significant amount of minor roads in their road network. In addition, probe data in these defined studies were only used to explain traffic conditions in term of average speed/acceleration [36, 37] and driving cycles [38] without considering fuel consumption and GHG emission estimation based on this data directly.

Therefore, it implies that further studies on calculating the fraction of duration of each driving mode, which was defined as “Time Sharing of Driving Modes” from probe data in various conditions, are necessary for estimating fuel consumption in order to study the impacts of promoting hybrid cars in Bangkok Metropolitan and Region (BMR).

2.4 Crawling Behavior of Vehicles

Crawling is a behavior of vehicles in traffic stream, which is the transition driving state between stopping/idling and full moving of vehicle. Since, Bangkok has been known as one of the worst cities in the world for traffic congestion, crawling behavior of vehicles is very common, especially during peak hours on weekdays. Therefore, the impacts of vehicle crawling during traffic congestion are the main cause of more fuel consumption and more CO_2 emission in transport sector, because by previous studies, traffic congestion, as indicated by low average speed and non-smooth traffic flow, increase fuel consumption and CO_2 emission [39, 40, 41] without considering crawling behavior of vehicles.

There were some studies similar to this behavior of vehicles, called stop-and-go. They indicated that frequent stop-and-go occurring during interruptions and congestion are the main causes of higher emissions on urban roads since stop-and-go lead to sharp increase or decrease in acceleration and deceleration [29, 30]. However, probe information cannot provide more details of speed data because vehicles in stop-and-go situation will stop and move immediately. Thus, crawling of vehicles can explain traffic congestion and can define as another driving mode better than using stop-and-go because it can explain traffic congestion although speed data obtained from probe information cannot provide more details.

There was some literature studying vehicles crawling for estimating stopped delay in traffic system, especially at signalized intersections. Although, considering zero speed is the threshold for stopping vehicle, a higher speed should be also applied to allow for the identification of vehicles crawling before stopping at a queue. For example, Mousa [40] utilized 1 - 1.5 m/s (3.6 – 5.4 km/h), and Colyar and Rouphail [41] indicated 4.8 km/h as the criteria for measuring stopped delay.

However, no previous studies considered about this behavior for more reliable estimation of fuel consumption, and crawling behavior of vehicles in different study sites and traffic conditions is probably different. These studies did not focus on congestion periods and different conditions (such as sub-area, days of week, or road category), and have not yet been analyzed to study the impacts on estimation of fuel consumption.

Consequently, the author is interested in this behavior and desire to add in as another driving mode for estimation of fuel consumption because it can define traffic congestion more accurately, is the cause of more fuel consumption, and is possible to reduce fuel consumption if hybrid cars replace conventional gasoline cars. In addition, crawling of vehicles is used to examine whether it corresponds to traffic congestion, especially during traffic congestion.

2.5 Concluding Remarks

Previous studies about estimation of fuel consumption in road transport sector considered only test vehicles in the fields without sufficient data reflecting driving patterns of all roadways in urban area; whereas, probe data, installed in many vehicles, can operate all roadways. There were using vehicle kilometer traveled (VKT) to estimate fuel consumption; however, VKT cannot determine and cannot well reflect driving pattern, which affect fuel consumption directly. Thus, this research applies the original equation for estimation of fuel consumption. Proposed equations in term of distance (VKT) are modified to the new term that collect of average speed, amount of detected probe cars, and time sharing of driving modes collected from probe data to better reflect driving patterns.

According to crawling behavior of vehicles, there were some studies similar to this behavior of vehicles, called stop-and-go. They indicated that frequent stop-and-go, occurring during interruptions and congestion of traffic, are the main causes of higher emissions on urban roads since stop-and-go lead to sharp increase or decrease in acceleration and deceleration. However, probe data cannot provide more details of speed data because vehicles in stop-and-go situation will stop and move immediately. Thus, crawling of vehicles can explain traffic congestion and can define as another driving mode better than using stop-and-go because, it can explain traffic congestion although speed data obtained from probe data cannot provide more details. In addition, no previous studies defined about crawling behavior for estimation of fuel consumption if hybrid cars or other environmentally friendly cars replace conventional gasoline cars. Consequently, this behavior of vehicles is added in as another driving mode in this study.

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CHAPTER 3

RESEARCH METHODOLOGY

This chapter describes the process of research methodology and explains the method for data collection in the field.

3.1 Methodological Process

The process of research methodology of this dissertation consists of five processes as shown in Figure 3.1.

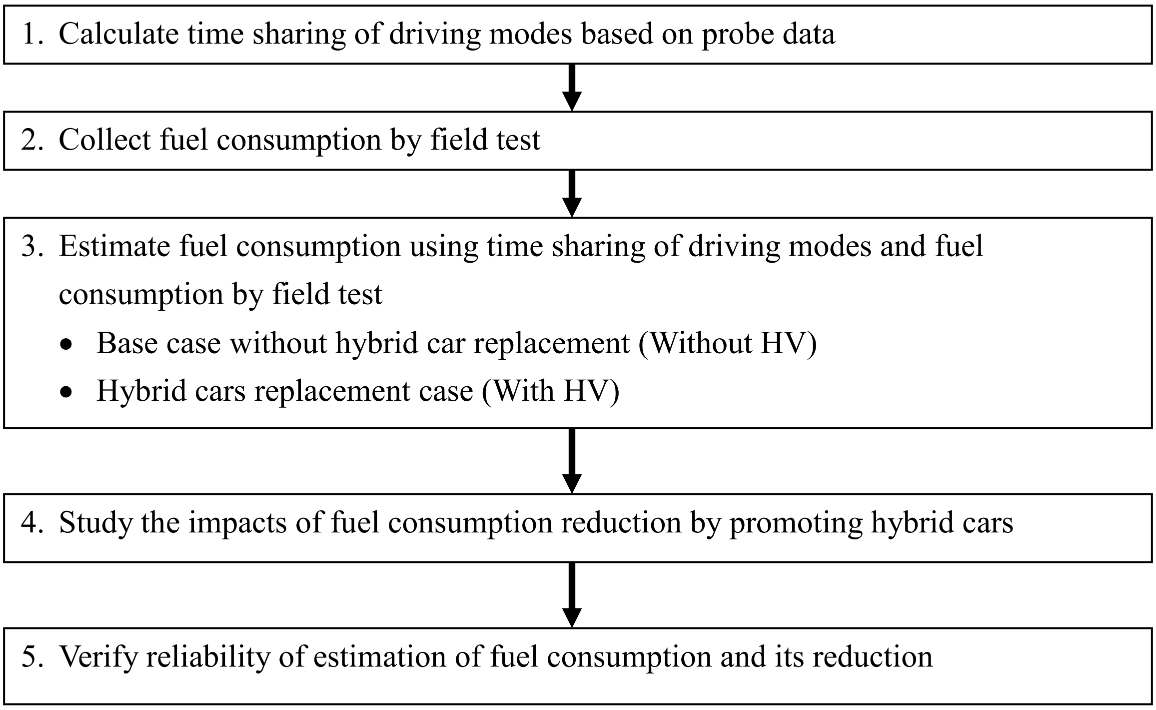

Figure 3.1 Methodological process

Each process is explained in detail as follow:

Process 1: Calculate time sharing of driving modes based on probe data

- Probe data from 10,000 taxis, operated within Bangkok, were gathered for one month period and used for calculating time sharing of driving modes, which were classified into 5 modes; stopping, accelerating, cruising, decelerating, and additional driving mode (crawling).
- Time sharing of driving modes was calculated in different conditions including days of week, periods, and road categories. Then, time sharing of

driving modes in each condition was used as the initial data for estimating fuel consumption.

Process 2: Collect fuel consumption by field test

- Fuel consumption was measured by field test both conventional gasoline car and hybrid car.
- For accurate validation of actual fuel consumption, two cars of the same type, manufacture year, and engine size were used in the field test. Moreover, they were operated together within the same traffic condition.
- In addition, additional driving mode (crawling) was investigated for different estimation compared without considering crawling mode.

Process 3: Estimate fuel consumption using time sharing of driving modes and fuel consumption by field test

- Measurement of fuel consumption from two cars by field test together with time sharing of driving modes from probe data on each driving mode were used for estimating fuel consumption.
- After that, time sharing of driving modes and fuel consumption by field test were used for estimating fuel consumption of both ordinary cars case (without HV) and hybrid car replacement case (with HV).

Process 4: Study the impacts of fuel consumption reduction by promoting of hybrid cars

- The impacts of fuel consumption reduction by promoting hybrid cars were determined under the scenarios that:
  1) All probe cars were replaced by hybrid cars.
  2) Private cars were replaced by hybrid cars.

Process 5: Verify reliability of estimation of fuel consumption and its reduction

- Actual fuel consumption by field test of hybrid and conventional gasoline cars were compared to see the reliability of estimation of fuel consumption.

3.2 Time Sharing of Driving Modes for Estimation of Fuel Consumption

Probe data can indicate driving patterns based on speed and time stamped data. Moreover, probe data can be used as an alternative method for estimation of fuel consumption depended on driving patterns or modes. Four basic driving modes consisting stopping, accelerating, cruising, and decelerating can be determined from speed profiles obtained from probe data. Speed profiles can be divided into four basic driving modes as shown in Figure 3.2. In this study, the fraction of duration of each driving mode was defined as "Time Sharing of Driving Modes".

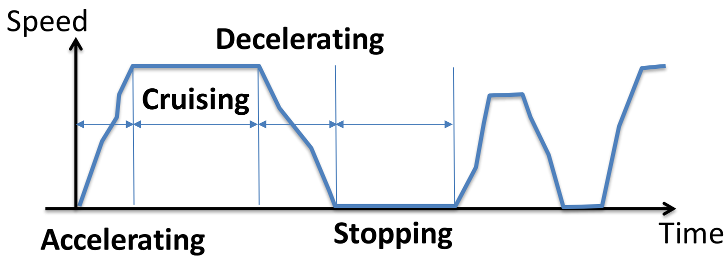

Figure 3.2 Speed profiles showing four basic driving modes

In Figure 3.2, four basic driving modes are normally used in literature driving pattern studies for fuel consumption and green house gas (GHG) emission. Since crawling situation frequently occurs in developing cities, which suffer from traffic congestion, crawling is considered as an additional driving mode for estimation of fuel consumption. Crawling mode in this study could be defined by analyzing speed profiles collected from probe cars. It was found that crawling of vehicles occur in speed range between 1 and 10 km/h. Figure 3.3 displays examples of speed profiles obtained from probe data in each road category including arterials, highways, and minor roads in peak hours in the evening. The figure shows that the crawling behavior can be found on every road category in which fluctuation of speed data are approximately between 1 to 10 km/h, and more than 10 km/h in some periods but not more than 15 km/h.

Therefore, crawling mode replaces other three basic driving modes including accelerating, cruising, and decelerating during speed between 1-10 km/h and some periods is not more than 15 km/h.

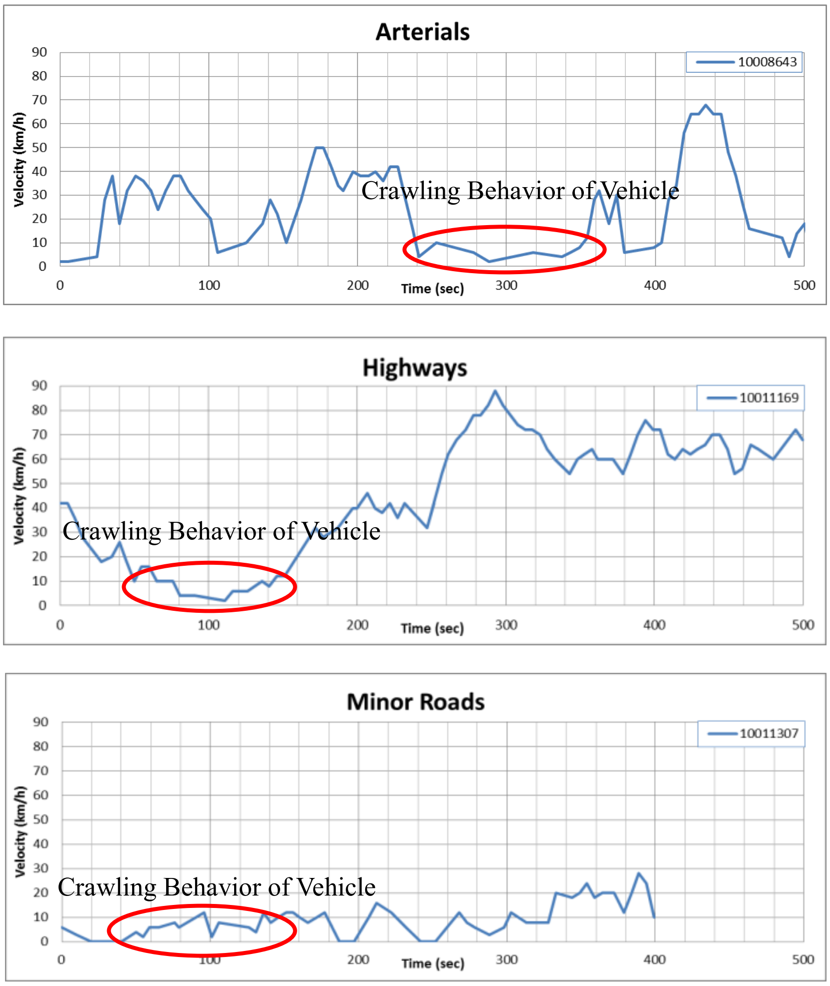

Figure 3.3 Examples of speed profiles obtained from probe data reflecting crawling behavior

The reason why this study indicates 10 km/h as the criteria for defining crawling mode is because crawling of vehicles can be defined by detection from speed profiles collected from probe data that it frequently occurs in speed range from 1 to around 10 km/h. The maximum speed for crawling can be less or more than 10 (4 - 16 km/h). In addition, when the author considered about the boundary of the maximum speed for crawling collected from samples of probe cars on all road categories, it was found that the average of the maximum speed is 9.8 km/h and the maximum frequency of maximum speed is at 10 km/h. Thus, for convenience of analysis, speed at 10 km/h is criteria for defining crawling mode in this study.

3.3 Case Study

A developing city, Bangkok Metropolitan and Region (BMR), Thailand was selected as the study area. BMR was divided into inner and outer BMR by differences in population and road network density, and land-use, as shown in Figure 3.4.

A promotion of environmentally friendly cars "Hybrid cars" in BMR is proposed for case study. The author is interested in this policy because hybrid cars have been introduced recently by TOYOTA in 2011 and a hybrid car consumes less gasoline, especially under traffic congestion. Therefore, they are expected to reduce fuel consumption in road transport sector in developing cities. However, this type of environmentally friendly car is not well-known because of some limitations such as high maintenance cost of battery within hybrid engine system and lack of proof on actual fuel consumption reduction impact. However, if auto industries can solve about this problem, more drivers especially of private cars may switch to use this type of car in the future. Consequently, promoting hybrid cars in BMR is interested for studying the impact of fuel consumption reduction.

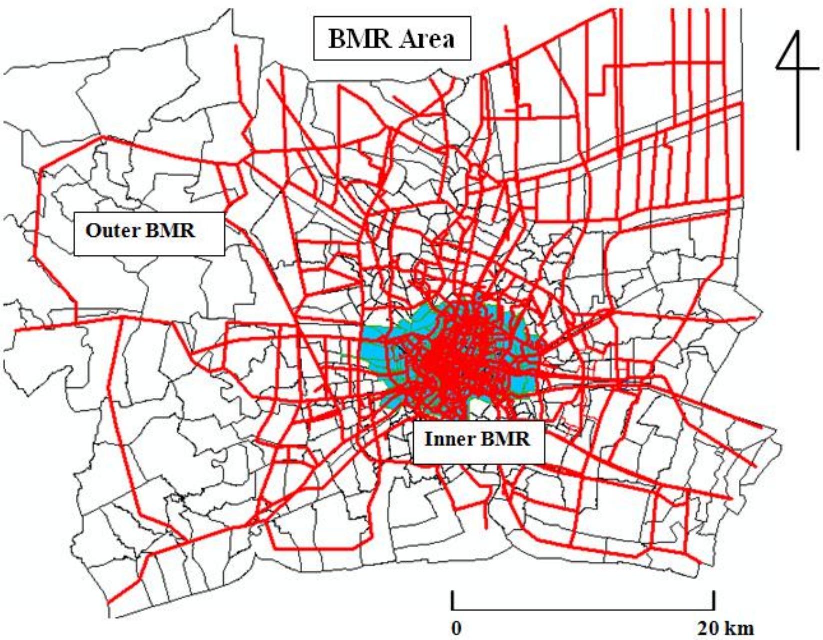

Figure 3.4 Study area for case study

In this case study, different conditions were defined by days of week (weekdays and weekends), periods [morning peak (07:00-09:00), off peak (09:00-16:00), and evening peak (16:00-19:00)], as referred by Traffic and Transportation Department [1], and road categories (highways, arterials, and minor roads). Regarding road category, highways are motorways, expressways, and main highways where traffic flow is commonly uninterrupted. Arterials are main roadways where traffic flow is interrupted by road crossings and signalized intersections. Minor roads are roadways that are branches of each arterial roadway. These road categories can be shown in Figure 3.5.

Highways/Expressways

Arterials Minor Roads

Figure 3.5 Examples of three road categories

3.4 Data Collection of Driving Modes and Fuel Consumption

Probe data from 10,000 taxis operated over BMR, with identification numbers (ID) of vehicles, positions (latitude and longitude), time stamps, and speeds were recorded in 5 second intervals. They were collected in 30 days during September 1st to October 31st, 2013 (21 days on weekdays and 9 days on weekends).

For how to measure fuel consumption by field test, the device called Touch-Brain (BLTZ), which was connected to a car, for monitoring instantaneous fuel consumption by different status of vehicle (speed) and engine (power, rpm). Then, Touch-Brain (BLTZ) was connected to a computer installing the software for collecting and storing fuel consumption data during field test data collection. For more understanding in this test, Figure 3.6 shows steps for collecting fuel consumption data in field test.

Apart from Touch-Brain (BLTZ) for monitoring instantaneous fuel consumption, Global Positioning System (GPS) devices were used in recording the travelling positions by time, and they could record the time when the cars start and stop operation. Also, GPS data could indicate the road category which cars traverse during the test.

(1) Test Car

(2) Connecting Touch-Brain (BLTZ) to the car

(3) Monitoring Data in Touch-Brain

(4) Testing in the real traffic conditions

Figure 3.6 Steps for collecting fuel consumption

3.5 Concluding Remarks

This chapter describes the process of research methodology and explains the method for data collection in the fields. Time sharing of driving modes can be calculated from speed profiles obtained from probe data. Additional driving mode (crawling) was considered by replacing four basic driving modes during fluctuation speed between 1-10 km/h and some periods not more than 15 km/h. Promoting hybrid cars in a developing city, "Bangkok Metropolitan and Region area (BMR)," Thailand was selected as case study for estimating fuel consumption reduction and considering vehicle crawling. Two main data were collected including probe data and fuel consumption data. Probe data were obtained from operating of 10,000 taxis in BMR to calculate time sharing of driving modes in each speed range. Fuel consumption data were obtained from field test of one conventional gasoline car and one hybrid car to determine fuel consumption rate in unit of cc per second in each driving modes and speed range. Two drivers of one conventional gasoline car and one hybrid car were asked to drive together along selected roadways in

BMR in each days of week, period, and road category. After that, time sharing of driving modes by probe data and fuel consumption by field test were used for estimating fuel consumption for both ordinary case without hybrid cars (without HV) and with hybrid car replacement case (with HV). Two cases were compared to each other and used for estimating fuel consumption reduction. Finally, the results of estimation of fuel consumption and its reduction were examined for reliability confirmation.

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CHAPTER 4

ESTIMATION OF TIME SHARING OF DRIVING MODES

This chapter shows the results of time sharing of driving modes in different conditions in term of sub-areas, periods, and road categories. Time sharing of driving modes is used as an important variable for estimation of fuel consumption. In addition, traffic congestion and fuel consumption is explained based on time sharing of driving mode results by indicating percentages of stopping and crawling modes. For proofing that the calculated time sharing of driving modes are reliable, time percentages from time sharing of driving modes on stopping and crawling mode are compared with their percentages from observation.

4.1 Definition of Driving Modes

Four basic driving modes and the additional mode (crawling) are separated by considering speed at 10 km/h that is the criteria for defining crawling mode, as already explained in Chapter 3 in section 3.2.

4.1.1 Four basic driving modes

Four basic driving modes consist of stopping (Speed = 0 km/h), accelerating (Speed increases more than 0.5 km/h in 1 second), cruising (Speed does not change or varies between ± 0.5 km/h in 1 second), and decelerating (Speed decreases more than 0.5 km/h in 1 second).

4.1.2 Additional driving modes (crawling)

In this study, crawling of vehicles is defined when (1) speeds fluctuate in the range between 1 to around 10 km/h., (2) speed may go above 10 km/h only once, and only if previous and following speeds within the period are below 10 km/h, and (3) speed steadily decreases and increases or is maintained within 10 km/h. This definition of vehicle crawling can represent the traffic congestion which has different impact on fuel consumption from the other driving modes. For more understanding of the definition in this study, Figure 4.1 shows methodology and the algorithm to identify crawling mode or four original driving modes. In addition, the algorithm to identify three original driving modes (accelerating, cruising, and decelerating) can be shown in Figure 4.2.

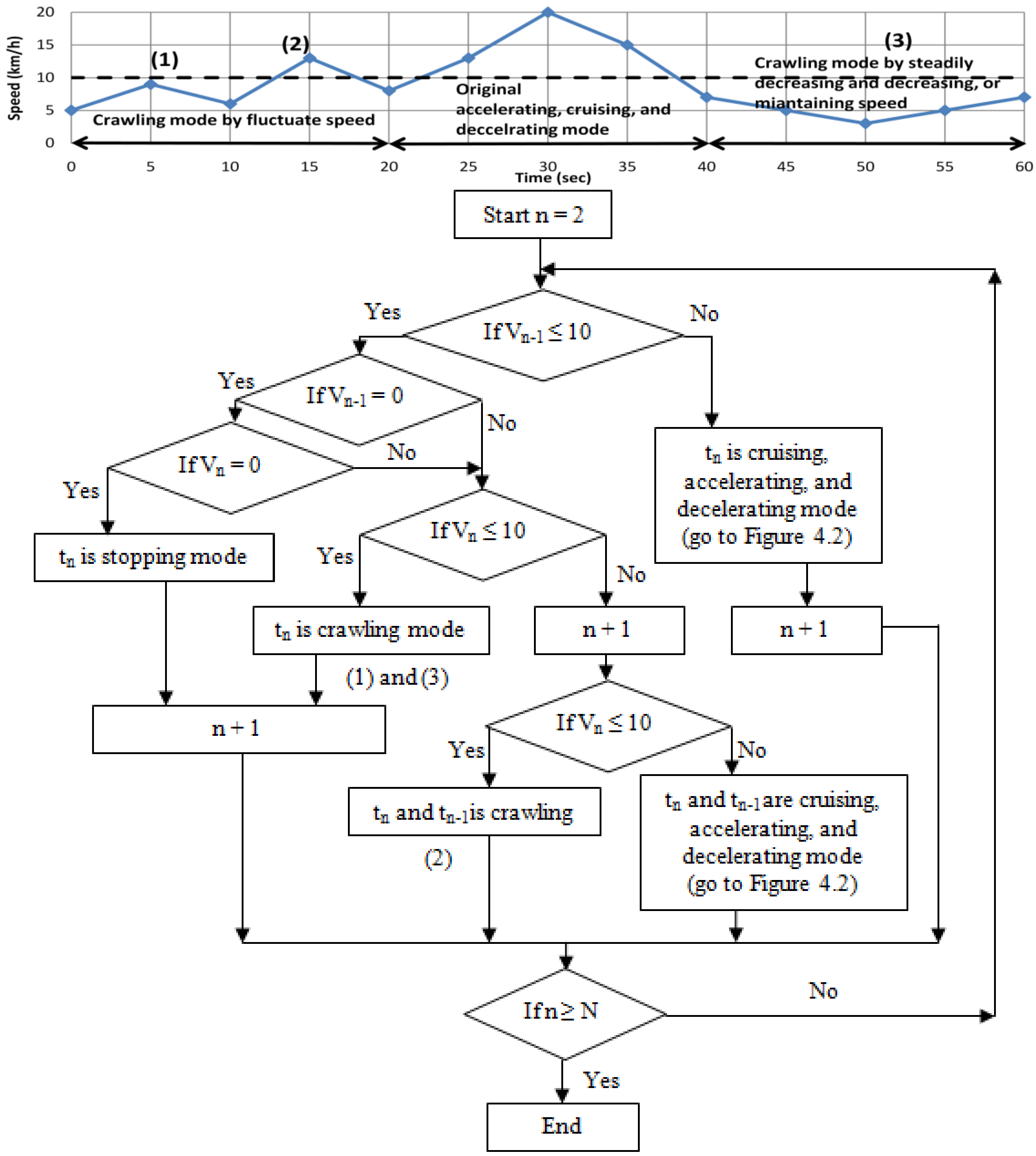


Figure 4.1 Methodology and the algorithm for identifying crawling mode

As indicated in Figure 4.1, n is the row of probe data from the total (N), V is speed, and t_n and t_{n-1} are time interval of probe data from the present data (n) and the previous data (n-1), respectively. In Figure 4.2, A_n is acceleration that can be calculated by difference between present data speed (V_n) and previous data speed (V_{n-1}) divided by time interval (second).

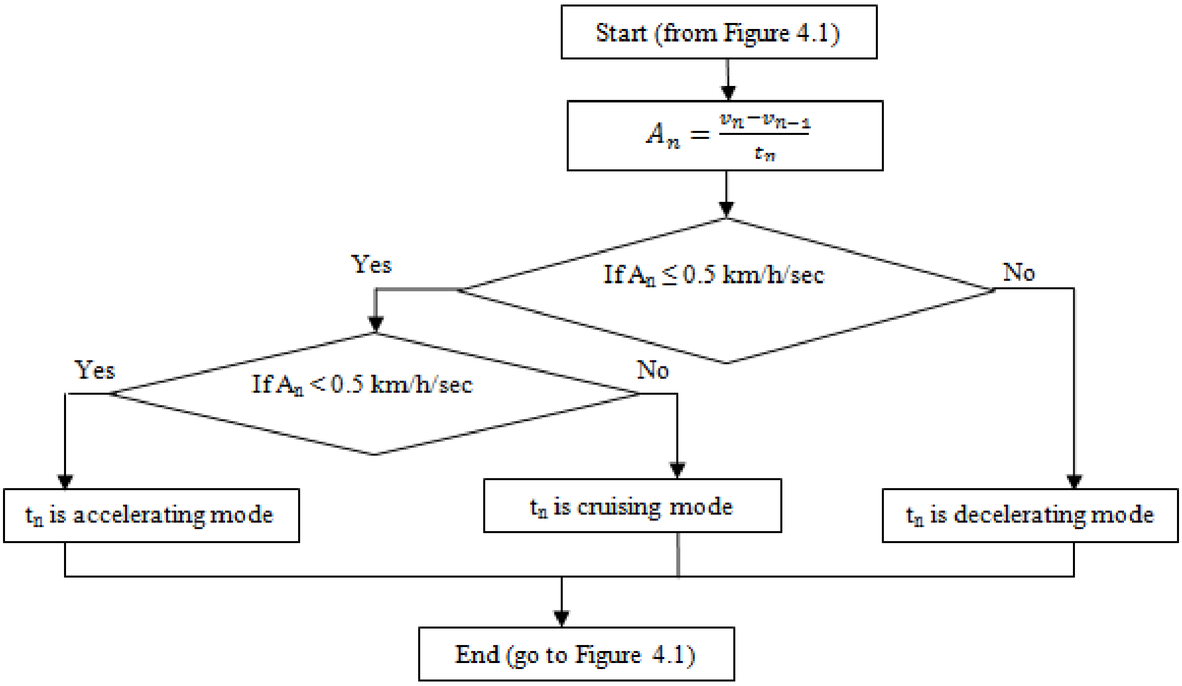


Figure 4.2 The algorithm for identifying 4 basic driving modes

4.2 Estimation of Time Sharing of Driving Modes based on Probe Data

To calculate time sharing of driving modes in this study, speeds obtained from probe data, were separated into 7 ranges from 0, 1-10, …., to 51-60, and > 61 km/hr. To analyze probe data in different conditions, firstly, probe data had to be filtered by required days and periods by using time stamps. Then, probe data were divided by sub-area (Inner and outer BMR), road category (Highways, arterials, and minor roads), days (weekdays and weekend), and periods (Morning, afternoon, and evening) as shown in Figure 4.3. Probe data were sorted using GIS Software, which filtered positions of probe data and located positions of probe data on indicated sub-area and road network in BMR.

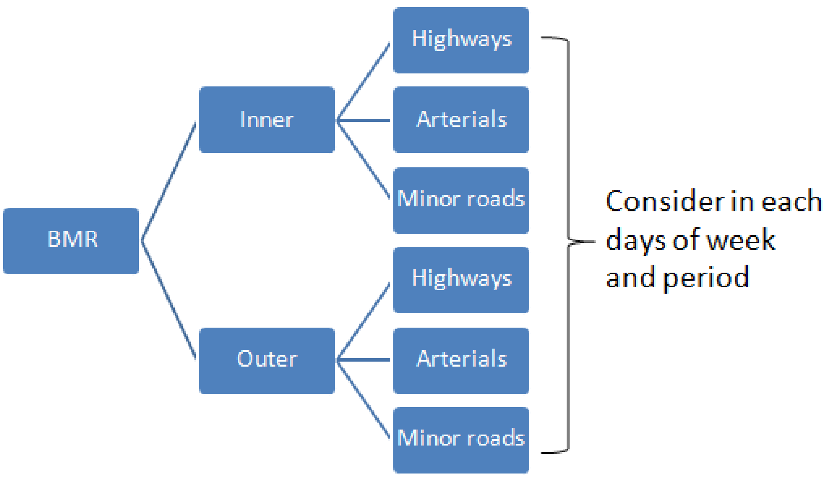


Figure 4.3 Characterization of probe data

After probe data were divided in each condition, identification number (ID) of each probe vehicle was determined. Speed and time stamps of probe data were used to indicate driving modes and cumulative time spent in each driving mode. In addition, they were used to calculate vehicle kilometers traveled (VKT) by speed multiplied by difference of time stamps (time intervals).

4.3 Results of Time Sharing of Driving Modes based on Probe Data

Figure 4.4 - 4.15 shows the results of time sharing of driving modes that indicate travel time percentage in each driving mode for different conditions. They are characterized by weekdays and weekends in the first step. Then, they are characterized into two sub-areas, three road categories, and three time periods, respectively.

4.3.1 Time sharing of driving modes on weekdays

- Inner area

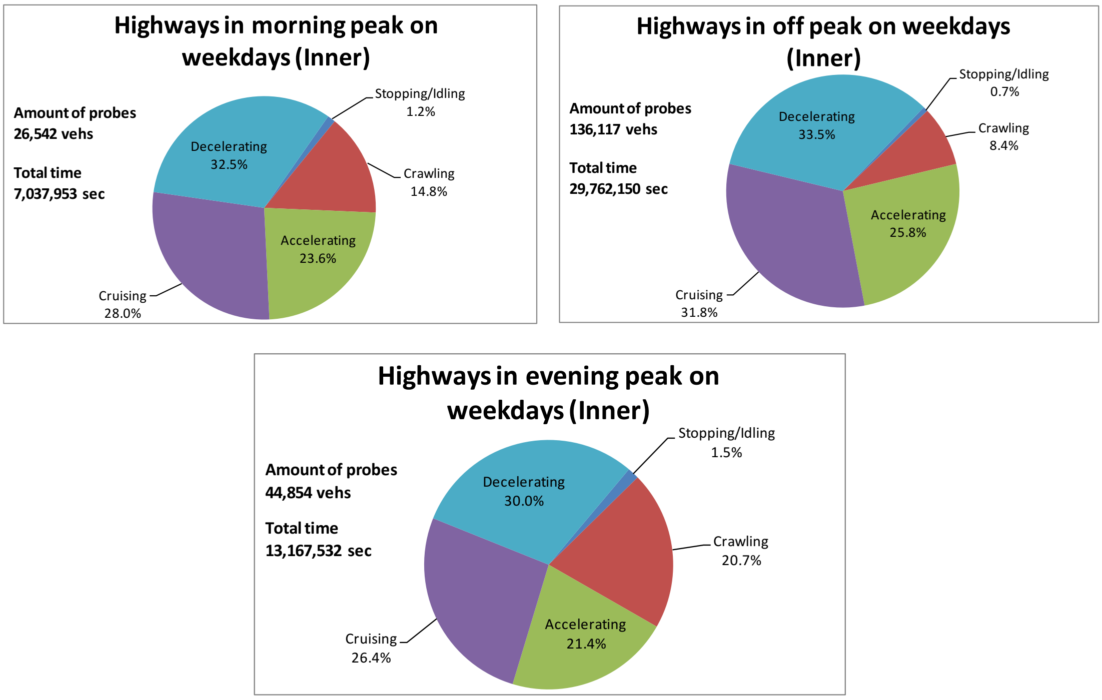


Figure 4.4 Time sharing of driving modes on highways on weekdays in inner area

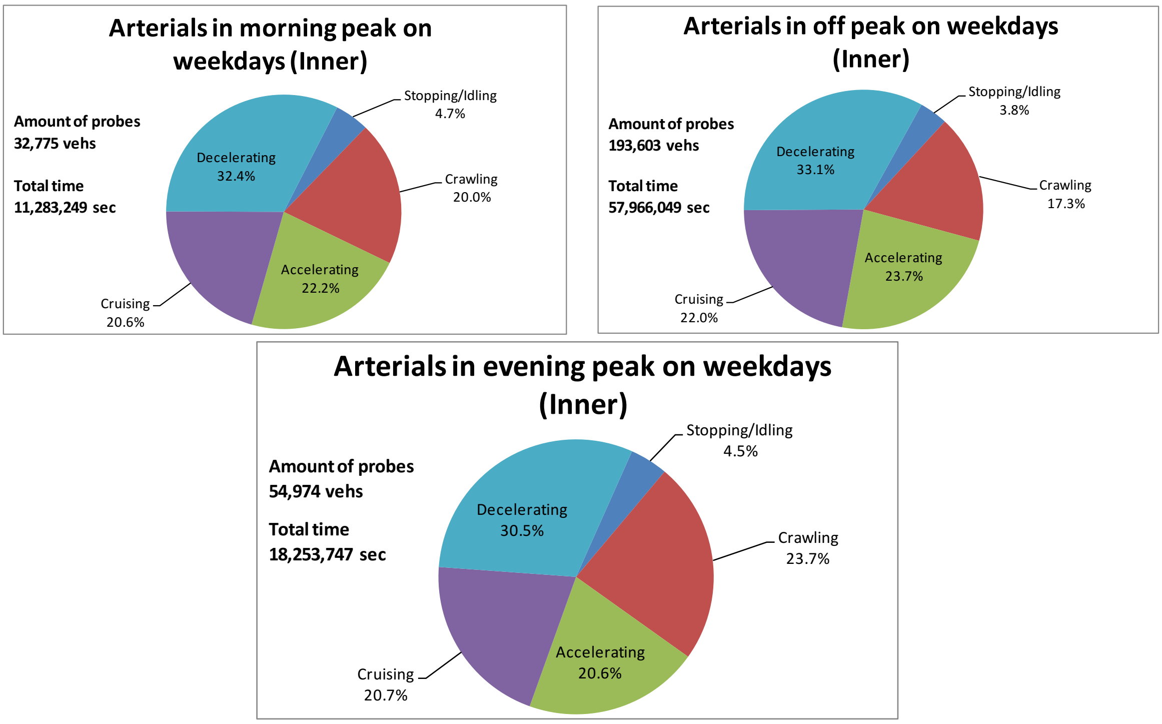


Figure 4.5 Time sharing of driving modes on arterials on weekdays in inner area

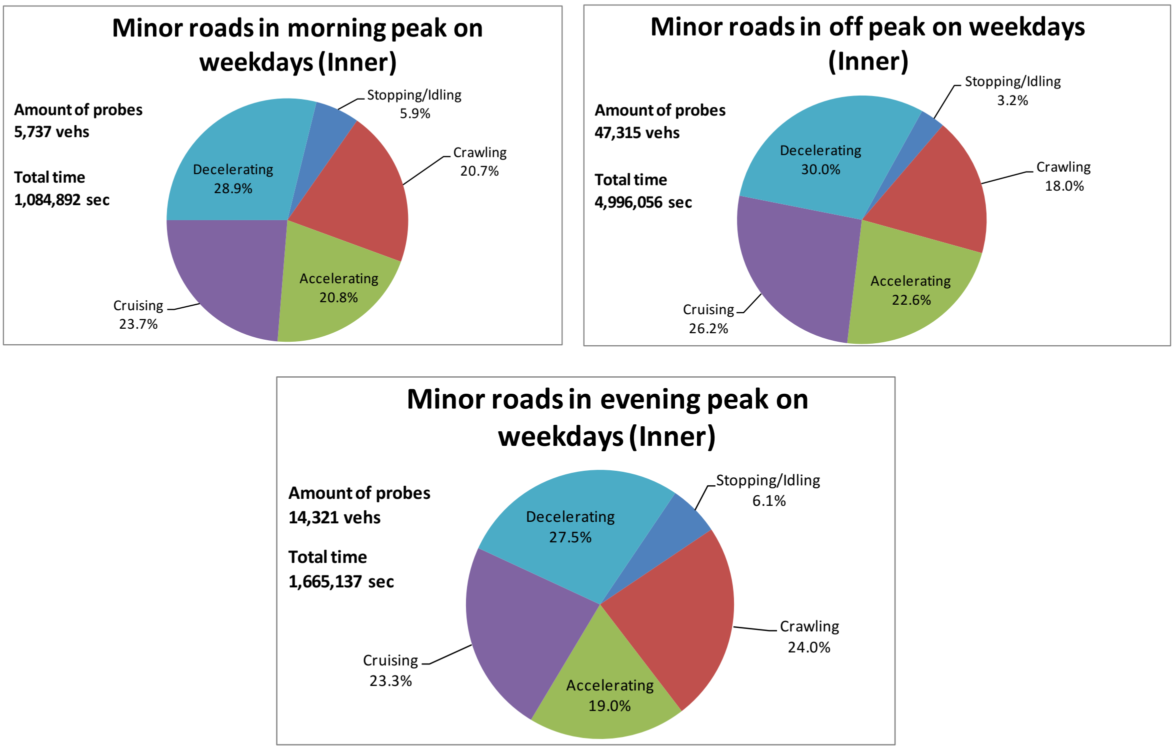


Figure 4.6 Time sharing of driving modes on minor roads on weekdays in inner area

- Outer area

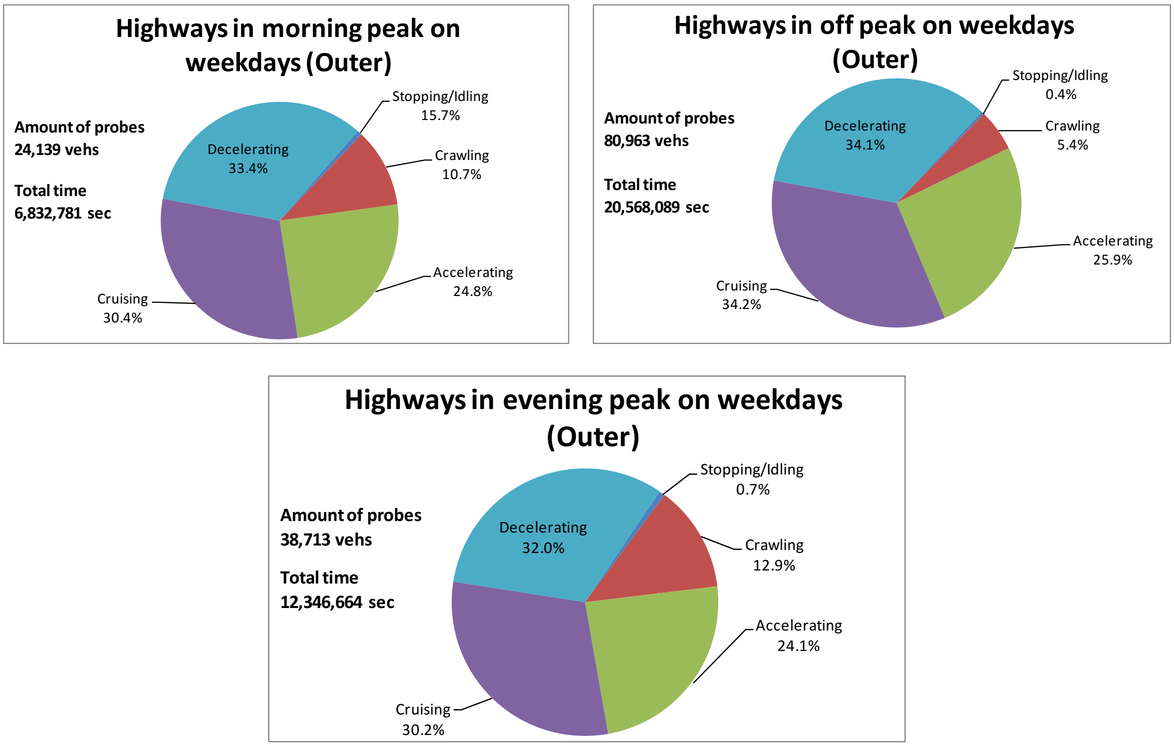


Figure 4.7 Time sharing of driving modes on highways on weekdays in outer area

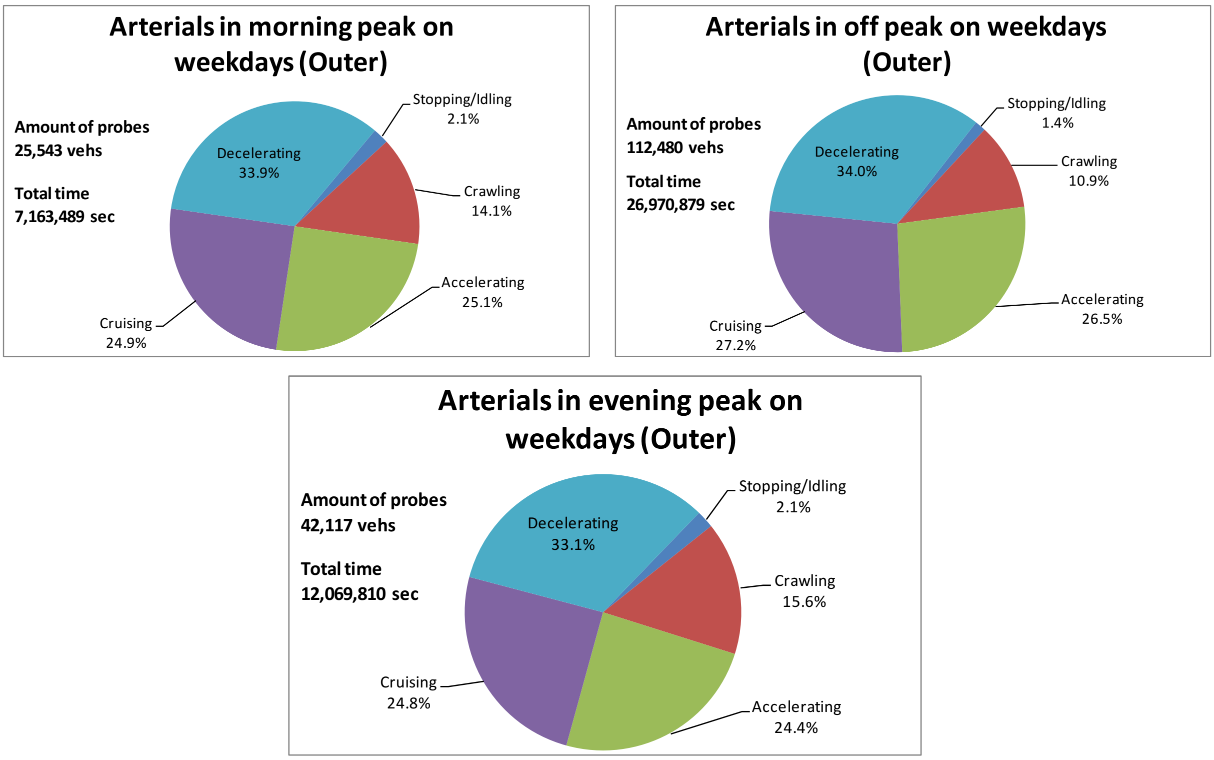


Figure 4.8 Time sharing of driving modes on arterials on weekdays in outer area

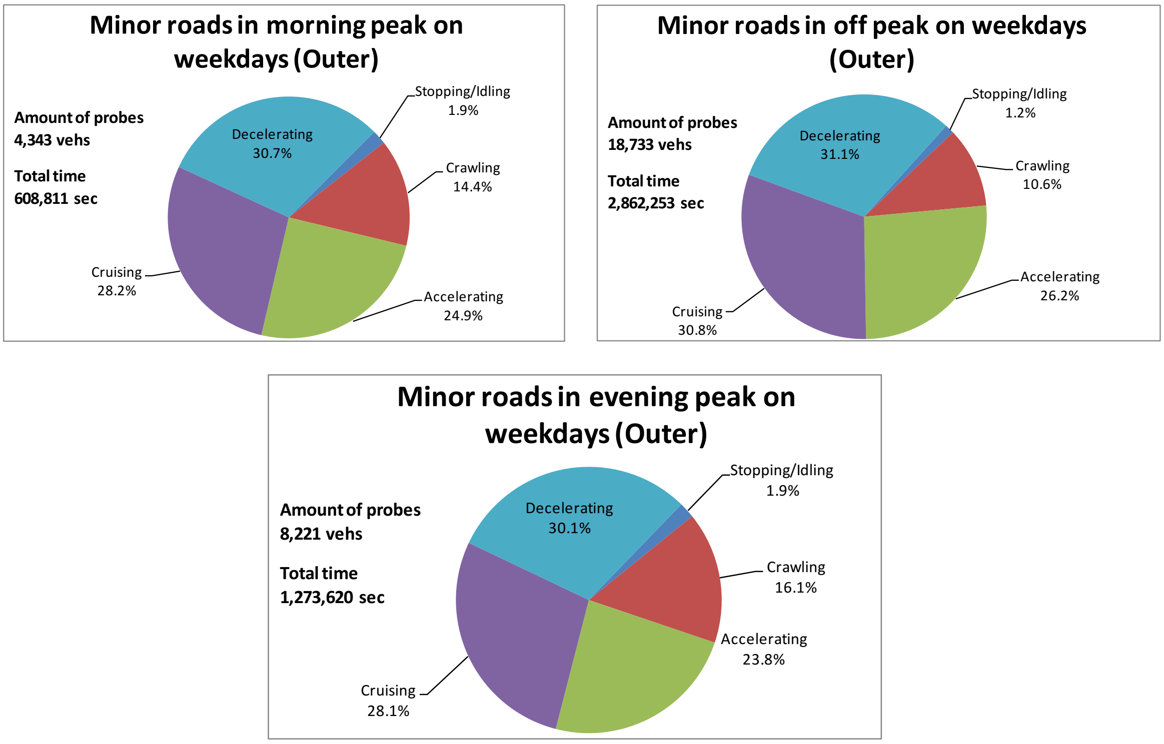


Figure 4.9 Time sharing of driving modes on minor roads on weekdays in outer area

4.3.2 Time sharing of driving mode diagrams on weekends

- Inner area

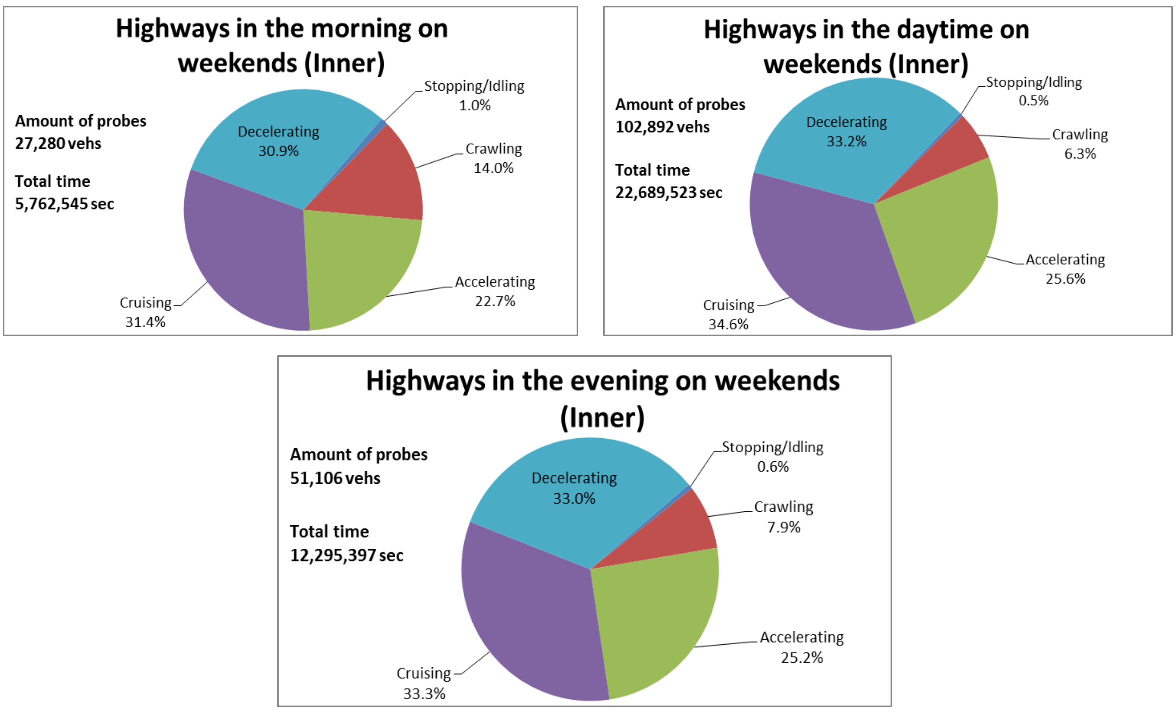


Figure 4.10 Time sharing of driving modes on highways on weekends in inner area

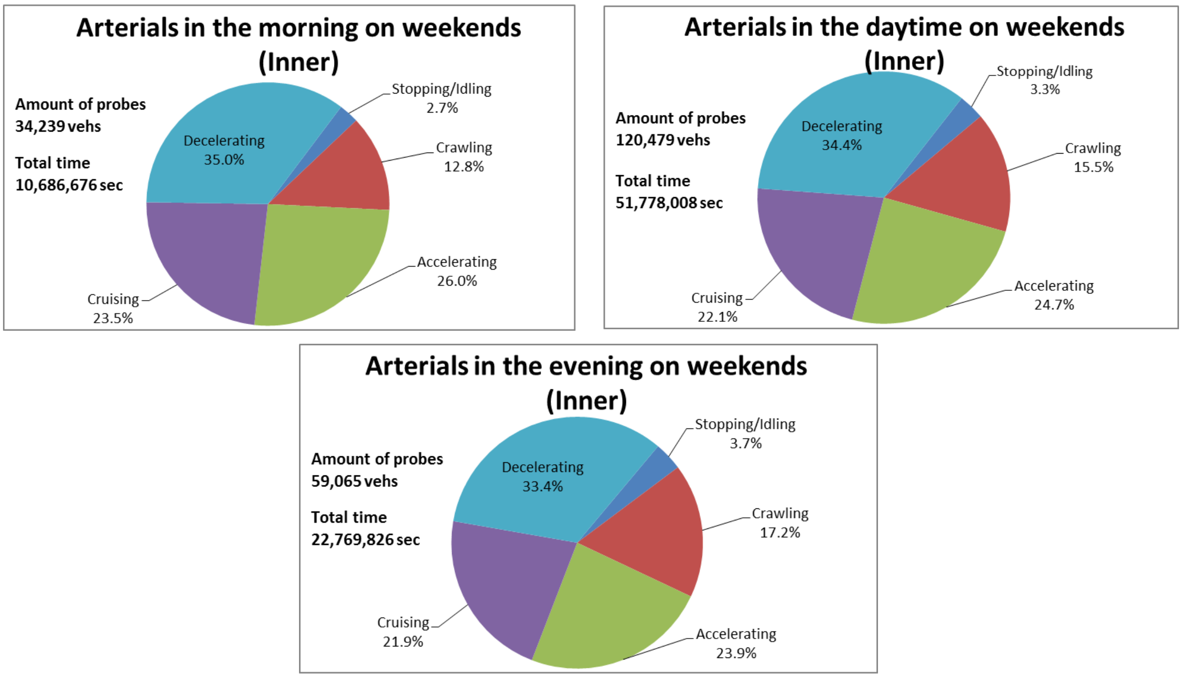


Figure 4.11 Time sharing of driving modes on arterials on weekends in inner area

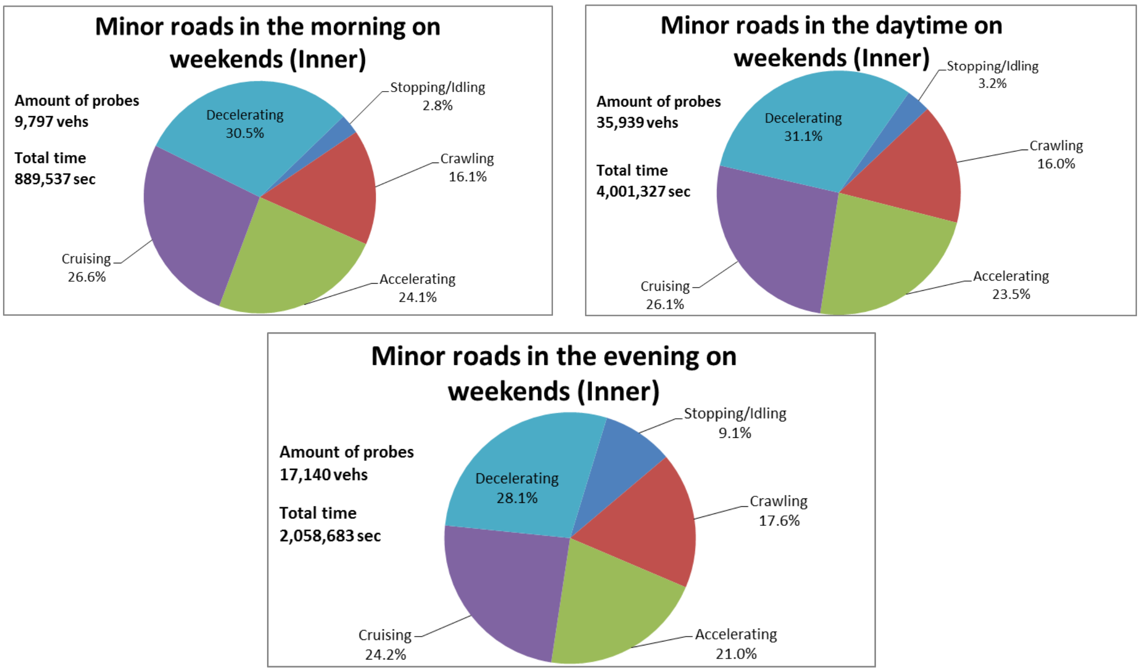


Figure 4.12 Time sharing of driving mode on minor roads on weekends in inner area

- Outer area

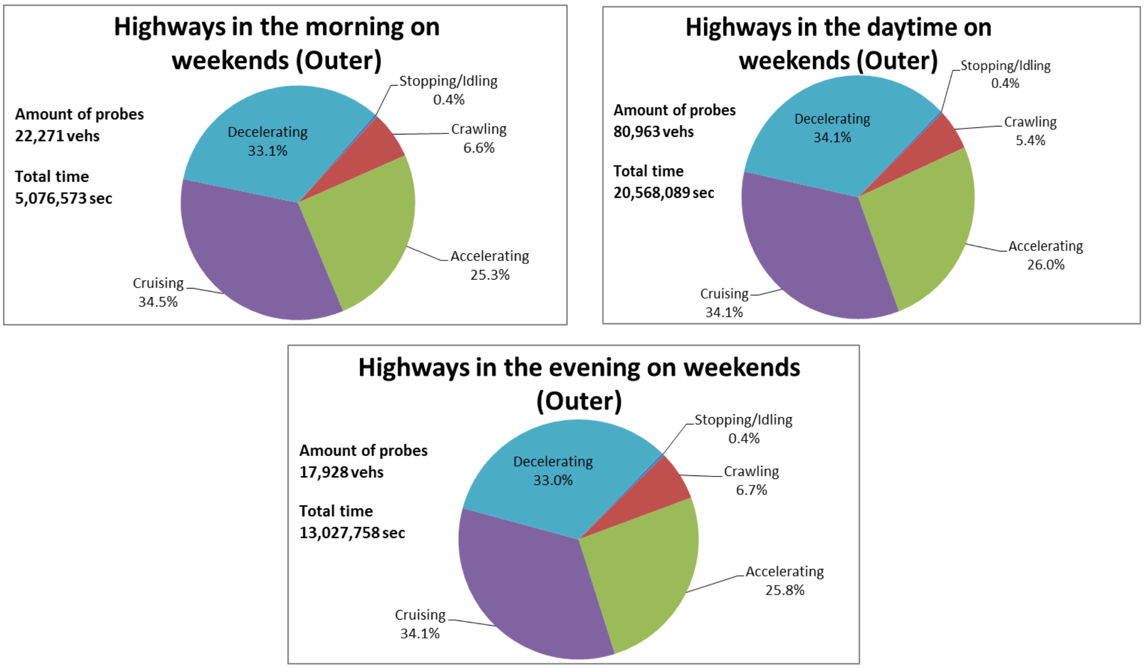


Figure 4.13 Time sharing of driving modes on highways on weekends in outer area

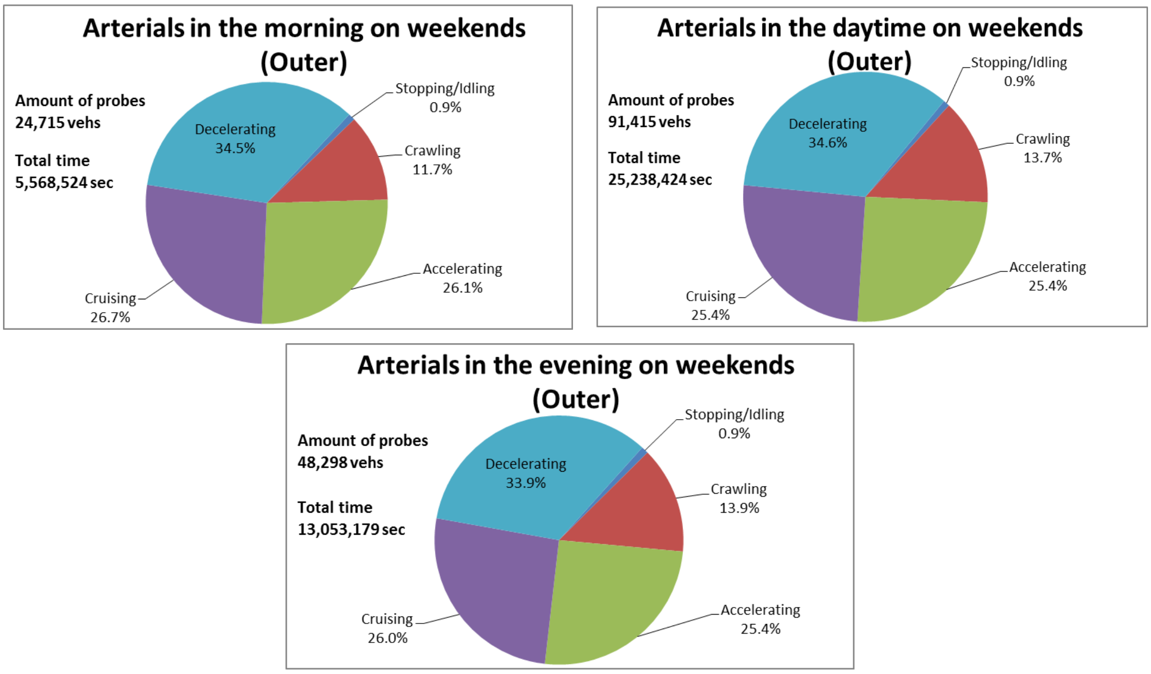


Figure 4.14 Time sharing of driving modes on arterials on weekends in outer area

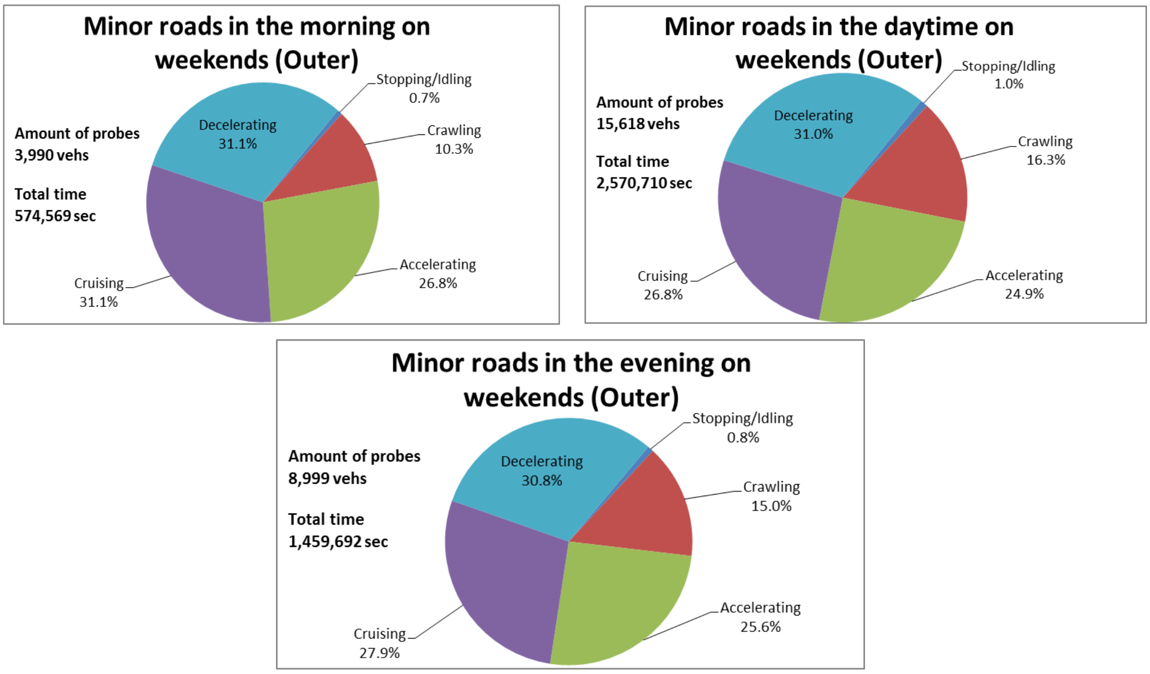


Figure 4.15 Time sharing of driving modes on minor roads on weekends in outer area

In Figure 4.4 - 4.15, time sharing of driving modes in all conditions indicates that decelerating mode spends the greatest time percentage in most cases, while cruising mode is the second, and the third is accelerating. The reason why decelerating mode is the most time percentages and is more than accelerating mode is because the nature of most drivers that speed up so fast, but slowly break. As a result, deceleration period may be longer and has more time percentages. Decelerating percentages in congestion period in cases of peak hours on weekdays decrease, while, accelerating percentages increase.

Regarding stopping and crawling modes, although percentages of them are less than decelerating, cruising, and accelerating, they have more impacts in low speed ranges from 0 to 20 km/h. From the results, stopping and crawling mode increase in inner areas on weekdays on all road categories while on minor roads increase only on weekends. Stopping and crawling percentages in inner areas are greater than in outer areas in all cases. On weekdays, evening peaks has the highest percentage of stopping and crawling. In addition, high percentages of them are readily seen on arterials and minor roads in inner areas. Meanwhile on weekends, their percentages in the morning are lower than those in the afternoon and evening, except on highways in inner area and in the morning where the percentages are the highest on weekends. Moreover, high percentages of them are readily seen only on minor roads in inner areas.

From time sharing of driving modes in Figure 4.4 - 4.15, if only stopping mode is considered, traffic congestion impact would not be clearly seen. When considering crawling mode, increased percentages of congestion are readily seen, and they account for almost 30% on arterials. Thus, additional driving mode (crawling) can make the difference between with and without considering it by indicating traffic congestion. Consequently, the difference in the impact on fuel consumption would be clearly observed.

Apart from time sharing of driving modes for different conditions shown in Figure 4.4 - 4.15, time percentages of driving modes could be displayed by speed ranges as examples in Figure 4.16 on arterials on weekdays in morning peak and off peak.

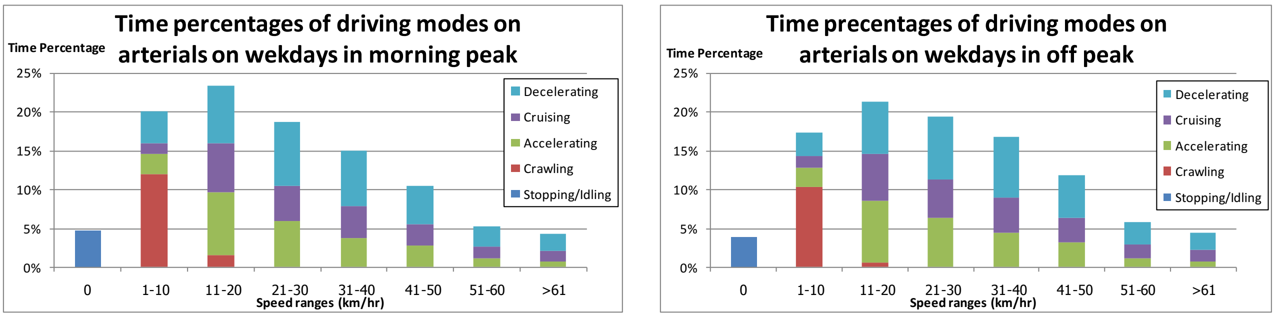


Figure 4.16 Time percentages of driving modes on arterials on weekdays

In Figure 4.16, difference of time percentages between morning peak and off peak can be seen in speed range of 0, 1-10, and 11-20 km/h. In 0 speeds, time percentage of stopping mode in morning peak is more than that in off peak. In speed range of 11-20 km/h, time percentage of crawling mode is obviously seen and its percentage in morning peak are more than that in off peak. In speed range of 11-20 km/h, a few time percentages on crawling mode are seen, but its percentages in morning peak are still more than those in off peak.

In Figure 4.16, accumulated time by separating each driving mode and in each speed range can be used as the initial data for estimation of fuel consumption that will be explained in Chapter 5 and 6. In Chapter 5, fuel consumption by field test in each driving mode and speed range in different conditions can be measured. In Chapter 6, the results of fuel consumption based on time sharing of driving modes can be estimated.

To better understandings on difference in driving mode percentages under various conditions, section 4.3.3 illustrates driving mode percentage results between inner and outer area using linear graphs.

4.3.3 Driving mode percentages

For more understanding of the results in each condition, the distributions (percentages) of driving modes among sub-areas, road categories, and days of week were compared on highways, arterials, and minor roads, as shown in Figure 4.17, 4.18, and 4.19, respectively. In this study, stopping and crawling modes were combined to identify traffic congestion, and used to explain the consistency with amount of fuel consumption rather than showing only stopping mode.

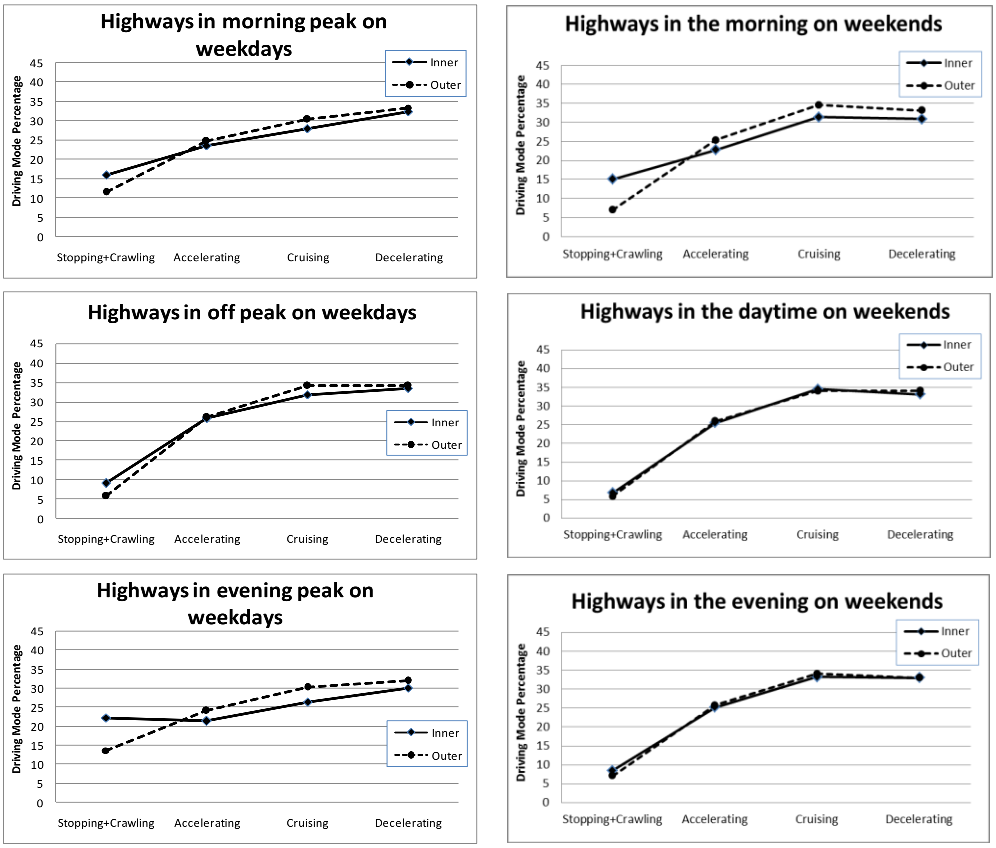


Figure 4.17 Driving mode percentages in each period and days of week on highways

In Figure 4.17 on weekdays, time sharing on decelerating mode has the greatest percentage in all periods and that on cruising mode is the second. Stopping and crawling modes increase in percentages where traffic is congested especially in inner (central) area of Bangkok in evening peak. Meanwhile on weekends, the overall results are similar to on weekdays, but stopping and crawling percentages in the evening are lower than those on weekdays.

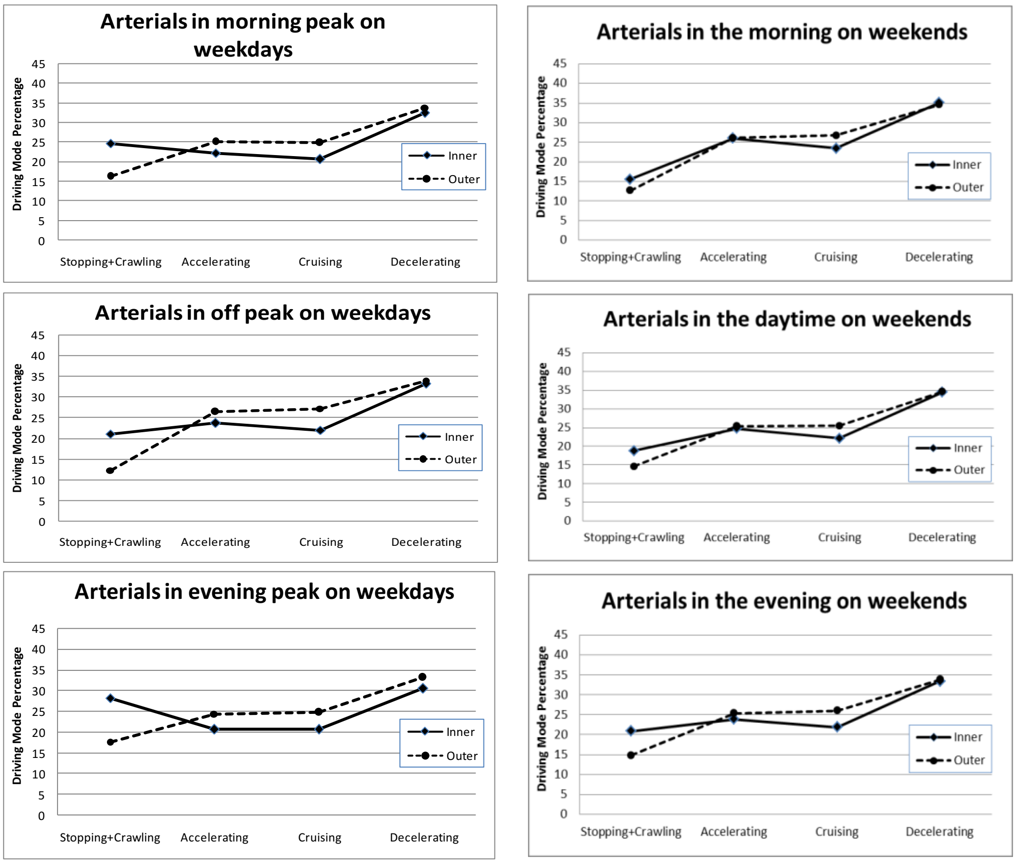


Figure 4.18 Driving mode percentages in each period and days of week on arterials

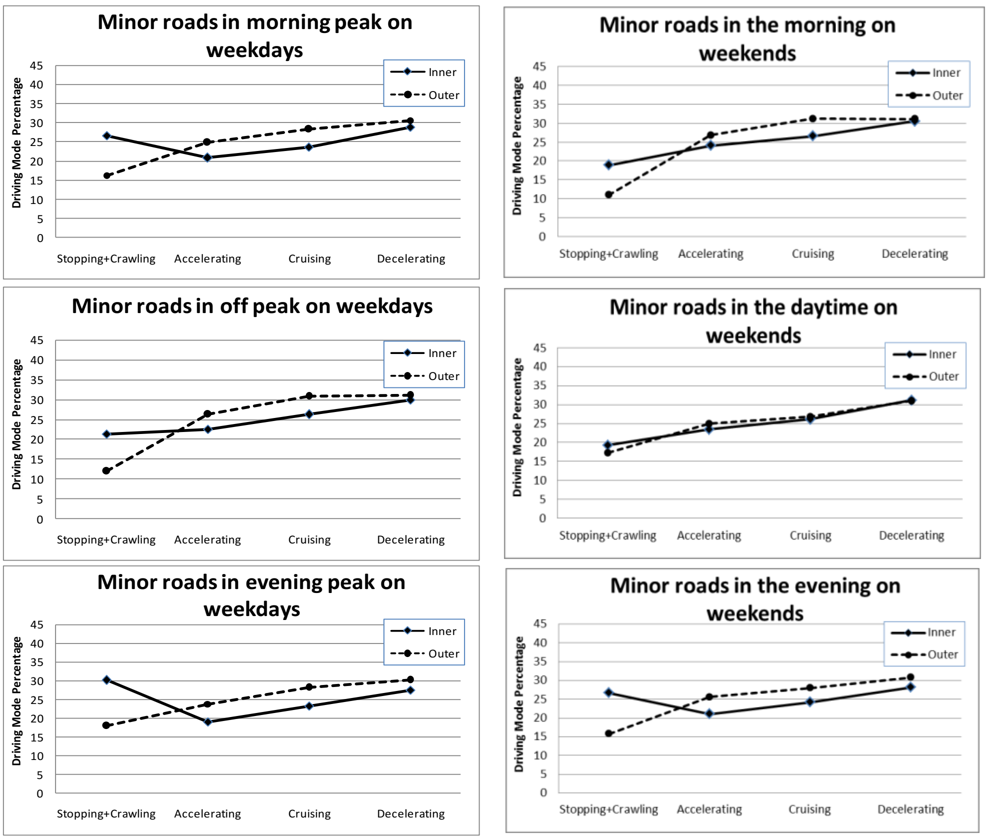


Figure 4.19 Driving mode percentages in each period and days of week on minor roads

In Figure 4.18, time sharing on decelerating mode on arterials is of greatest percentage in all periods, similar to the situation on highways. Cruising mode together with accelerating mode are the second. Stopping and crawling mode has greater percentage in some cases if traffic situation is congested especially in the inner area (morning and evening peak on weekdays, and evening time on weekends). As expected, stopping percentages on weekends are lower than weekdays.

In Figure 4.19, on minor roads, time sharing on decelerating mode is of greatest percentage in all periods that are similar to that of highways and arterials, excluding in the evening in inner area that stopping mode is the greatest instead. Stopping and crawling percentages on weekends in the evening are lower than on weekdays.

From Figure 4.17 - 4.19, it can be concluded that time sharing on decelerating mode is of greatest percentage in most of cases while cruising mode is the second. Percentage of stopping and crawling mode is greater than accelerating and cruising modes in many cases if traffic is congested especially in the inner (central) area of Bangkok on weekdays in morning and evening peak on arterials and minor roads. These figures can describe traffic conditions in Bangkok and can be used to explain the consistency with amount of fuel consumption efficiency during that time period.

Time sharing of driving modes in each condition can be summarized in Table 4.1 and 4.2. These results are used as the initial data for estimation of fuel consumption which will be explained in chapter 6.

Table 4.1 Summary of time sharing of driving modes on weekdays

Sub-area	Road category	Period	Time sharing of driving modes represented by time (sec) and percentage									
			Stopping		Crawling		Accelerating		Cruising		Decelerating	
			Time (sec)	%	Time (sec)	%	Time (sec)	%	Time (sec)	%	Time (sec)	%
Inner	Highways	Morning peak	81,871	1.2	1,040,361	14.8	1,659,662	23.6	1,972,136	28.0	2,283,923	32.5
		Off peak	200,136	0.7	2,486,651	8.4	7,665,778	25.8	9,450,839	31.8	9,958,746	33.5
		Evening peak	199,889	1.5	2,722,142	20.7	2,812,416	21.4	3,479,965	26.4	3953,120	30.0
	Arterials	Morning peak	533,233	4.7	2,251,967	20.0	2,508,577	22.2	2,328,929	20.6	3,660,543	32.4
		Off peak	2,216,407	3.8	10,042,684	17.3	13,724,501	23.7	12,770,173	22.0	19,212,284	33.1
		Evening peak	812,623	4.5	4,334,506	23.7	3,762,614	20.6	3,772,693	20.7	5,571,312	30.5
	Minor roads	Morning peak	62,307	5.9	217,837	20.7	218625	20.8	249076	23.7	303879	28.9
		Off peak	156,881	3.2	875,998	18.0	1,097,520	22.6	1,274,059	26.2	1,456,044	30.0
		Evening peak	98,334	6.1	385,931	24.0	304,646	19.0	374,660	23.3	442,138	27.5
Outer	Highways	Morning peak	47,571	0.7	732,644	10.7	1,692,003	24.8	2,075,782	30.4	2,284,782	33.4
		Off peak	76,581	0.4	1,119,269	5.4	5,346,962	25.9	7,047,743	34.2	7,017,734	34.1
		Evening peak	88,325	0.7	1,596,537	12.9	2,980,449	24.1	3,733,889	30.2	3,947,464	32.0
	Arterials	Morning peak	147,574	2.1	1,009,970	14.1	1,798,820	25.1	1,782,256	24.9	2,424,869	33.9
		Off peak	372,529	1.4	2,950,740	10.9	7,147,118	26.5	7,339,435	27.2	9,161,057	34.0
		Evening peak	248,396	2.1	1,882,660	15.6	2,944,776	24.4	2,997,609	24.8	3,996,368	33.1
	Minor roads	Morning peak	11,517	1.9	87,547	14.4	151,419	24.9	171,720	28.2	186,608	30.7
		Off peak	35,128	1.2	304,415	10.6	750,614	26.2	882,330	30.8	889,767	31.1
		Evening peak	24,381	1.9	204,697	16.1	302,889	23.8	357,863	28.1	383,790	30.1

Table 4.2 Summary of time sharing of driving modes on weekends

Sub-area	Road category	Period	Time sharing of driving modes represented by time (sec) and percentage									
			Stopping		Crawling		Accelerating		Cruising		Decelerating	
			Time (sec)	%	Time (sec)	%	Time (sec)	%	Time (sec)	%	Time (sec)	%
Inner	Highways	Morning	58,368	1.0	805,091	14.0	1,310,435	22.7	1,807,375	31.4	1,781,276	30.9
		Daytime	109,384	0.5	1,419,864	6.3	5,798,126	25.6	7,840,126	34.6	7,522,023	33.2
		Evening	75,003	0.6	970,741	7.9	3,099,175	25.2	4,089,763	33.3	4,060,715	33.0
	Arterials	Morning	282,244	2.7	1,362,490	12.8	2,758,169	26.0	2,488,529	23.5	3,717,244	35.0
		Daytime	1,714,275	3.3	8,022,955	15.5	12,785,851	24.7	11,446,307	22.1	17,808,620	34.4
		Evening	835,999	3.7	3,924,820	17.2	5,430,639	23.9	4,981,027	21.9	7,597,341	33.4
	Minor roads	Morning	24,614	2.8	143,046	16.1	214,140	24.1	236,522	26.6	271,215	30.5
		Daytime	129,464	3.2	640,225	16.0	939,434	23.5	1,046,306	26.1	1,245,899	31.1
		Evening	187,668	9.1	361,519	17.6	432,432	21.0	498,263	24.2	578,801	28.1
Outer	Highways	Morning	21,917	0.4	332,734	6.6	1,286,023	25.3	1,753,683	34.5	1,682,216	33.1
		Daytime	76,581	0.4	1,119,269	5.4	5,346,962	26.0	7,007,543	34.1	7,017,734	34.1
		Evening	49,157	0.4	754,531	6.7	2,913,204	25.8	3,852,150	34.1	3,729,748	33.0
	Arterials	Morning	51,268	0.9	651,369	11.7	1,453,087	26.1	1,489,336	26.7	1,923,464	34.5
		Daytime	215,110	0.9	3,466,506	13.7	6,399,157	25.4	6,420,623	25.4	8,737,028	34.6
		Evening	121,200	0.9	1,810,758	13.9	3,309,225	25.4	3,392,944	26.0	4,419,053	33.9
	Minor roads	Morning	4,050	0.7	59,237	10.3	153,823	26.8	178,952	31.1	178,507	31.1
		Daytime	25,668	1.0	418,241	16.3	641,150	24.9	689,591	26.8	796,061	31.0
		Evening	11,645	0.8	218,352	15.0	372,963	25.6	407,848	27.9	448,884	30.8

4.4 Impact of Considering Crawling Mode in Driving Modes

Indication of traffic congestion which affects higher fuel consumption, time sharing of stopping and crawling mode is represented in Figure 4.20, where it shows the comparison of its percentage between the inner and outer areas considerably in each case.

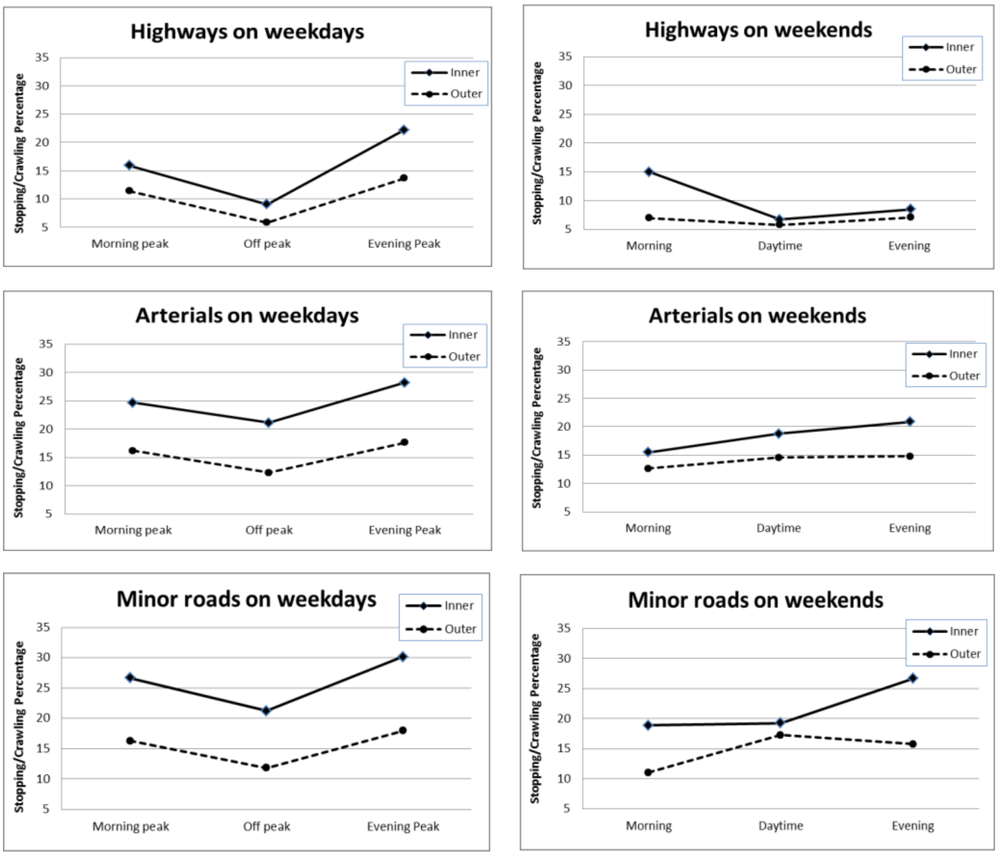


Figure 4.20 Stopping and crawling percentages in each condition

Stopping and crawling percentages in the inner areas are greater than that in the outer areas in all cases. On weekdays, stopping and crawling proportions are the highest in evening peak period, and the trend lines of its percentages look like a V-shape from in the morning to evening peak. In addition, high percentages of stopping and crawling mode are obviously seen on arterials and minor roads in the inner areas.

Meanwhile on weekends, stopping and crawling percentages in morning peaks are lower than those in the daytime and evening, except on highways in the inner area and in the morning peak where the percentage is the highest.

4.5 Examination of Reliability of Time Sharing of Driving Modes

For ensuring that time sharing of driving mode from probe data is reliable, actual time sharing from observation is the best possible method for examination. Since accelerating, decelerating, and cruising modes are difficult to measure by observation, only stopping and crawling mode occurring near the intersection caused by congestion queue is the most possible way to examine. In this study, percentages of time sharing in stopping and crawling mode from field observation were determined on a selected section of arterial roadway. Then, time sharing of driving modes collected from probe and observation data were compared at the same period in evening peak. This study could detect only one probe vehicle in each traffic cycle time, and was carried out for 9 traffic cycle times.

For comparison, a non-parametric statistic, named Wilcoxon Signed-Rank Test [1], is used for reliability judgment. This method uses only the plus and minus signs of the differences between the expected and the measured median. This test procedure is then improved to test both direction (sign) and magnitude. The comparison between the stopping and crawling percentage from probe data and field observation in each cycle time was considered in this study. Firstly, hypothesis (H_0) is specified as measured median equal to expected median, which is average stopping and crawling percentage from observation. Secondly, in each cycle time, the difference values are calculated by measured median from stopping and crawling percentage of probe vehicle subtracted by expected median. Table 4.3 summarizes different values from stopping and crawling percentages between the field observation and probe data in each traffic cycle time, and also order of absolute different percentage from fewest to highest.

Table 4.3 Time percentage of stopping and crawling modes between field observation and probe data in each traffic cycle time

No. of traffic cycle time (No. of observed vehicles)	Average stopping and crawling % from observation	Average stopping and crawling % from probe cars	Difference Percentage	Order
Cycle 1 (4)	18.5	20.0	-5.9	5
Cycle 2 (7)	17.8	19.1	2.6	2
Cycle 3 (6)	16.5	28.6	10.8	8
Cycle 4 (4)	20.7	21.1	4.8	4
Cycle 5 (3)	16.3	16.0	-4.7	3
Cycle 6 (3)	39.7	27.1	6.8	6
Cycle 7 (6)	11.9	10.3	-1.6	1
Cycle 8 (5)	20.3	33.3	14.8	9
Cycle 9 (3)	25.9	30.8	-8.9	7
		Average % difference	6.67	

Then, each difference value is ordered from the lowest to the highest by using absolute value, separated into the group of positive and negative values, and ordered values in each group were summarized. Lastly, between positive and negative group, the minimum summary is compared with the critical value of Wilcoxon Signed-Rank Test that equals to 5 in this study. The result found that the summary negative group ordered value (1+3+5+7 = 16) is selected, and this value is greater than the critical value at 95% interval (= 5). That means the summary value is not significantly different (Accept H_0). In addition, average different percentage is 6.77% showing that the different is not much. Therefore, time sharing of driving mode from probe data can be proved that it is reliable when compared to observed data.

4.6 Concluding Remarks

This Chapter shows the determination of time sharing of driving modes based on probe data. The results of them in all conditions indicate that decelerating mode spends the greatest time percentage in most cases (25-35%), while cruising mode is the second (20-30%), and the third is accelerating. Although time percentages of crawling mode are less than first three driving modes, crawling mode can indicate traffic congestion that is readily seen by increased time percentages of crawling mode (5-25%). If only stopping mode is considered, traffic congestion impact would not be clearly seen. Stopping and crawling percentages in the inner areas are greater than in the outer areas in all cases, and high percentages of them are readily seen only on minor roads in the inner areas. In addition, time sharing of driving mode from probe data can be proved that it is reliable when compared to observe data obtained from video detection. Thus, time sharing of driving modes including 4 basic driving modes and additional driving mode (crawling) based on probe data can be used for estimation of fuel consumption.

REFERENCES

1. Traffic Montgomery, D.C., Runger, G.C. (2002). *Applied Statistics and Probability for Engineers*, Third Edition, JohnWiley & Sons, Inc., New York.

CHAPTER 5

MEASUREMENT OF FUEL CONSUMPTION BY FIELD TEST

This chapter explains descriptive fuel consumption data analysis of conventional gasoline car and hybrid car obtained by field test in various traffic conditions. In addition, difference of fuel consumption between with and without considering crawling is identified.

5.1 Field Test

Fuel consumption was measured by field test in order to represent fuel consumption of generic private cars in Bangkok. In this study, two cars, including one gasoline-only conventional car and one hybrid car, were used for the test. Two test cars and their properties can be shown in Table 5.1 and Figure 5.1.

Table 5.1 Properties of two cars for field test

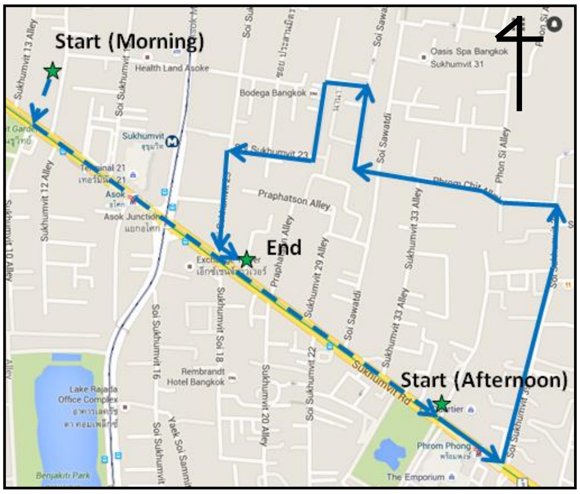
Properties	**Conventional Gasoline Car**	**Hybrid Car**
Type of Car	TOYOTA CAMRY 2.5G A/T	TOYOTA CAMRY 2.5 HV Navigator
Manufacture Year	2012	2012
Engine Size	2,494 cc	2,494 cc
Weight	1,475 kg	1,600 kg
Battery Capacity	-	6.5 A-hr (3 hrs)

Source: (TOYOTA Motor Thailand Company, 2015) [1]

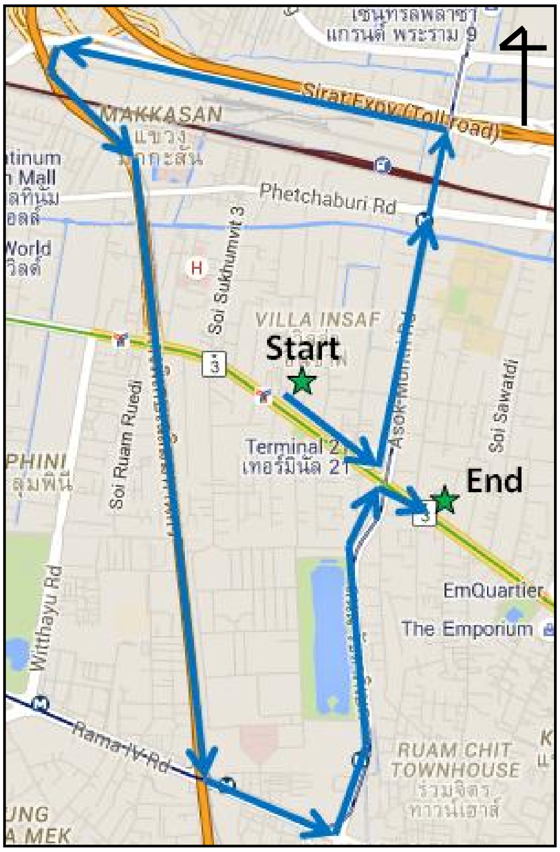
Conventional gasoline Car   Hybrid Car

Figure 5.1 Two cars for field test

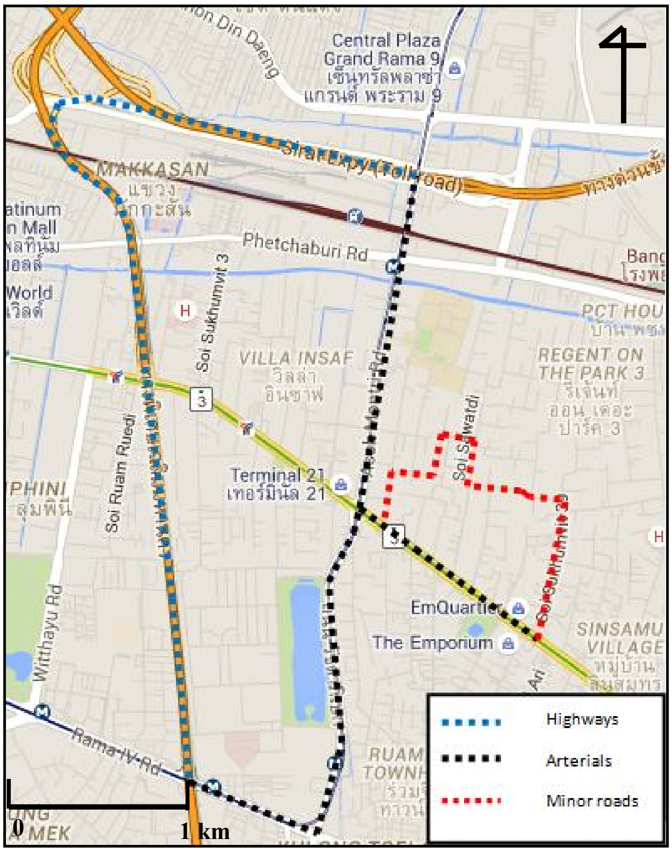
Fuel consumption data were collected on selected roadways during June 13-14 (weekdays) and June 11-12 (weekends), 2016. According to period of data collection, in the morning and afternoon were selected both on weekdays and weekends. On weekdays, 07:00-09:00 in the morning (peak hours) and 12:00-14:00 in the afternoon (off peak) were chosen; whereas on weekends, 09:00-11:00 in the morning and 13:00-15:00 in the afternoon (daytime) were chosen. Selected roadways covered all three road categories and was divided into two routes (A and B), as shown in Figure 5.2. Route A focused on minor roads; meanwhile, Route B focused on highways and arterials. The field test spent more than one round of each route. During the test, conventional and hybrid cars were operated in the real test together in the same traffic condition. One vehicle led the other so that the two vehicles were in the similar driving condition. The other run on the same route would switch leading vehicle between conventional and hybrid cars.



Route A



Route B



The overview of selected roadways

Figure 5.2 Two routes for field test

5.2 Analysis of Data Measured by Field Test

Before fuel consumption by field test in each condition is summarized, descriptive data analysis from survey is explained for understanding its characteristic of conventional and hybrid cars and for ensuring that probe data can be used for estimation of fuel consumption.

5.2.1 Driving comparison between conventional and hybrid cars

The first step for proving the confidence of fuel consumption by field test between conventional gasoline car and hybrid car are not much different. Speed and acceleration ranges are two basic traffic data to prove the vicinity between two cars. As examples on weekdays in Table 5.2, the comparison shows results of speed and acceleration in peak hours and off peak.

Table 5.2 Comparison of speed and acceleration between conventional car (CON) and hybrid car (HV) on weekdays

Period	Road category	Average speed (km/h)		Maximum speed (km/h)		Acceleration ranges (km/h/sec)	
		CON	HV	CON	HV	CON	HV
Peak hours	Highways	21.5	22.1	78	77	-10 to 8	-9 to 8
	Arterials	8.2	8.0	44	41	-8 to 9	-7 to 10
	Minor roads	5.3	5.2	36	35	-7 to 7	-8 to 5
Off peak	Highways	55.0	54.8	81	81	-6 to 9	-9 to 7
	Arterials	26.6	29.6	44	45	-6 to 8	-6 to 7
	Minor roads	9.7	9.5	36	38	-6 to 7	-5 to 6

From Table 5.2, average speed, maximum speed, and acceleration ranges between conventional and hybrid cars are not much different; although, 4 of 6 cases in acceleration ranges of conventional car are wider than those of hybrid car. It can be concluded that driving behavior of conventional car driver were slightly aggressive than hybrid car driver and the aggressiveness of drivers did not have affect to the experiment results.

The next step of comparison is on speed profiles between conventional and hybrid cars, as shown in Figure 5.3.

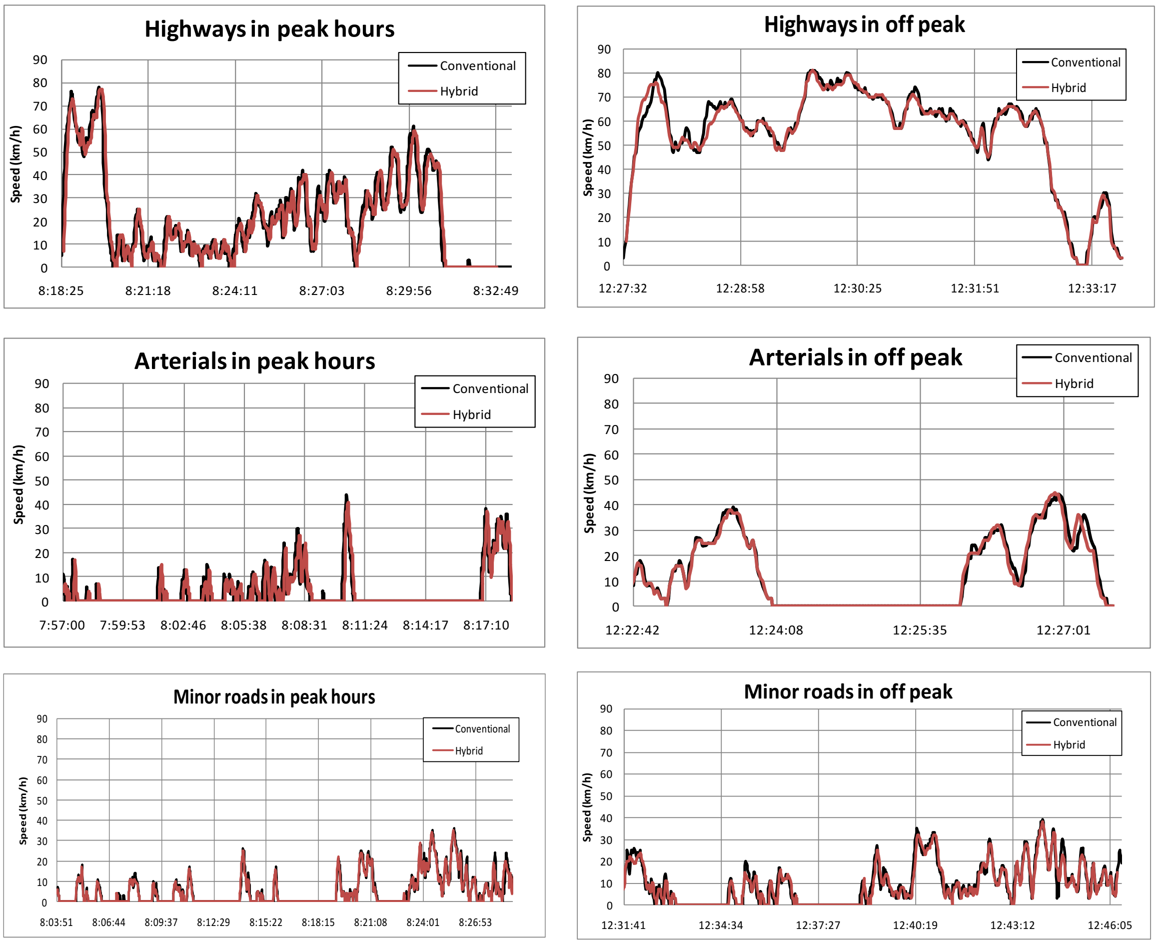


Figure 5.3 Comparison of speed profiles between conventional and hybrid cars

From Figure 5.3, speed profiles between conventional and hybrid cars are very similar. That means data from the two cars represent similar driving conditions and can be used for estimation of fuel consumption reduction.

Figure 5.4 and 5.5 show measured fuel consumption in the unit of kilometer per liter (km/L) and revolution of engine in the unit of revolution per minute of engine (rpm) both conventional and hybrid cars on weekdays.

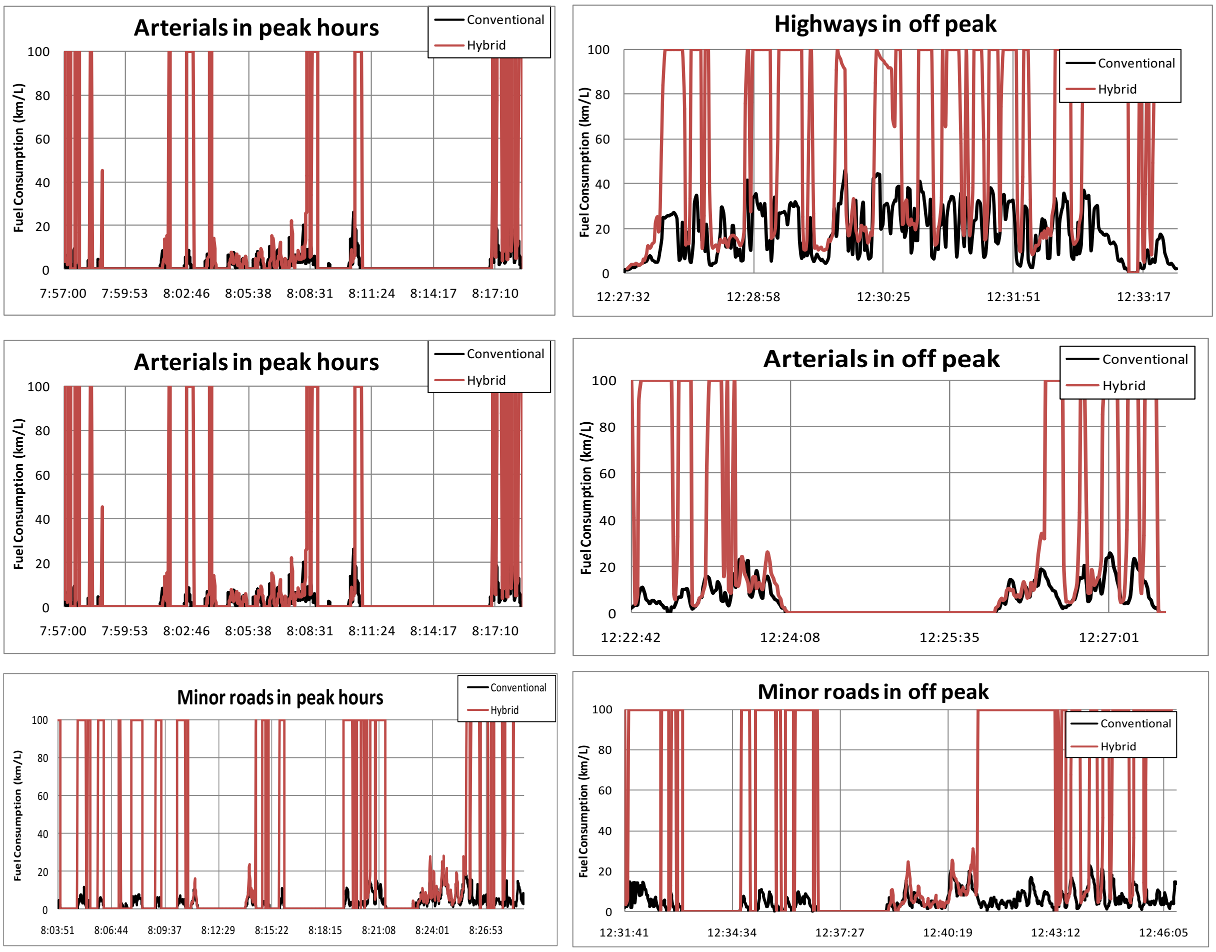


Figure 5.4 Comparison of instantaneous fuel consumption between conventional and hybrid cars

From Figure 5.4, measured fuel consumption in hybrid car is lower than that of conventional car significantly at many particular moments (showing >100 km/L in the graph). This implies that using hybrid cars can save more fuel than conventional car at those particular instants. Considering fuel consumption of conventional cars, fuel consumption in off peak period is lower than the value in peak-hour period, particularly on highways and arterials. Among road categories, minor roads consume more fuel than others. Moreover, when speed = 0, fuel consumption = 0.0 for both conventional gasoline car and hybrid car.

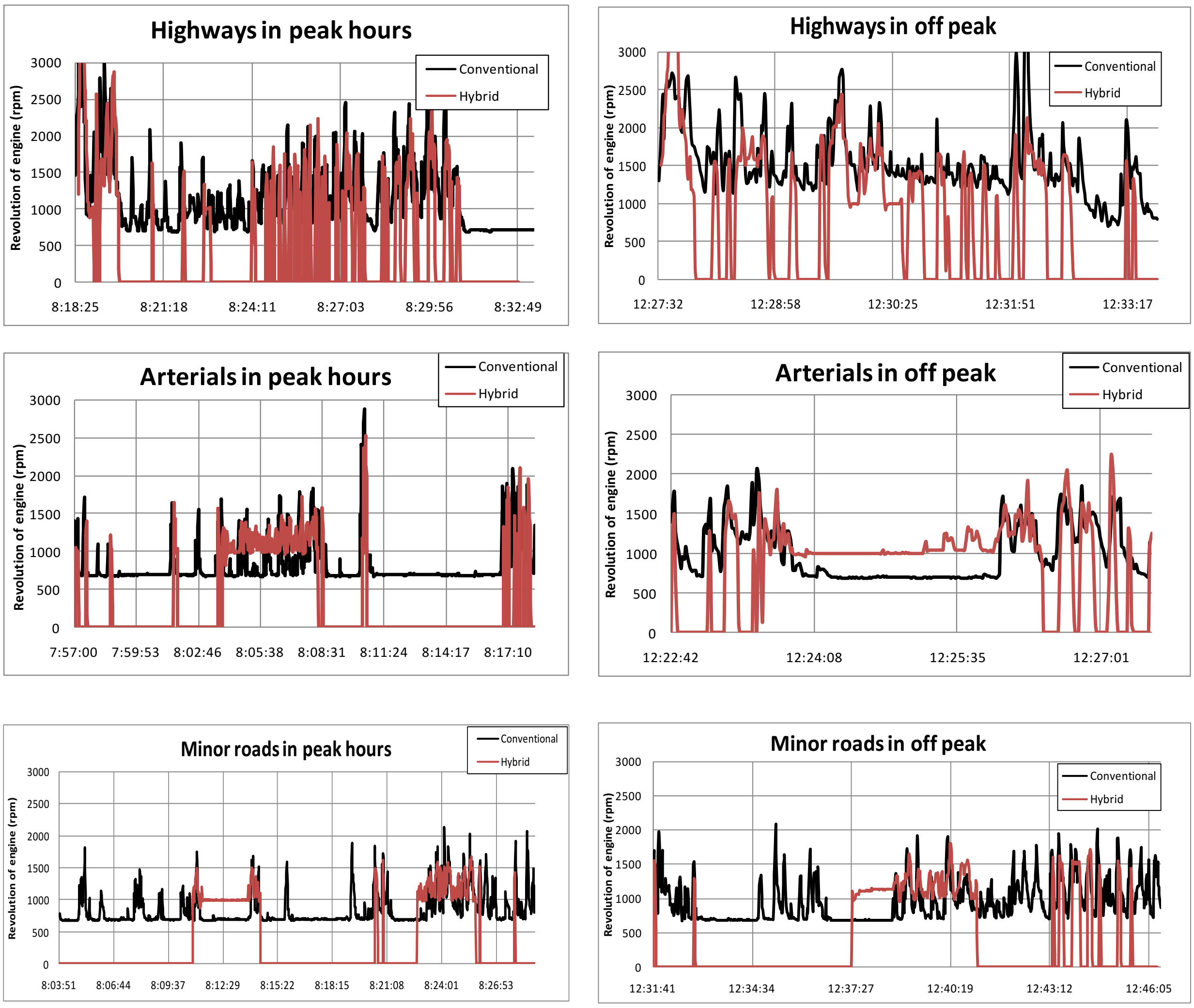


Figure 5.5 Comparison of revolution of engine between conventional and hybrid cars

From Figure 5.5, hybrid car operates at revolution of engine = 0 in many time periods, particularly in low speed on minor roads and stopping on arterials. That means that hybrid cars can save fuel consumption during low speed and stopping from using their battery powered.

By comparing instantaneous fuel consumption and revolution of engine, conventional cars consume more fuel than hybrid car because hybrid cars operate with batteries (without consuming gasoline) in many time instants, especially during low speed and stopping.

5.2.2 Driving comparison between field test data and probe data

After the comparison of traffic data, measured fuel consumption, and revolution of engine between conventional gasoline car and hybrid car is proven in vicinity, the next comparison is to verify if conventional gasoline car and hybrid car by field test can be used for estimation of fuel consumption. Probe data from taxis, which were detected in the same period and roadways as field test, are used for comparison with test vehicles by fuel test. Thus, in this comparison, data from two sources should be not much different.

Since speed data are only available in both field test data and probe data, the average speeds from both dataset are used for comparison and for proving that data from field test can be comparable to probe data. The comparison of average speeds by the two data sources can be shown in Table 5.3.

Table 5.3 Comparison of average speed between probe data and field test data

Days of Week	Road Category	Period	Avg. speed by probe data (km/h)	Avg. speed by field test (km/h)			
				Conventional		Hybrid	
				Avg.	Diff	Avg.	Diff
Weekdays	Highways	Peak hours	30	25.3	-4.7	25.0	-5.0
		Off peak	54	55.0	1.0	54.8	0.8
	Arterials	Peak hours	12	8.2	-3.8	8.0	-4.0
		Off peak	26	26.6	0.6	29.6	3.6
	Minor roads	Morning	7	5.3	-1.7	5.2	-1.8
		Off-peak	14	9.7	-4.3	9.5	-4.5
Weekends	Highways	Morning	56	58.0	2.0	58.6	2.6
		Daytime	65	63.6	-1.4	63.7	-1.3
	Arterials	Morning	23	16.2	-6.8	16.0	-7.0
		Daytime	20	16.7	-3.3	15.9	-4.1
	Minor roads	Morning	23	23.5	0.5	22.6	-0.4
		Daytime	21	18.9	-2.1	17.9	-3.1

Note: Diff + or- means that speed from field test is more or less than that of probe data, respectively

In Table 5.3, although the average speeds of conventional and hybrid cars are not different, there are some problems only on weekends on arterials in the morning that the difference in speeds is more than 5 km/h. The possible reason is when test vehicles passed through arterial sections which are in a critical traffic congestion in Bangkok, they encountered a long waiting time at the traffic signal. For the overall results, however, it can be proven that data from field test can be referred to probe data and thus estimation of fuel consumption based on probe data can be determined.

Apart from average speed, time sharing of driving modes from 2 test cars by field test could be calculated. As examples in Table 5.4 – 5.8, conventional car (CON) and hybrid car (HV) on weekdays could be compared with time sharing from probe data in each percentages of driving mode in the term of different percentages (Diff).

Table 5.4 Comparison of stopping mode between probe data and field test

Road Category	Period	Stopping/Idling (%)					
		Probe	Field Test				
			CON	Diff	HV	Diff
Highways	Peak hours	1.2	4.8	3.6	5.2	4.0
	Off peak	0.7	0.7	0.0	0.8	0.1
Arterials	Peak hours	4.7	9.5	4.8	9.7	5.0
	Off peak	3.8	5.3	1.5	5.4	1.6
Minor roads	Peak hours	5.9	10.1	4.2	9.9	4.0
	Off peak	3.2	2.5	0.7	2.4	0.8

Table 5.5 Comparison of crawling mode between probe data and field test

Road Category	Period	Crawling (%)				
		Probe	Field Test			
			CON	Diff	HV	Diff
Highways	Peak hours	14.8	10.6	4.2	11.3	3.5
	Off peak	8.4	3.3	5.1	2.8	5.6
Arterials	Peak hours	20.0	18.0	2.0	17.5	2.5
	Off peak	17.3	13.1	4.2	13.4	3.9
Minor roads	Peak hours	20.7	23.2	2.5	24.0	3.3
	Off peak	18.0	21.7	3.7	21.6	3.6

Table 5.6 Comparison of accelerating mode between probe data and field test

Road Category	Period	Accelerating (%)				
		Probe	Field Test			
			CON	Diff	HV	Diff
Highways	Peak hours	23.6	26.9	3.3	25.6	2.0
	Off peak	25.8	24.5	1.3	25.7	0.1
Arterials	Peak hours	22.2	22.6	0.4	23.1	0.9
	Off peak	23.7	19.5	4.2	20.0	3.7
Minor roads	Peak hours	20.8	18.6	2.2	19.1	1.7
	Off peak	22.6	22.0	0.6	21.0	1.6

Table 5.7 Comparison of cruising mode between probe data and field test

Road Category	Period	Cruising (%)					
		Probe	Field Test				
			CON	Diff	HV	Diff
Highways	Peak hours	28.0	25.6	2.4	24.4	3.6
	Off peak	31.8	31.7	0.1	31.5	0.3
Arterials	Peak hours	20.6	19.6	1.0	20.2	0.4
	Off peak	22.0	26.2	4.2	27.2	5.2
Minor roads	Peak hours	23.7	23.0	0.7	22.2	1.5
	Off peak	26.2	26.4	0.2	27.0	0.8

Table 5.8 Comparison of decelerating mode between probe data and field test

Road Category	Period	Decelerating (%)				
		Probe	Field Test			
			CON	Diff	HV	Diff
Highways	Peak hours	32.5	32.2	0.3	33.4	0.9
	Off peak	33.5	39.9	6.4	39.1	5.6
Arterials	Peak hours	32.4	30.3	2.1	29.5	2.9
	Off peak	33.1	35.9	2.8	33.9	0.8
Minor roads	Peak hours	28.9	25.1	3.8	24.8	4.1
	Off peak	30.0	27.5	2.5	28.1	1.9

From Table 5.4 to Table 5.8, in most conditions, the stopping percentages by field test data are higher than that from probe data. Considering overall percentages of driving mode, the differences (Diff) are in between 0.0% to 6.4% and the average aggregated difference is 2.5%. Consequently, it can be concluded that percentages of each driving mode are not much different.

In addition, speed distributions of test vehicles by field test and probe data in each road category can be compared, as shown in Figure 5.6 - 5.8.

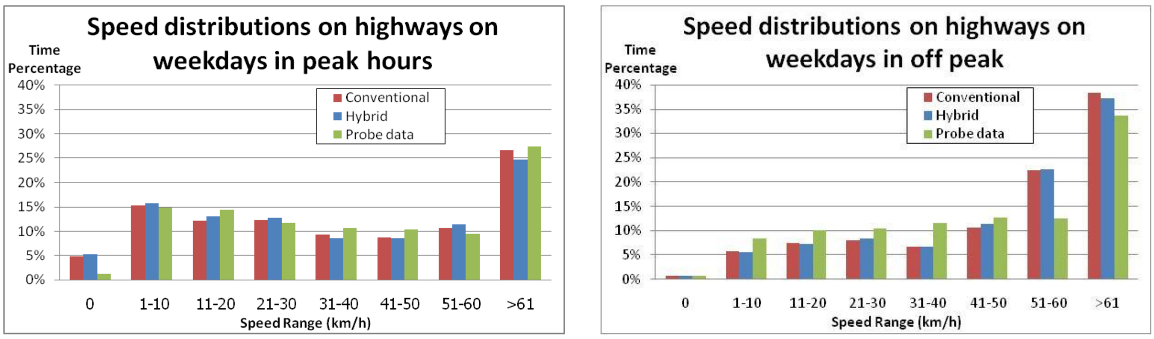


Figure 5.6 Speed distributions between probe data and field test on highways

From the results of speed distributions of highways, it can be concluded that there is the difference in stopping range in peak hours due to forced stopping on expressway. A notable difference can be seen at 51-60 km/h speed ranges in off peaks.

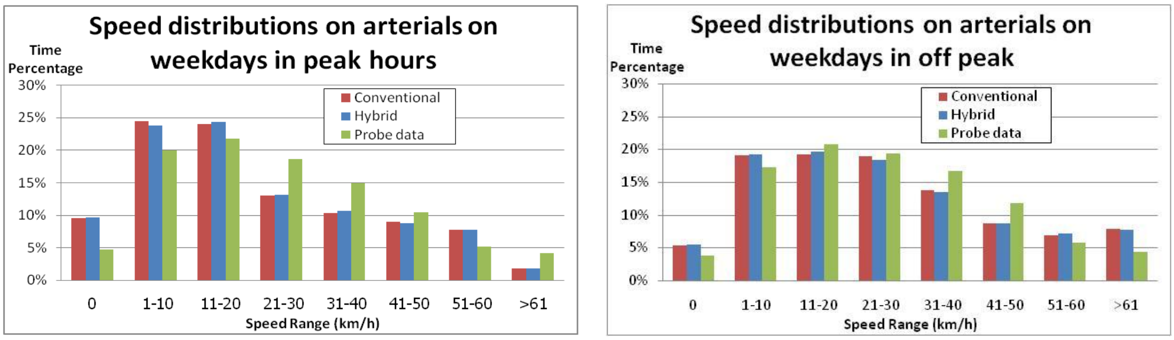


Figure 5.7 Speed distributions between probe data and field test on arterials

The results of speed distributions on arterials shows that test vehicles operated lower speed ranges than the probe in peak hours, but speed distribution of probe data spreads wider than that of test vehicles. Whereas in off peak, the distributions from the two dataset are not much different.

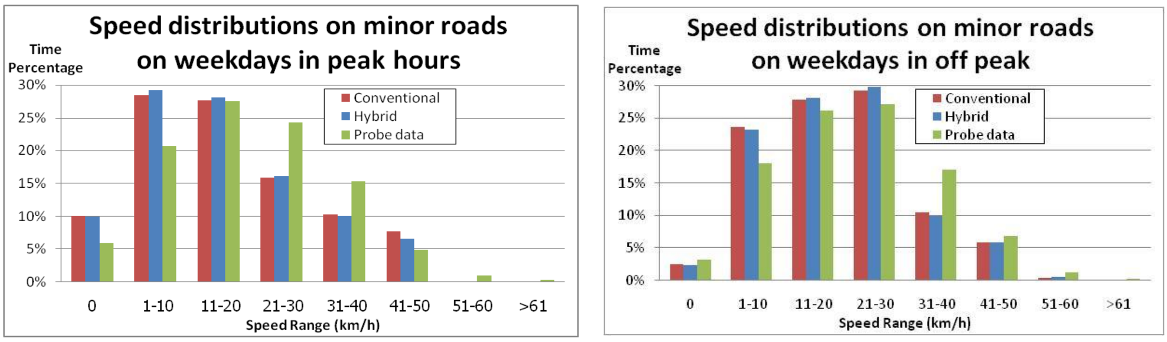


Figure 5.8 Speed distributions between probe data and field test on minor roads

From the results of speed distributions of minor roads both in peak hours and off peak, the difference could be observed in the 1-10 km/h range that percentages of test vehicles are more than that of probe data, whereas in the 21-30 km/h range, the speeds from test vehicles are less than that of probe data.

From the results of speed distributions of all road categories and periods, the main cause of the difference between test vehicles and probe data is that test vehicles ran in the selected roadways that are more critical in term of traffic congestion in Bangkok. However, the trends of distributions between test vehicles and probe data are similar, and the different percentages are not significant. Therefore, data from field test can be referred to probe data and can be used for estimation of fuel consumption.

By comparison between probe data and field test data, it can conclude that fuel consumption by field test in both conventional car and hybrid car can be used for estimation of fuel consumption and its reduction.

5.3 Results of Measurement of Fuel Consumption by Categories

After proving that fuel consumption by field test can well represent traffic data and driving behavior, they can be used for estimation of fuel consumption. The results of fuel consumption by field test, as the examples on weekdays, both conventional gasoline car and hybrid car can be represented in the summary tables in the next pages. By the summary tables, average fuel consumption (cc/sec) can be compared on each driving mode between conventional and hybrid cars, as shown in Figure 5.9.

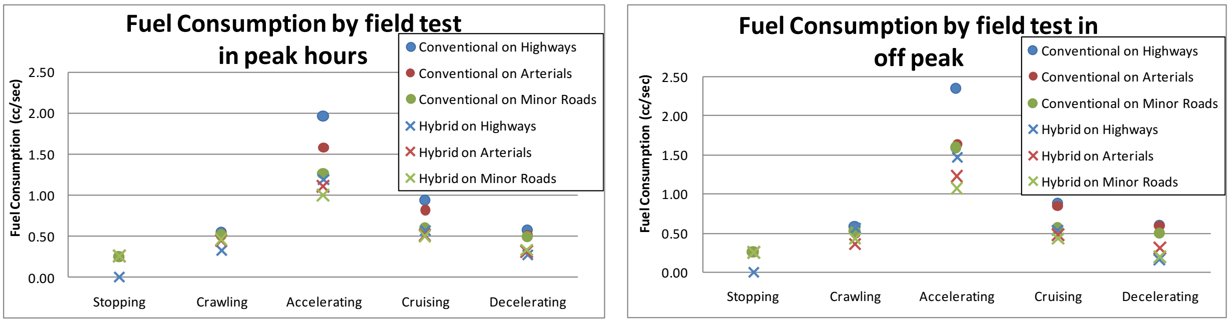


Figure 5.9 Fuel consumption between conventional and hybrid cars in each condition

In Figure 5.9, fuel consumption in conventional gasoline car is more than hybrid car and accelerating mode consumes most fuel consumption. The most fuel consumption is on highways, and the second is arterials. In addition, from summary tables (Table 5.9), gasoline engine off-operated (OFF) cannot be detected in conventional gasoline car (There are a few time frequency on accelerating mode by hybrid car) and no fuel consumption on stopping mode in hybrid car on highways both peak-hours and off-peak.

Since fuel consumption by field test data in each condition was not collected in the evening period both on weekdays and weekend, thus data collected on weekdays in morning peak were also used for in the evening peak. The same applied for the case of weekends in the evening where the data on weekends in daytime were used instead.

From field test, fuel consumption both hybrid and conventional cars can be calculated for different days of week (weekdays and weekends), and periods (peak hours and off peak) in each driving mode, speed range, and indicated time frequency (sec) in case of gasoline engine operated (ON) or off-operated (OFF).

Table 5.9 Fuel consumption (cc/sec) and time frequency (sec) in each condition

Weekdays_Highways_Off-Peak_Conventional

Driving Modes	Stopping/Idling				Crawling				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	7	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1-10	-	-	-	-	0.58	32	0	1	1.08	7	0	1	0.97	5	0	0	0.33	13	0	0	
11-20	-	-	-	-					2.24	3	0	0	0.54	8	0	0	0.43	13	0	0	
21-30	-	-	-	-	-	-	-	-	2.67	5	0	0	0.62	9	0	0	0.43	16	0	0	
31-40	-	-	-	-	-	-	-	-	3.37	3	0	0	0.53	6	0	0	0.44	8	0	0	
41-50	-	-	-	-	-	-	-	-	3.06	8	0	0	1.12	18	0	0	0.91	30	0	0	
51-60	-	-	-	-	-	-	-	-	2.22	51	0	0	1.09	79	0	0	0.74	96	0	0	
>61	-	-	-	-	-	-	-	-	1.83	168	0	0	1.26	194	0	0	0.84	225	0	0	
Total (sec)	-	7	-	0	-	32	-	1	-	245	-	1	-	319	-	0	-	401	-	0	1006 Sec
Average (CC/sec)	0.25	-	-	-	0.58	-	-	-	2.35	-	-	-	0.88	-	-	-	0.59	-	-	-	17 Min

Weekdays_Arterials_Off-Peak_Conventional

Driving Modes	Stopping/Idling				Crawling				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	120	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1-10	-	-	-	-	0.50	296	0	0	1.73	39	0	4	0.46	90	0	0	0.36	93	0	0	
11-20	-	-	-	-					1.28	92	0	0	0.69	84	0	0	0.43	145	0	0	
21-30	-	-	-	-	-	-	-	-	1.55	101	0	0	0.69	95	0	0	0.51	164	0	0	
31-40	-	-	-	-	-	-	-	-	1.45	87	0	0	0.90	97	0	0	0.54	126	0	0	
41-50	-	-	-	-	-	-	-	-	1.65	39	0	0	0.90	71	0	0	0.60	86	0	0	
51-60	-	-	-	-	-	-	-	-	1.98	18	0	0	1.07	65	0	0	0.84	74	0	0	
>61	-	-	-	-	-	-	-	-	1.92	59	0	0	1.25	88	0	0	0.89	122	0	0	
Total (sec)	-	120	-	0	-	296	-	0	-	435	-	4	-	590	-	0	-	810	-	0	2255 Sec
Average (CC/sec)	0.25	-	-	-	0.5	-	-	-	1.65	-	-	-	0.85	-	-	-	0.60	-	-	-	38 Min

Table 5.9 Fuel consumption (cc/sec) and time frequency (sec) in each condition (Con.)

Weekdays_MinorRoads_Off-Peak_Conventional

Driving Modes	Stopping/Idling				Crawling				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	53	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
1-10	-	-	-	-	0.53	467	0	0	1.98	60	0	4	0.48	116	0	0	0.39	79	0	0		
11-20	-	-	-	-					1.31	156	0	0	0.69	163	0	0	0.47	217	0	0		
21-30	-	-	-	-	-	-	-	-	1.17	165	0	0	0.66	126	0	0	0.49	191	0	0		
31-40	-	-	-	-	-	-	-	-	1.27	66	0	0	0.76	89	0	0	0.50	70	0	0		
41-50	-	-	-	-	-	-	-	-	2.35	22	0	0	0.54	71	0	0	0.54	33	0	0		
51-60	-	-	-	-	-	-	-	-	1.48	2	0	0	0.22	4	0	0	0.56	3	0	0		
>61	-	-	-	-	-	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0		
Total (sec)	-	53	-	0	-	467	-	0	-	471	-	4	-	569	-	0	-	593	-	0	2157	Sec
Average (CC/sec)	0.25	-	-	-	0.53	-	-	-	1.59	-	-	-	0.56	-	-	-	0.49	-	-	-	36	Min

Weekdays_Highways_Off-Peak_Hybrid

Driving Modes	Stopping/Idling				Crawling				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	0.00	0	0	8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
1-10	-	-	-	-	0.57	2	0	26	0.00	8	0	2	1.69	2	0	5	0.00	0	0	11		
11-20	-	-	-	-					1.45	6	0	0	0.00	0	0	6	0.14	2	0	9		
21-30	-	-	-	-	-	-	-	-	1.51	7	0	2	0.00	0	0	9	0.00	0	0	16		
31-40	-	-	-	-	-	-	-	-	2.66	4	0	0	0.00	0	0	5	0.00	0	0	9		
41-50	-	-	-	-	-	-	-	-	1.74	8	0	2	0.50	6	0	13	0.18	2	0	32		
51-60	-	-	-	-	-	-	-	-	1.54	48	0	5	0.73	35	0	42	0.35	16	0	80		
>61	-	-	-	-	-	-	-	-	1.47	154	0	11	0.90	143	0	49	0.39	93	0	121		
Total (sec)	-	0	-	8	-	2	-	26	-	235	-	22	-	186	-	129	-	113	-	278	999	Sec
Average (CC/sec)	0.00	-	-	-	0.57	-	-	-	1.48	-	-	-	0.55	-	-	-	0.15	-	-	-	17	Min

Table 5.9 Fuel consumption (cc/sec) and time frequency (sec) in each condition (Con.)

Weekdays_Arterials_Off-Peak_Hybrid

Driving Modes	Stopping/Idling				Crawling				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	26	0	96	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1-10	-	-	-	-	0.36	97	0	205	1.66	8	0	31	0.36	31	0	65	0.22	28	0	57	
11-20	-	-	-	-					0.87	26	0	72	0.39	9	0	79	0.19	74	0	70	
21-30	-	-	-	-	-	-	-	-	1.15	45	0	49	0.53	10	0	88	0.29	98	0	57	
31-40	-	-	-	-	-	-	-	-	1.14	33	0	56	0.48	27	0	73	0.41	75	0	39	
41-50	-	-	-	-	-	-	-	-	1.30	20	0	20	0.40	22	0	48	0.33	63	0	23	
51-60	-	-	-	-	-	-	-	-	1.31	12	0	16	0.40	28	0	42	0.46	41	0	23	
>61	-	-	-	-	-	-	-	-	1.23	51	0	11	0.82	53	0	37	0.28	94	0	20	
Total (sec)	-	26	-	96	-	97	-	205	-	195	-	255	-	180	-	432	-	473	-	289	2248 Sec
Average (CC/sec)	0.25	-	-	-	0.36	-	-	-	1.24	-	-	-	0.48	-	-	-	0.31	-	-	-	37 Min

Weekdays_MinorRoads_Off-Peak_Hybrid

Driving Modes	Stopping/Idling				Crawling				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	24	0	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1-10	-	-	-	-	0.43	88	0	374	1.25	20	0	37	0.44	52	0	65	0.20	26	0	50	
11-20	-	-	-	-					0.90	54	0	96	0.44	74	0	95	0.24	43	0	178	
21-30	-	-	-	-	-	-	-	-	1.08	56	0	103	0.50	97	0	41	0.36	65	0	125	
31-40	-	-	-	-	-	-	-	-	0.99	36	0	25	0.62	61	0	21	0.23	33	0	37	
41-50	-	-	-	-	-	-	-	-	1.29	17	0	2	0.37	68	0	0	0.14	13	0	26	
51-60	-	-	-	-	-	-	-	-	0.95	3	0	0	0.22	3	0	0	0.00	4	0	0	
>61	-	-	-	-	-	-	-	-	0.00	0	0	0	0.00	0	0	0	0.00	0	0	0	
Total (sec)	-	24	-	27	-	88	-	374	-	186	-	263	-	355	-	222	-	184	-	416	2139 Sec
Average (CC/sec)	0.25	-	-	-	0.43	-	-	-	1.07	-	-	-	0.43	-	-	-	0.20	-	-	-	36 Min

Table 5.9 Fuel consumption (cc/sec) and time frequency (sec) in each condition (Con.)

Weekdays_Highways_Peak_Conventional

Driving Modes	Stopping/Idling				Crawling				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	55	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1-10	-	-	-	-	0.55	122	0	0	2.84	12	0	0	0.68	23	0	0	0.33	20	0	0	
11-20	-	-	-	-					1.17	42	0	0	0.59	40	0	0	0.43	59	0	0	
21-30	-	-	-	-	-	-	-	-	1.42	49	0	0	0.63	38	0	0	0.51	55	0	0	
31-40	-	-	-	-	-	-	-	-	1.94	38	0	0	1.35	29	0	0	0.43	40	0	0	
41-50	-	-	-	-	-	-	-	-	2.23	32	0	0	0.92	29	0	0	0.70	39	0	0	
51-60	-	-	-	-	-	-	-	-	2.34	39	0	0	1.13	37	0	0	0.82	47	0	0	
>61	-	-	-	-	-	-	-	-	1.82	98	0	0	1.25	99	0	0	0.79	111	0	0	
Total (sec)	-	55	-	0	-	122	-	0	-	310	-	0	-	295	-	0	-	371	-	0	1153 Sec
Average (CC/sec)	0.25	-	-	-	0.55	-	-	-	1.97	-	-	-	0.94	-	-	-	0.57	-	-	-	19 Min

Weekdays_Arterials_Peak_Conventional

Driving Modes	Stopping/Idling				Crawling				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	3127 Sec
Avg. Fuel consumption (CC/sec)	0.25	-	-	-	0.53	-	-	-	1.58	-	-	-	0.82	-	-	-	0.52	-	-	-	52 Min

Table 5.9 Fuel consumption (cc/sec) and time frequency (sec) in each condition (Con.)

Weekdays_MinorRoads_Peak_Conventional

Driving Modes	Stopping/Idling				Crawling				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	248	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1-10	-	-	-	-	0.51	572	0	0	1.89	101	0	2	0.42	144	0	0	0.38	126	0	0	
11-20	-	-	-	-					1.24	138	0	0	0.66	119	0	0	0.46	178	0	0	
21-30	-	-	-	-	-	-	-	-	1.18	114	0	0	0.59	127	0	0	0.49	149	0	0	
31-40	-	-	-	-	-	-	-	-	1.04	64	0	0	0.68	96	0	0	0.53	94	0	0	
41-50	-	-	-	-	-	-	-	-	0.93	40	0	0	0.61	80	0	0	0.57	70	0	0	
51-60	-	-	-	-	-	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	
>61	-	-	-	-	-	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	
Total (sec)	-	248	-	0	-	572	-	0	-	457	-	2	-	566	-	0	-	617	-	0	2462 Sec
Average (CC/sec)	0.25	-	-	-	0.51	-	-	-	1.26	-	-	-	0.59	-	-	-	0.49	-	-	-	41 Min

Weekdays_Highways_Peak_Hybrid

Driving Modes	Stopping/Idling				Crawling				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	0.00	0	0	62	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1-10	-	-	-	-	0.32	10	0	124	0.72	3	0	10	0.44	5	0	14	0.00	0	0	20	
11-20	-	-	-	-					0.84	22	0	25	0.37	5	0	34	0.36	10	0	59	
21-30	-	-	-	-	-	-	-	-	0.89	34	0	10	0.42	13	0	29	0.17	12	0	53	
31-40	-	-	-	-	-	-	-	-	1.23	33	0	2	0.37	5	0	14	0.39	13	0	34	
41-50	-	-	-	-	-	-	-	-	1.57	33	0	1	0.61	12	0	11	0.19	8	0	36	
51-60	-	-	-	-	-	-	-	-	1.62	36	0	2	0.87	28	0	22	0.30	13	0	34	
>61	-	-	-	-	-	-	-	-	1.46	91	0	1	0.93	74	0	23	0.49	50	0	53	
Total (sec)	-	0	-	62	-	10	-	124	-	252	-	51	-	142	-	147	-	106	-	289	1183 Sec
Average (CC/sec)	0	-	-	-	0.32	-	-	-	1.19	-	-	-	0.57	-	-	-	0.27	-	-	-	20 Min

Table 5.9 Fuel consumption (cc/sec) and time frequency (sec) in each condition (Con.)

Weekdays_Arterials_Peak_Hybrid

Driving Modes	Stopping/Idling				Crawling				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	3150 Sec
Avg. Fuel consumption (CC/sec)	0.25	-	-	-	0.44	-	-	-	1.11	-	-	-	0.51	-	-	-	0.29	-	-	-	53 Min

Weekdays_MinorRoads_Peak_Hybrid

Driving Modes	Stopping/Idling				Crawling				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	26	0	217	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1-10	-	-	-	-	0.46	55	0	533	1.28	45	0	60	0.37	68	0	72	0.24	61	0	66	
11-20	-	-	-	-					0.93	65	0	72	0.48	58	0	68	0.31	78	0	103	
21-30	-	-	-	-	-	-	-	-	1.05	74	0	39	0.54	66	0	63	0.33	75	0	76	
31-40	-	-	-	-	-	-	-	-	0.93	62	0	0	0.59	93	0	0	0.36	92	0	0	
41-50	-	-	-	-	-	-	-	-	0.83	50	0	0	0.50	56	0	0	0.39	55	0	0	
51-60	-	-	-	-	-	-	-	-	0.00	0	0	0	0.00	0	0	0	0.00	0	0	0	
>61	-	-	-	-	-	-	-	-	0.00	0	0	0	0.00	0	0	0	0.00	0	0	0	
Total (sec)	-	26	-	217	-	55	-	533	-	296	-	171	-	341	-	203	-	361	-	245	2448 Sec
Average (CC/sec)	0.25	-	-	-	0.46	-	-	-	0.72	-	-	-	0.35	-	-	-	0.233	-	-	-	41 Min

From the results of fuel consumption by field test in Table 5.9, all cases of both conventional and hybrid cars can be calculated for different days of week (weekdays and weekends), and periods (peak hours and off peak) in each driving mode, speed range, road category and indicated time frequency (sec) in case of gasoline engine operated (ON) or off-operated (OFF). In addition, fuel consumption on crawling mode can be detected in speed ranges of 1-10, and 11-20 km/h. However, by defining crawling mode in this study, time frequency in speed range of 1-10 km/h is more than 11-20 km/h.

5.4 Verification of Fuel Consumption Measured by Field Test

After actual fuel consumption by field test was measured, it is compared with fuel consumption calculated by devices of probe data, which are also installed into test vehicles, for checking verification. Table 5.10 and 5.11 indicate comparison of fuel consumption rate in the unit of cubic centimeter per vehicle per second (cc/veh/sec) together with percentage errors between calculation from actual measurement by field test and probe data in different conditions both on weekdays and weekends.

In this verification, devices of probe data collection were also installed into one conventional gasoline car and hybrid car, which installed devices of actual fuel consumption measurement. Then, two devices for collecting probe data and actual fuel consumption were tested together along selected roadways. Probe data, including positions and speed data, were used to estimate fuel consumption; whereas, fuel consumption by field test can be used for reporting actual fuel consumption directly.

Table 5.10 Fuel consumption rates (cc/veh/sec) between estimation from probe data and actual measurement by field test on weekdays

Road Category	Period	Conventional			Hybrid		
		Actual	Estimation	% Error	Actual	Estimation	% Error
Highways	Peak	0.971	1.019	4.9%	0.408	0.414	1.4%
	Off peak	1.306	1.172	10.2%	0.659	0.550	16.4%
Arterials	Peak	0.704	0.786	11.6%	0.217	0.256	18.1%
	Off peak	0.664	0.709	6.8%	0.233	0.229	1.7%
Minor roads	Peak	0.561	0.640	14.1%	0.235	0.252	7.1%
	Off peak	0.639	0.720	12.6%	0.200	0.213	6.2%

Table 5.11 Fuel consumption rates (cc/veh/sec) between estimation from probe data and actual measurement by field test on weekends

Road Category	Period	Conventional			Hybrid		
		Actual	Probe Data	% Error	Actual	Estimation	% Error
Highways	Morning	1.189	1.179	0.8%	0.594	0.584	1.6%
	Afternoon	1.264	1.096	13.3%	0.724	0.708	2.2%
Arterials	Morning	0.593	0.590	0.6%	0.159	0.156	1.9%
	Afternoon	0.653	0.647	0.9%	0.201	0.196	2.5%
Minor roads	Morning	0.737	0.722	2.1%	0.250	0.238	4.7%
	Afternoon	0.715	0.700	2.2%	0.233	0.220	5.7%

From Table 5.10 and 5.11, percentage errors of estimation both conventional car and hybrid car are not more than 20%. That means fuel consumption by field test can be confirmed for estimation of fuel consumption based on probe data.

Then, Figure 5.10 summarizes comparison of fuel consumption rates of them by separating vehicle type by scatter analysis.

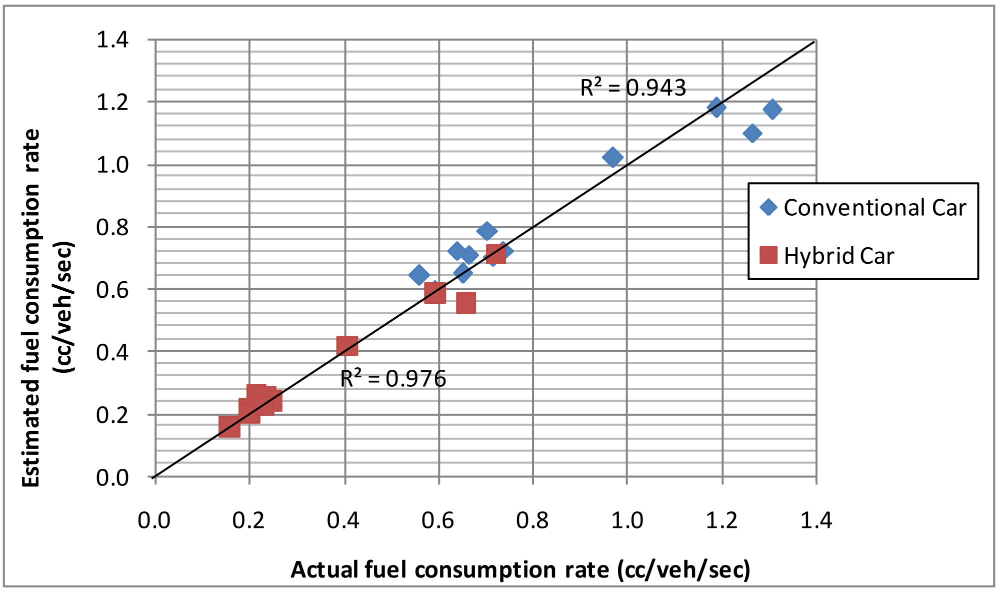


Figure 5.10 Comparison of fuel consumption rates between actual measurement and estimation of probe data

From Figure 5.10, fuel consumption rates in conventional car are higher than hybrid car. Regarding accuracy analysis, the results of hybrid car is more accuracy than conventional car by more coefficient of determination (R^2) value.

5.5 Difference of Estimation of Fuel Consumption between With and Without Considering Crawling Mode

In order to prove crawling that is the originality of this study has sufficient impacts for estimation of fuel consumption, difference of estimation between with and without considering crawling mode should be determined.

First, the author attempted to consider total fuel consumption results between with and without considering crawling mode. It was found that they are not much different, because crawling is only sharing of total fuel consumption from 4 basic driving modes as shown in Figure 5.11.

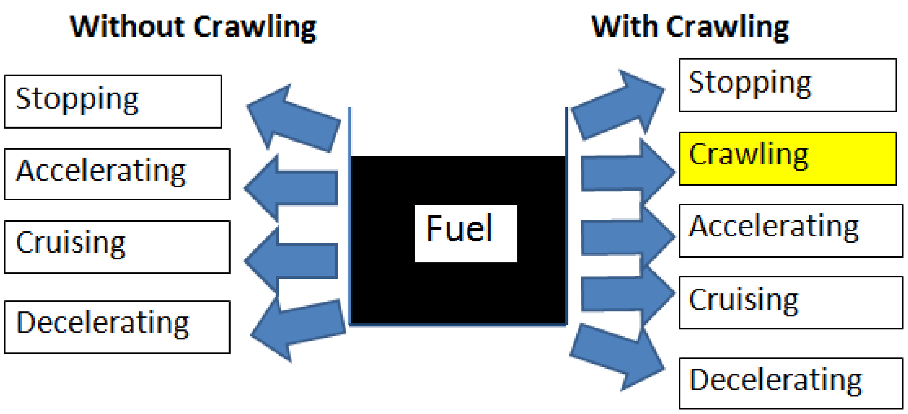


Figure 5.11 Total fuel consumption between with and without considering crawling mode

When total fuel consumption cannot be proved that crawling mode provide the difference of estimation of fuel consumption, another method is necessary to find. If fuel consumption in speed range of 1-10 and 11-20 km/h that crawling occurs, the results of fuel consumption both with and without considering crawling can be shown and compared in order to determine the difference in Table 5.12 for conventional gasoline car and Table 5.13 for hybrid car. These tables are examples of fuel consumption by field test on arterials on weekdays.

Table 5.12 Fuel consumption with and without considering crawling in conventional gasoline car

Without Crawling

Driving Modes	Stopping/Idling				Accelerating				Cruising				Decelerating			
Speed Range (km/h)	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec
0	0.25	298	0	0	-	-	-	-	-	-	-	-	-	-	-	-
1-10	-	-	-	-	1.29	249	0	0	0.46	220	0	0	0.42	263	0	0
11-20	-	-	-	-	1.06	263	0	0	0.61	216	0	0	0.48	305	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

With Crawling

Driving Modes	Stopping/Idling				Crawling				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

From Table 5.12, fuel consumption on accelerating mode with crawling is higher than without crawling because acceleration in low speed is removed from original accelerating mode. Fuel consumption on crawling mode affect to accelerating mode rather than other modes. Fuel consumption in accelerating mode in speed range of 1-10 km/h increases 51% from original accelerating mode, while fuel consumption in speed range of 11-20 km/h increases 17% that is less significant than the first one.

Table 5.13 Fuel consumption with and without considering crawling in hybrid car

Without Crawling

Driving Modes	Stopping/Idling				Accelerating				Cruising				Decelerating			
Speed Range (km/h)	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec
0	0.25	18	0	286	-	-	-	-	-	-	-	-	-	-	-	-
1-10	-	-	-	-	0.78	156	0	127	0.41	119	0	131	0.32	144	0	160
11-20	-	-	-	-	0.73	134	0	98	0.49	85	0	84	0.33	130	0	153
21-30	-	-	-	-	1.05	74	0	39	0.54	66	0	63	0.33	75	0	76
31-40	-	-	-	-	0.93	62	0	0	0.59	93	0	0	0.36	92	0	0

With Crawling

Driving Modes	Stopping/Idling				Crawling				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	98	0	70	0.39	79	0	72	0.21	92	0	88
11-20	-	-	-	-					0.82	133	0	74	0.51	97	0	64	0.30	130	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

In Table 5.13, fuel consumption in accelerating mode with crawling is also higher than without crawling, but fuel consumption in speed range of 1-10 km/h on accelerating mode increases 39% that is less than conventional gasoline car. That means hybrid car can support much electricity during crawling mode. Thus, by measurement of fuel consumption by field test, crawling mode can provide the different results between with and without considering it in conventional gasoline car on accelerating mode.

5.6 Concluding Remarks

This chapter shows the results of fuel consumption collected by one hybrid car and one conventional gasoline car. Two cars were operated together along the same selected roadways in the inner area of BMR for different days of week, periods, and road categories. Fuel consumption can be calculated in the unit of cc per second both conventional gasoline car and hybrid car in each driving mode and speed range. In addition, time frequency during gasoline engine operated (ON) and off-operated (OFF) can be also indicated. Time frequency during off-operated (OFF) can be detected in hybrid car and there is also no fuel consumption because hybrid system is operated by electricity. When fuel consumption in each driving mode both with and without considering crawling mode are compared, the fuel consumption in accelerating mode in with case is higher than in without case. The reason of difference is because acceleration in low speed ranges is removed from original acceleration mode. Moreover, crawling mode can provide much difference results of fuel consumption in conventional gasoline car. Thus, fuel consumption on crawling mode can be significantly reduced if hybrid car replace conventional gasoline car.

REFERENCES

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CHAPTER 6

ESTIMATION OF FUEL CONSUMPTION REDUCTION BY PROMOTING HYBRID CARS

This chapter determines the results of estimation of fuel consumption based on probe data from 10,000 taxis, the impacts of promoting hybrid cars in BMR, and reliability of estimation of fuel consumption and its reduction. This chapter consists of scenarios for estimation of fuel consumption reduction by promoting hybrid cars, estimation of fuel consumption reduction in case of replacing all probe cars by hybrid cars and in case of replacing private cars in BMR by hybrid cars, and verification of reliability estimation of fuel consumption and its reduction.

6.1 Scenarios for Estimation of Fuel Consumption Reduction by Promoting Hybrid Cars

In order to find the impacts on fuel consumption reduction by promoting hybrid cars, two scenarios are defined including (1) all probe cars are replaced by hybrid cars for comparing fuel consumption rate results in each consideration, and (2) private cars in BMR are replaced by hybrid cars for studying overall impacts of promoting hybrid cars from the present to 15 years later.

6.1.1 The first scenario

All probe cars from 10,000 taxis operated in BMR are replaced by hybrid cars for comparing fuel consumption rate results between without hybrid cars and with hybrid cars cases by 3 considerations including (1) area and days of week, (2) road category, and (3) driving modes. In this scenario, hybrid cars are assumed to replace detected probe cars. Additional data are not necessary to collect. The aim of this scenario is to estimate fuel consumption rate for studying the impacts and reductions of hybrid cars for different sub-area, road category, days of week, and periods.

6.1.2 The second scenario

Private cars in BMR are replaced by hybrid cars. Since the first scenario is not possible to occur, because probe cars are taxis, in which most of them consume compress natural gas (CNG). In order to reflect the real world situation, another scenario should be identified. The aim of this scenario is to estimate fuel consumption for studying reduction impacts if amount of hybrid cars increase from the present year to 15 years later. The policy of Ministry of Energy of Thailand, which identified energy efficiency development plan (EEDP) [1] proposed in 2011, called “the 20-year energy efficiency plan (2011 to 2030), were used for this scenario.”

The details of this energy plan have explained about share of vehicle sales of hybrid cars (HV) and other environmentally friendly vehicles from 2011 to 2031. In this study, amount private cars in BMR during that period by are replaced by private cars that use hybrid system by using share of HV for private cars for vehicle sales from 2011 to 2031, as shown in Table 6.1. After that, share percentages of HV sales are recalculated for studying the impacts of increasing HV comparing with without using HV.

Table 6.1 Share of HV for private cars for vehicle sales in EEDP scenario (%)

Year	2011	2016	2021	2026	2031
HV for PC	0.4	4.6	18.3	24.3	25.0

Source: (Ministry of Energy of Thailand, Energy Planning and Policy Office, 2011) [1]

6.2 Estimation of Fuel Consumption Reduction in Case of Replacing All Probe Cars by Hybrid Cars

For the first scenario, after time sharing of driving modes collected from probe data, as shown by figures in Chapter 4, and fuel consumption collected by field test data, as shown by Table 5.9 in Chapter 5 in each condition, fuel consumption can be estimated by Equation (6.1) for base case without hybrid car replacement, and Equation (6.2) for with hybrid car replacement.

- **For without hybrid car replacement (Without HV)**

$$FC_{WithoutHV} = \sum_{m,s}\left(FC^{Con}_{m,s} \times TS_{m,s}\right) \quad (6.1)$$

- **For with hybrid car replacement (With HV)**

$$FC_{WithHV} = \sum_{m,s}\left(FC^{HV}_{m,s} \times TS_{m,s} \times \frac{Freq_{on,m,s}}{Freq_{on,m,s}+Freq_{off,m,s}}\right) \quad (6.2)$$

Where $FC_{WithoutHV}$ = Fuel consumption for Without HV (cubic centimeter; cc)

FC_{WithHV} = Fuel consumption for With HV (cc)

$FC^{Con}_{m,s}$ = Fuel consumption by field test (cc/sec) of conventional car in each driving mode m and speed range s

$FC_{m,s}^{HV}$ = Fuel consumption by field test during gasoline engine operated (ON) (cc/sec) of hybrid car in each driving mode m speed range s

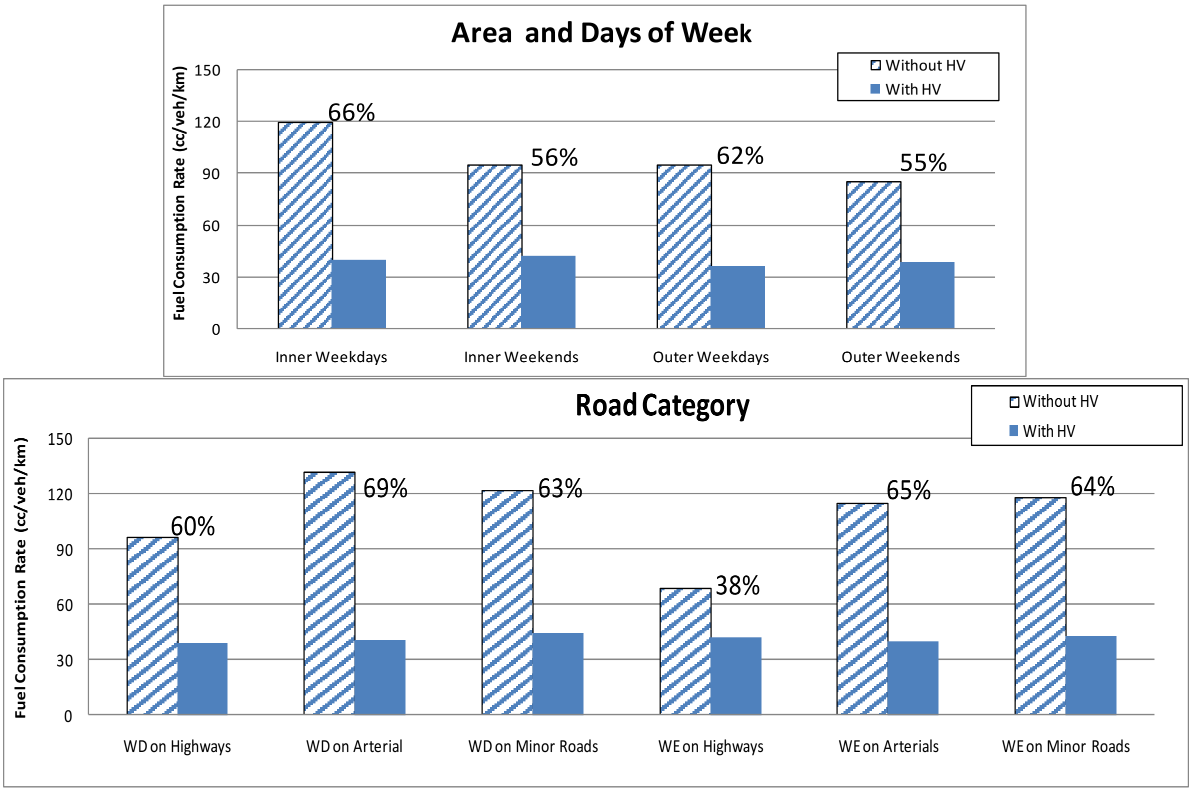
$TS_{m,s}$ = Time sharing in each driving mode m and speed range s collected from probe data (sec)

$Freq_{on,m,s}$ and $Freq_{off,m,s}$ = Time frequency (sec) of gasoline engine operated (ON) or off-operated (OFF) collected from field test

From Equation (6.1) and (6.2), fuel consumption in both conventional and hybrid cars can be estimated in all conditions. However, for an effective analysis, total fuel consumption is divided by vehicle kilometer traveled (VKT) calculated from all probe cars to obtain fuel consumption rate (cc/veh/km), as shown in Equation (6.3).

$$Fuel\ consumption\ rate = \frac{FC_{With\ or\ WithoutHV}}{VKT\ from\ probe\ data} \tag{6.3}$$

Fuel consumption rates and reduction percentages (difference percentages between without HV and with HV rates) are summarized in 2 types of considerations (area and days of week, and road category), as shown in Figure 6.1.



Note: WD = weekdays, WE = weekends

Figure 6.1 Results of fuel consumption rates and reduction percentages in each consideration

From area and days of week results, the highest consumption rate is in the inner area on weekdays in without HV case. The second is both the inner area on weekends and the outer area on weekdays, which are not significantly different. When road category is considered, the highest consumption rate is on arterials and minor roads on weekdays in which the average speed is low. The second is on arterials on weekends. Regarding reduction percentages, fuel reduction impacts are clearly observed in the inner area on weekdays on arterials.

High consumption rates from area and days of week and road category considerations correspond to high stopping and crawling percentages from time sharing results. Thus, they can indicate that fuel consumption increases when traffic is congested, as measured by time sharing of driving modes, similar to that shown in previous studies [2, 3, 4].

6.3 Estimation of Fuel Consumption Reduction in Case of Replacing Private Cars in BMR by Hybrid Cars

6.3.1 Necessary data for estimation of fuel consumption reduction by promoting hybrid cars

For the first scenario, only using all amounts of probe cars can calculate fuel consumption without additional data. For the second scenario, on the other hand, addition data are necessary to help estimate fuel consumption in all type of vehicles on road network in BMR. These data consist of link traffic volume data, vehicle type share identification, fuel share identification, fuel economy identification, and assumption of hybrid cars growth from the proposed policy.

(1) Link traffic volume data collection

For how to identify link traffic volume, firstly, road network collected in 2011, which can cover highways, arterials, and minor roads in area of BMR, together with data of average annual daily traffic volume (AADT), was used in this scenario. Road network and AADT data covering over 4,000 links can indicate link position, average speed, and link traffic volume both 2 directions, as shown in Figure 6.2.

	A	B	C	D	E	F	G	L	Q	R	S	T
1	Rank	Link Name	Node name i	Node name j	Average speed (km/h)	Final Speed (km/h)	Link Traffic Volume (All modes) i → j	Link Traffic Volume(All modes) j → i	Xi	Yi	Xj	Yj
2	1	A1577	10955	12046	17	13.1	44529	40251	664935	1516946	664796	1516902
3	2	A1578	10955	12048	17.4	13.9	40251	44529	664935	1516946	665081	1516993
4	3	A1580	10956	12041	17.9	3.1	66634	25963	665754	1517587	665695	1517716
5	4	A1581	10956	12042	25.5	21.8	25963	66634	665754	1517587	665921	1517260
6	5	A1583	10957	12045	12.9	2	61117	90250	666466	1518040	666199	1517903
7	6	A1584	10957	12135	9.7	2	90250	61117	666466	1518040	666579	1518130
8	7	A1586	10958	11170	15.9	9.2	42910	42911	673427	1515738	673355	1515878
9	8	A1587	10958	11502	15.9	9.2	42911	42910	673427	1515738	673585	1515433
10	9	A1589	10959	11110	16.8	12.7	34920	31060	668775	1519205	668308	1519518
11	10	A1590	10959	11181	17.3	13.7	31060	34920	668775	1519205	668957	1519078
12	11	A1595	10961	11273	17.6	14.5	46810	30204	668261	1525981	668117	1525726
13	12	A1596	10961	11352	18.5	16.6	32132	48054	668261	1525981	668513	1526452
14	13	A1598	10962	10963	27.8	26.9	4706	2607	675169	1519492	675073	1519595
15	14	A1599	10962	13016	28.1	27.7	2607	4706	675169	1519492	675093	1519428
16	15	A1600	10963	11792	24.5	19.5	33027	33723	675073	1519595	675202	1520919
17	16	A1601	10963	12975	24.8	20.1	31116	28321	675073	1519595	675073	1519512
18	17	A1602	10966	10967	14.4	2.3	45352	0	652885	1526046	652755	1524060
19	18	A1603	10967	10970	20.5	18.1	17240	0	652755	1524060	652688	1523536
20	19	A1604	10967	11604	12	1.8	39680	0	652755	1524060	652962	1523869
21	20	A1605	10968	11605	7.5	2.3	57052	17216	652665	1524067	652707	1524067
22	21	A1606	10968	13283	18.8	12.3	28471	0	652665	1524067	652811	1526062
23	22	A1607	10969	10968	16.2	3.6	38372	0	652601	1523561	652665	1524067
24	23	A1608	10969	11599	18.7	11.6	29145	0	652601	1523561	652348	1523774
25	24	A1609	10970	10971	19.9	17	21402	0	652688	1523536	652397	1520796
26	25	A1610	10970	11610	9.8	1.7	25950	0	652688	1523536	652638	1523536
27	26	A1612	10971	11586	13.5	11.4	10735	11544	652397	1520796	653885	1520387
28	27	A1613	10971	12835	19.9	16.9	21893	0	652397	1520796	652379	1519679

Figure 6.2 Road network data together with link traffic volume

Since link traffic volume obtained from road network is AADT and this study consider the difference of traffic volume of each period and days of week, AADT should be analyzed in variations of traffic conditions recommended by Highway capacity manual [5].

Link AADT can be divided into percentage of daily traffic volume showing hourly variations. Figure 6.3 shows hourly percentages of average daily traffic volume (ADT) collected in September 2011 at 44 main intersections covering in BMR area both on weekdays and weekends [6].

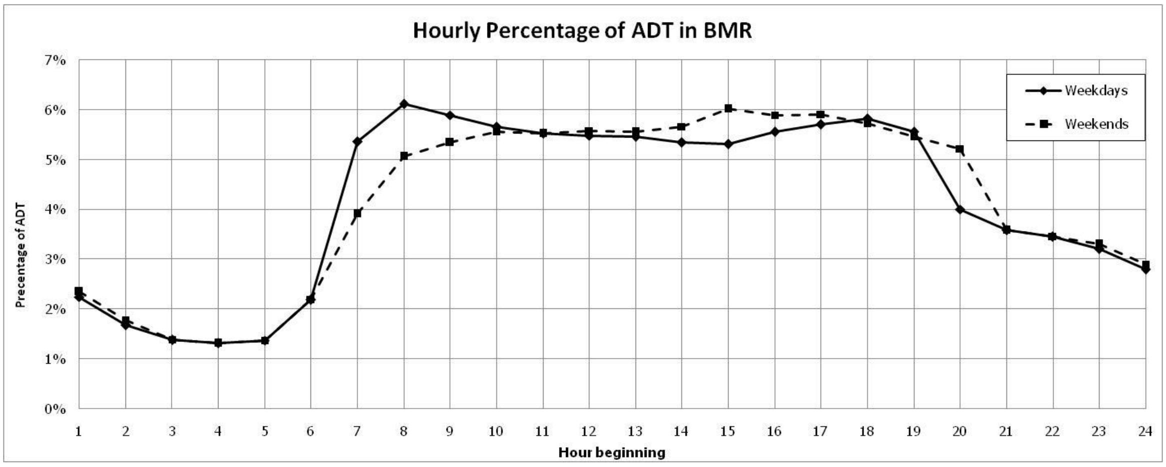


Figure 6.3 Hourly percentages of ADT on weekdays and weekends

Source: (Narupiti et.al, 2012) [6]

Firstly, for how to identify amount of ADT on weekdays and weekends, by traffic data collection [6], it was found weekday daily traffic volume is 1.01 time of ADT and weekend daily traffic volume on weekends is 0.97 time of ADT. These 2 values are used as days of week factors (DF) as a multiplier of AADT in each link.

Secondly, for how to identify traffic volume in each period, hourly percentage of traffic volume in BMR in Figure 6.3 can be used for another multiplier of AADT in each link in each period [6] as period factor (PF). The results of cumulative percentage of ADT in each period on weekdays and weekends can be shown in Table 6.2.

Table 6.2 Cumulative percentage of ADT in each period

Period	% of ADT on weekdays	% of ADT on weekends
7-9	15.6	10.4
9-16	38.3	39.8
16-19	17.0	17.1

In Table 6.2, variations of ADT percentage can be seen and represent the difference of percentages between weekdays and weekend in each period. On weekdays, percentages in morning and evening peaks are higher than off peaks. On weekends, percentages in day time and evening are higher than in the morning.

For how to predict AADT in the future, traffic growth factor, which are proposed by AASHTO [7], is used for traffic volume prediction by Equation (6.4).

$$Y(t)_{r,l} = X(t_{Base})_{r,l}(1+R)^n \tag{6.4}$$

Where $Y(t)_{r,l}$ = Link l AADT in each road category r for future year t (vehicles per day; vpd)

$X(t_{Base})_{r,l}$ = Link l AADT in each road category r in base year t_{Base} (vpd)

R = Traffic growth rate (5.1% in this study)

n = Duration between base time to future (year)

For how to find traffic growth factor, it can be found by using several data including traffic and socio-economy data [8] and predicting traffic forecast models, those are the best method. Since there were limitations of collecting data in this study, the assumption by using the trend of yearly number of all types registered vehicles in BMR during 2004 to 2016 collected from Department of Land Transport of Thailand (DLT) [9] are used to calculate traffic growth factor for predicting traffic volume for future years, as shown in Figure 6.4. This assumption is used on all road categories, in all periods, days of week, and sub-areas.

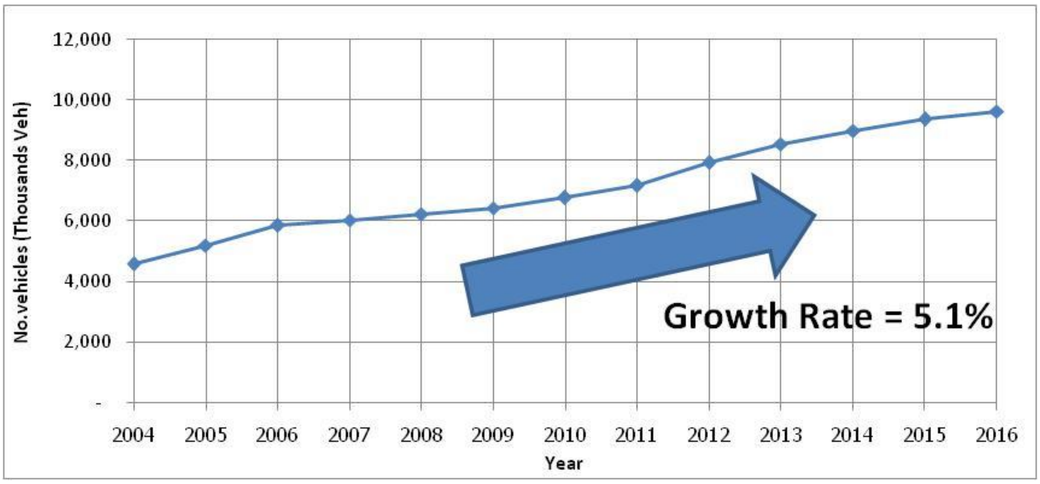


Figure 6.4 Number of all types registered vehicles in BMR during 2004 to 2016 and the trend of growth rate

From Figure 6.4, number of all types registered vehicles continuously increase by growth rate equal to 5.1%. This growth rate is used to predict link traffic volume for future years. By factors considering from variations of traffic between days of week, period, and future years, link traffic volume in each days of week and period can be calculated and summarized by Equation (6.5).

$$N(t)_{r,l,d,p} = Y(t)_{r,l} \times DF \times PF \qquad (6.5)$$

Where $N(t)_{r,l,d,p}$= Link l traffic volume in each road category r in future year t (vpd) in each days of week d and period p

$Y(t)_{r,l}$ = Link l AADT in each road category r in future year t (vpd)

DF = Days of week factor (1.01 on weekdays and 0.97 on weekends)

PF = Period factor (% of ADT/100)

(2) Vehicle type share identification

In this scenario, 8 types of vehicles are defined consisting of personal cars (PC), pick-up truck (PU), urban taxi (TAXI), commercial car (COMC), three-wheeler (3WL), motorcycle (MC), bus (BUS), and truck (TRK) [9]. For how to find % of each vehicle type in each period and days, data of vehicle type share are received from yearly number registered vehicles in each vehicle type in BMR from 2004 to 2016, obtained from DLT [9]. Number of registered vehicles in each vehicle type and percentage of vehicle share can be shown in Figure 6.5. After that, the trend of number of registered vehicles in each vehicle type can be also identified.

From Figure 6.5, personal cars (PC), motorcycle (MC), and pick-up truck (PU) have the great impacts and continuously increase, especially number of PC that is the most impact. So, the trend of number of each vehicle type can be identified and predicted for future using growth rate.

Since vehicle type share in each road category and period is definitely different, there are a few 3WL and MC on highways, and BUS and TRK on minor roads. Therefore, 3WL and MC are not considered on highways, and BUS and TRK are not considered on minor roads in this study.

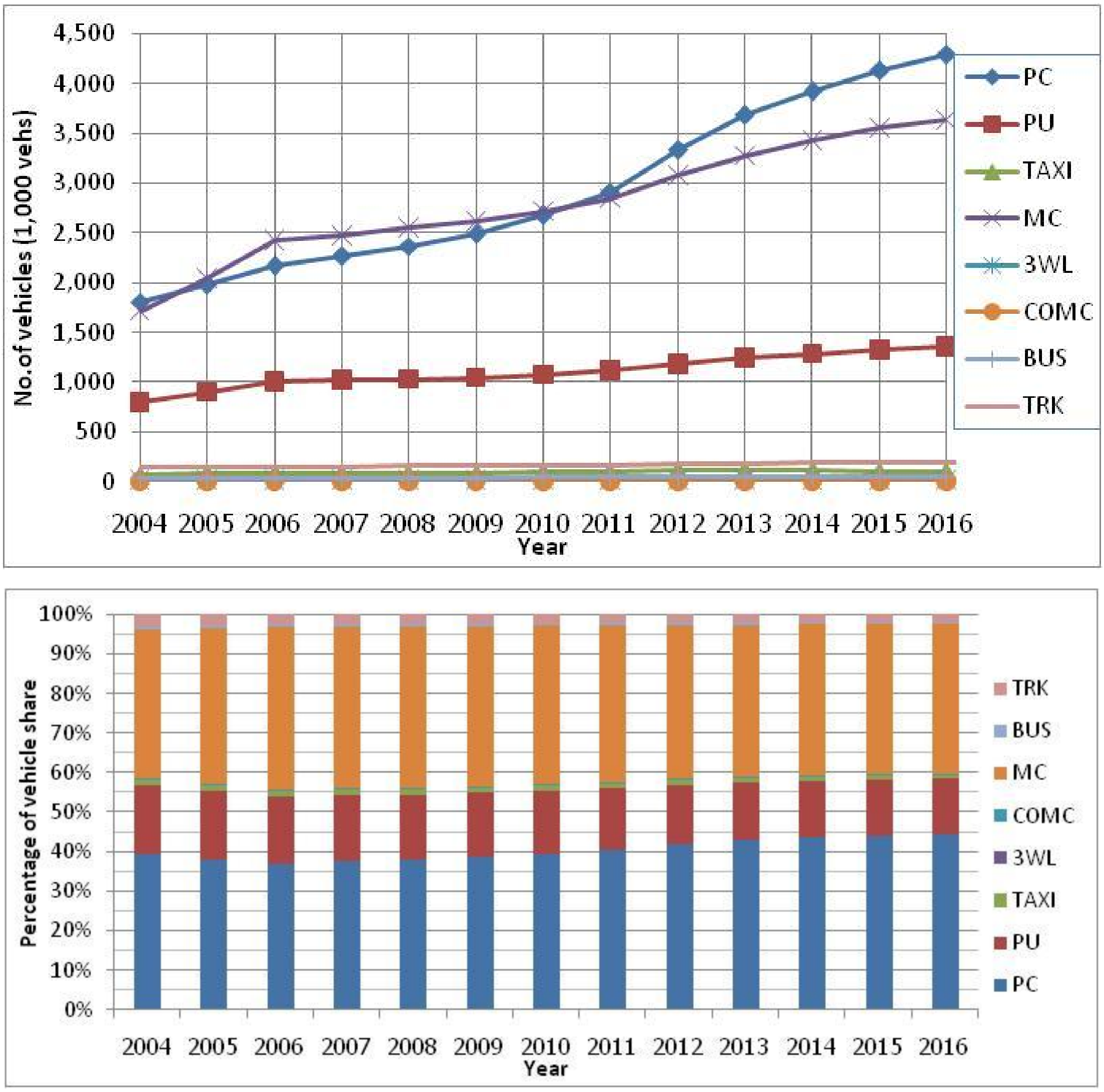


Figure 6.5 Number of registered vehicles and percentage of vehicle share by vehicle type from DLT [9]

(3) Fuel share identification

Data of fuel type share are also obtained from the results of DLT [9] and Pongthanaisawan [10] by showing percentage of vehicle stock in 1997 and vehicle sale during 1997 to 2008 in each vehicle and fuel type, as shown in Table 6.3. It was found that the trend of fuel sale percentages can be obviously seen. These percentages during 1997 to 2008 are used to predict fuel share from vehicle stock in each vehicle type from 1997 to future years by using growth rates.

Table 6.3 Fuel share percentage of vehicle stock in 1997 in each vehicle type and vehicle sales during 1997 to 2008

Vehicle Type	Fuel Type	Vehicle Stock	Vehicle Sales											
		1997	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
PC	Gasoline	68.32%	76.76%	78.15%	79.64%	81.12%	82.61%	84.09%	85.58%	87.06%	88.55%	86.70%	84.85%	83.00%
	Diesel	31.59%	23.33%	21.85%	20.36%	18.88%	17.39%	15.91%	14.42%	12.94%	11.45%	9.97%	8.48%	7.00%
	LPG	0.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.33%	4.67%	7.00%
	CNG	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.00%	2.00%	3.00%
PU	Gasoline	100.00%	4.09%	3.91%	3.72%	3.54%	3.35%	3.17%	2.98%	2.80%	2.80%	2.43%	2.24%	2.06%
	Diesel	9.55%	95.91%	96.09%	96.28%	96.46%	96.65%	96.83%	97.02%	97.20%	97.20%	97.57%	97.26%	96.94%
	CNG	90.45%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.50%	1.00%
TAXI	Gasoline	0.00%	10.00%	6.67%	3.33%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	LPG	100.00%	90.00%	93.33%	96.67%	100.00%	100.00%	100.00%	100.00%	96.00%	92.00%	88.00%	84.00%	80.00%
	CNG	61.32%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	4.00%	8.00%	12.00%	16.00%	20.00%
3WL	Gasoline	38.68%	12.54%	11.40%	10.26%	9.12%	7.98%	6.84%	5.70%	4.56%	3.42%	2.28%	1.14%	0.00%
	Diesel	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	LPG	100.00%	87.46%	87.46%	89.74%	90.88%	92.02%	93.16%	94.30%	95.44%	96.58%	97.72%	98.86%	100.00%
COMC	Gasoline	36.73%	50.00%	55.00%	60.00%	65.00%	70.00%	75.00%	77.78%	80.56%	83.35%	86.13%	88.91%	91.69%
	Diesel	2.11%	50.00%	45.00%	40.00%	35.00%	30.00%	25.00%	22.22%	19.44%	16.66%	13.87%	11.09%	8.31%
MC	Gasoline	61.16%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
BUS	Diesel	70.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	99.75%	99.50%	95.00%
	CNG	30.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.25%	0.50%	5.00%
TRK	Diesel	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	97.50%	95.00%
	CNG	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.50%	5.00%

Source: (DLT, 2016 and Pongthanaisawan, 2011) [9, 10]

(4) Fuel economy identification

Fuel economy in each vehicle and fuel type can be identified by survey data of King Mongkut's Institute of Technology Thonburi (KMUITT) [11] and Energy Planning and Policy Office (EPPO) [12] covering all vehicle types in Thailand's road transport sector. This data can be shown in Table 6.4 in term of kilometer per liter.

Table 6.4 Fuel economy of vehicles by fuel types

Vehicle Type	Fuel Economy (kilometer per liter)			
	Gasoline	Diesel	LPG	CNG*
PC	12.27	11.31	10.69	10.86
PU	11.82	11.93	11.06	10.78
TAXI	13.50	10.00	9.66	11.16
COMC	9.37	8.34	11.22	8.71
3WL	17.68	15.37	10.80	10.25
MC	28.71	-	-	-
BUS	-	3.91	-	2.26
TRK	-	4.14	-	1.67

Source: (KMUITT, 1997 and EPPO, 2007) [11, 12]
Note: *Unit of CNG fuel economy is kilometer per kilogram.

(5) How to calculate fuel consumption for the second scenario

Firstly, the original equation for estimation of fuel consumption can be shown in equation (6.6).

$$FC(t)_{k,f} = \left\{\sum_r \sum_l \sum_d \sum_p \left(N(t)_{r,l,d,p} \times VKT(t)_{r,l,d,p}\right)\right\} \times k(t) \times f(t)_k \times \frac{1}{FE_{k,f}} \quad (6.6)$$

Equation (6.6) can estimate fuel consumption by multiplying of (1) number of vehicles, (2) vehicle kilometer traveled (VKT), and (3) percentage of vehicle type and fuel share and fuel economy. Impact of fuel consumption reduction by promoting hybrid under the scenario is private cars are replaced by hybrid cars has been proposed by equation (6.7) and (6.8), which are estimation of fuel consumption both without hybrid cars and with hybrid cars cases, respectively. These equations are modified from original equation of estimation of fuel consumption in term of distance (VKT), which is changed to the new term that collect of average speed and time sharing of driving modes collected from probe data in order to better reflect driving patterns.

$$FC(t)_{k,f} = \left\{\sum_r \sum_l \sum_d \sum_p \left(N(t)_{r,l,d,p} \times \left(\frac{V}{3600} \times \frac{\sum_{s,m} TS_{s,m}}{Probes}\right)_{r,l,d,p}\right)\right\} \times k(t) \times f(t)_k \times \frac{1}{FE_{k,f}} \quad (6.7)$$

$$FC(t)_{HV} = \left\{\sum_r \sum_d \sum_p \left(\sum_l N(t)_{r,l,d,p} \times \frac{\left(\sum_{m,s}[TS_{m,s} \times FC_{m,s}]\right)_{r,d,p}}{\sum_l Probes_{r,l,d,p}}\right)\right\} \times PC(t) \times HV(t) \quad (6.8)$$

Where	$FC(t)_{k,f}$	=	Fuel consumption in each vehicle type and fuel share in future year *t* (liters per day)
	$N(t)_{r,l,d,p}$	=	Link *l* traffic volume in each road category *r* in future year *t* (vehicles per day) in each days of week *d* and period *p*
	VKT(t)	=	Vehicle kilometer traveled of all vehicle (km) in each link *l* in each road category *r* in future year *t* in each days of week *d* and period *p*
	V	=	Link average speed calculated from probe data (km/hr)
	$TS_{s,m}$	=	Time sharing of each driving mode *m* and speed range *s* (sec)
	Probes	=	Amount of detected probe cars in each link
	k(t)	=	Vehicle type % in each year *t*
	$f(t)_k$	=	Fuel share in each vehicle type *k* in each year *t*
	$FE_{k,f}$	=	Fuel economy (kilometer per liter) in each vehicle type *k* and fuel type *f*
	$FC(t)_{HV}$	=	Fuel consumption of hybrid cars in each road in future year *t* (liters per day)
	$FC_{m,s}$	=	Fuel consumption by field test (liter/sec) of hybrid cars in each driving mode *m* and speed range *s*
	PC(t)	=	Percentage of private cars in future year *t*
	HV(t)	=	Percentage of hybrid share in each vehicle type in future year *t*

Equation (6.7) in term of average speed, time sharing of driving modes, and amount of detected probe cars is modified from vehicle kilometer traveled (VKT) in order to better reflect driving patterns, and percentage of vehicle type, fuel share, and fuel economy are considered later. Equation (6.8) both time sharing of driving modes and amount of detected probe cars and fuel consumption results obtained from field test are modified without term of distance and fuel economy. This equation is used to replace estimation of fuel consumption only in private car in equation (6.7) in case of using hybrid cars (HV). Both two equations, amount of detected probe cars is defined as divisor for rule of three in arithmetic in order to be representative of driving patterns of all vehicles.

Both Equation (6.7) and (6.8) are under the assumption that time sharing of driving modes are stable for future years, although time sharing of driving mode should be forecasted for future years. However, other factors affecting higher fuel consumption are considered in this scenario including of number of increasing vehicles, changing of share percentage of vehicle types and fuel that can help to more accurate estimation.

6.3.2 Results

The results of the second scenario is begun from showing total traffic volume and VKT for future years, amount of vehicles in each vehicle type and fuel share, and estimation of fuel consumption and its reduction.

(1) Total traffic volume and vehicle distance traveled results for future years

All links traffic volume for future years in this study can be forecasted from base year in 2011 to future years by using growth rate calculated from the trend of registered vehicles collected from the Department of Land Transport of Thailand (DLT) [9] during 2004 to 2016. The growth rate already calculated is equal to 5.1%. Traffic volume in term of total daily traffic volume for future years both base year in 2011 and future years during 2016 to 2031 can be shown in Figure 6.6 by separating on weekday and weekend.

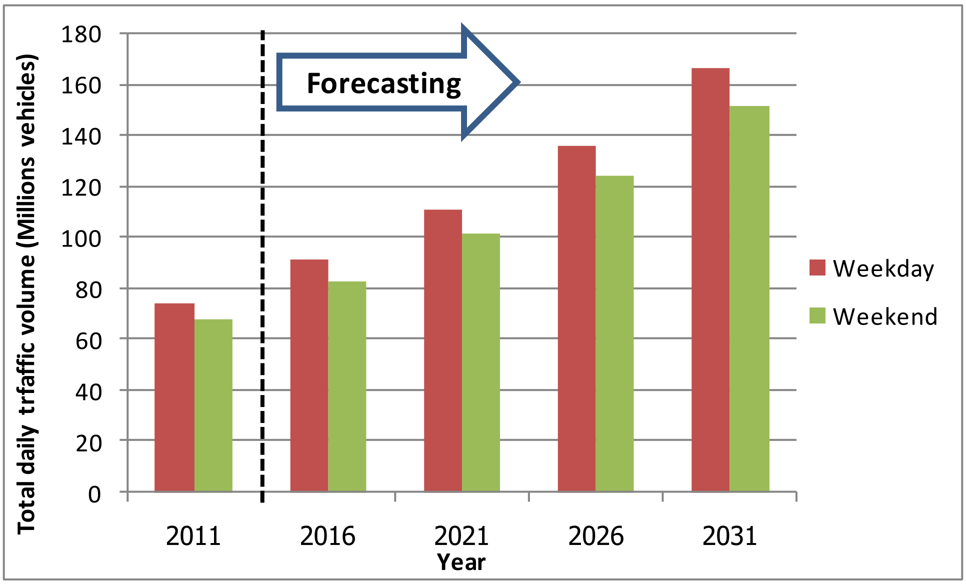


Figure 6.6 Total daily traffic volume during 2011 to 2031

Source: (DLT, 2016) [9]

From Figure 6.6, traffic volume on weekday is more than on weekend. During 2011 to 2031, traffic volumes increase from 75 million vehicles to 167 million vehicles and 68 million vehicles to 152 million vehicles on weekday and weekend, respectively.

In addition, average speed, time sharing of driving modes, and amount of detected probe cars, collected from probe data, can be calculated in term of vehicle kilometer traveled (VKT). Therefore, Figure 6.7 shows the results of VKT collected from probe data compared with VKT estimated by previous research of Pongthanaisawan [10] during 2011 to 2031. However, since VKT results considered them in Thailand, percentages of registered vehicles in BMR are used for finding estimated VKT only in BMR. The results found that percentage of registered vehicles in BMR is around 30% in each year.

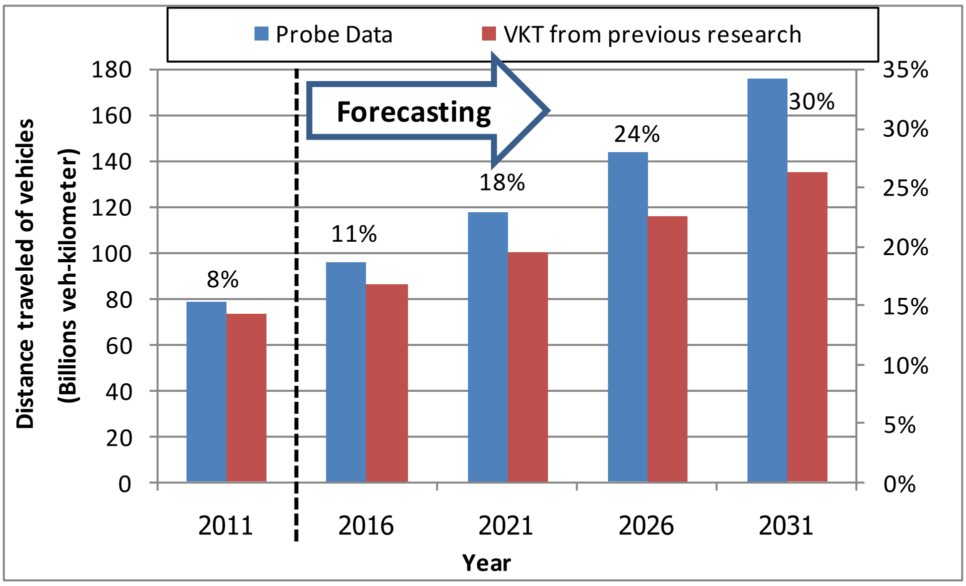


Figure 6.7 VKT from probe data compared with previous research [6] during 2011 to 2031

From Figure 6.7, VKT from probe data are higher than previous research, and different percentage increases whenever future years increase. Although, the maximum different percentage is 30% in 2031, the results of VKT from probe data can be still utilized because different values are from less percentage to more percentages from base year (8% in 2011) to future years (30% in 3031) and different percentage in base year (8% in 2011), in which this period was already passed, is not much different. Thus, estimation of VKT calculated from probe data can reflect and correspond to previous research [6] that can confirm in reliability.

(2) Percentage of vehicle type and fuel share

The results of percentage share of vehicle type and fuel only in private cars during 2016 to 2031 can be shown in Figure 6.8 and 6.9, respectively. Percentage of each vehicle types can be forecasted by using growth rates calculated from trend of each registered vehicle in BMR collected from DLT [9] during 2004 to 2016.

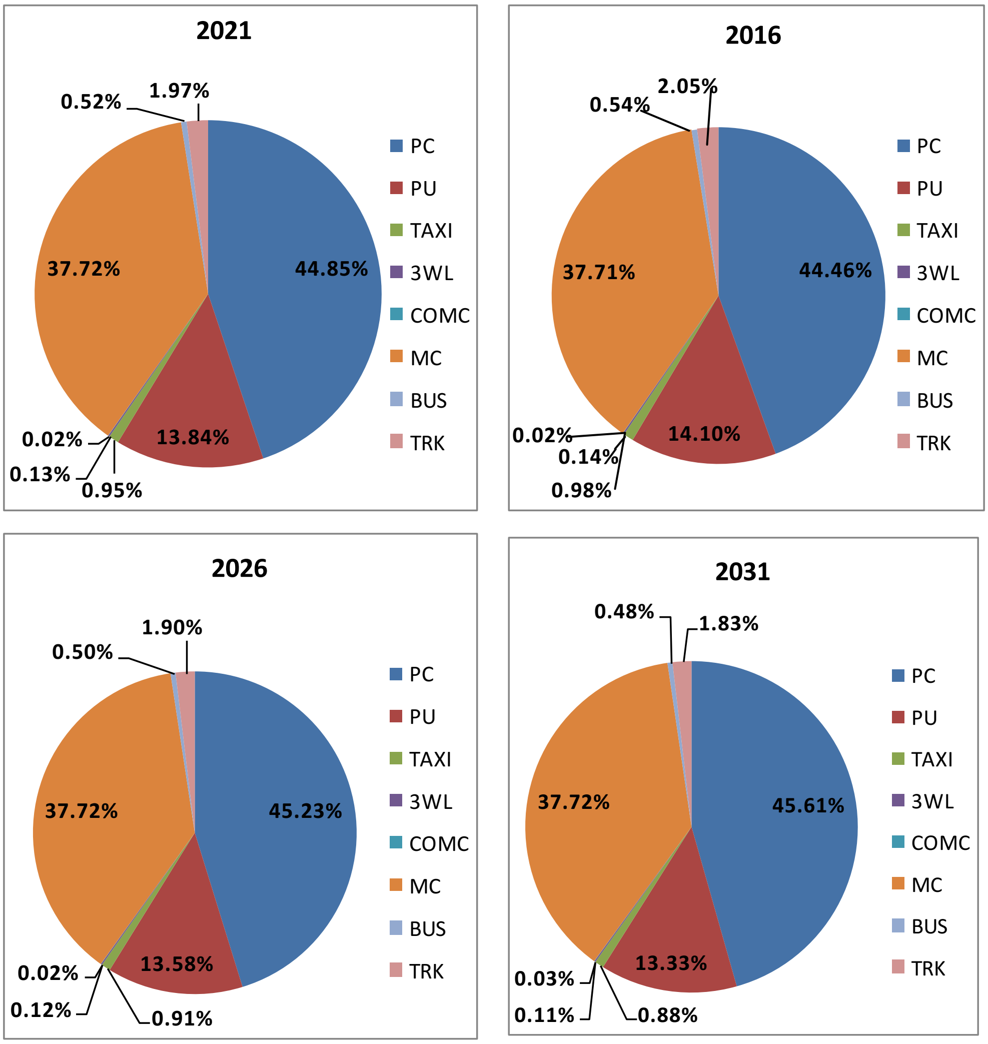


Figure 6.8 Percentage share of vehicle type during 2016 to 2031

In Figure 6.8, the highest percentage share of vehicle type in BMR is private cars (PC) in all year, which is around 44 - 45%. The second is motorcycles (MC), which is around 37%. And the third one is pick up cars (PU), which is around 13 - 14%. Other vehicle types are a few impacts. From these pie charts, they can be implied that PC, MC, and PU have major impacts for fuel consumption in BMR, especially in MC that have not yet a new technology to reduce fuel consumption.

Figure 6.9 shows percentage share of fuel only on private cars only in private cars in BMR during 2016 to 2031. They can be forecasted by using by using growth rate calculated from the trend of vehicle sales in each vehicle type and fuel collected from Pongthanaisawan [10] and DLT [9] during 2004 to 2016.

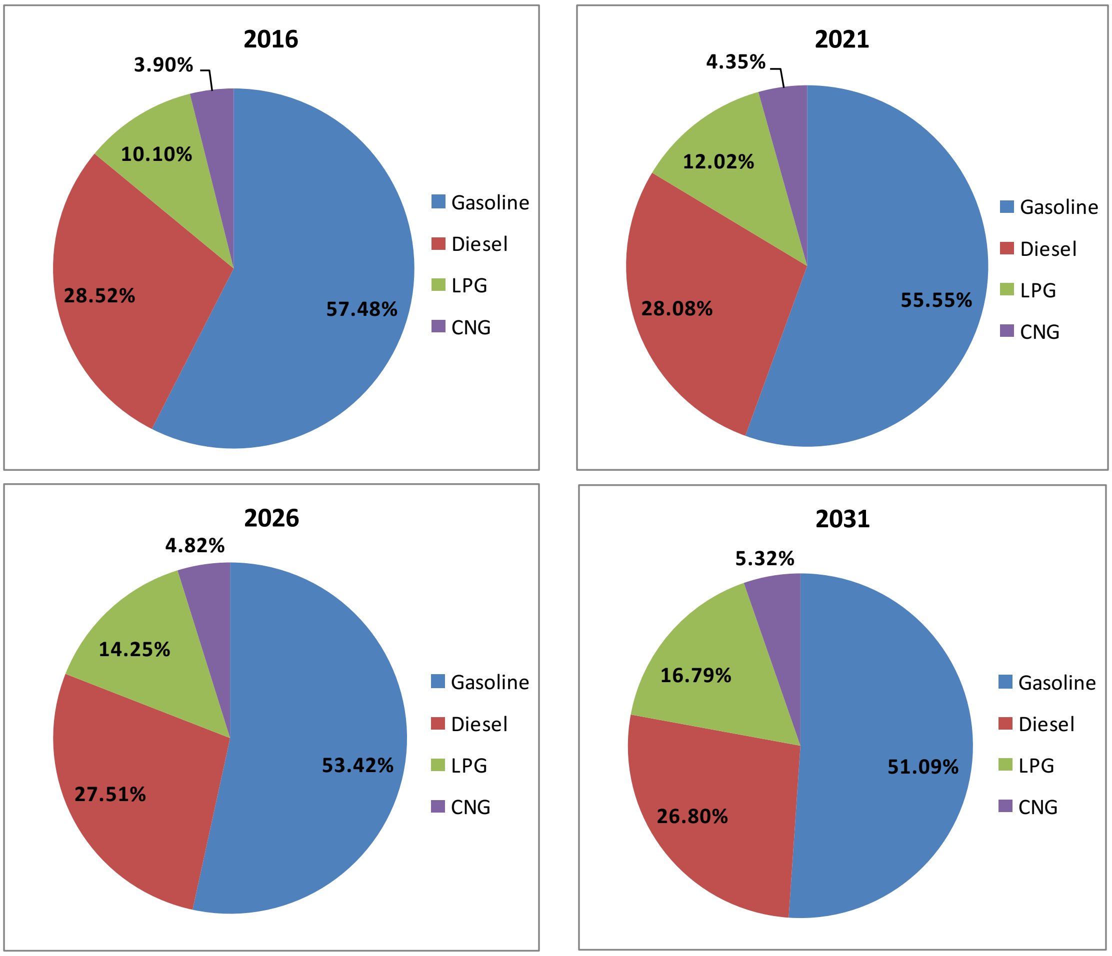


Figure 6.9 Percentage share of fuel during 2016 to 2031 in private cars in case of without HV

From Figure 6.9, the highest percentage share of fuel is gasoline, which is around 51 - 57%. However, the trend of percentage decreases due to increasing of compressed natural gas (CNG) and liquid petroleum gas (LPG) usage. The second is diesel, which is around 26 - 28%. However, the trend of percentage also decreases due to the same reason of gasoline. Therefore, if hybrid cars are more promoted, the trends of gasoline and diesel usage are definitely decreased.

In case of HV, percentage share of hybrid cars change percentage share of fuel in private cars from without HV case. This percentage can be calculated by using growth rates collected from hybrid car sales proposed by the policy of EPPO [1]. Table 6.5 shows the results of calculation of share of hybrid cars after considering hybrid car sales, and Figure 6.10 shows percentage share of fuel in case of HV replacing.

Table 6.5 Share of HV sales for private cars from proposed policy

Year	2011	2016	2021	2026	2031
HV for PC (%)	0.41	4.94	11.10	15.99	17.27

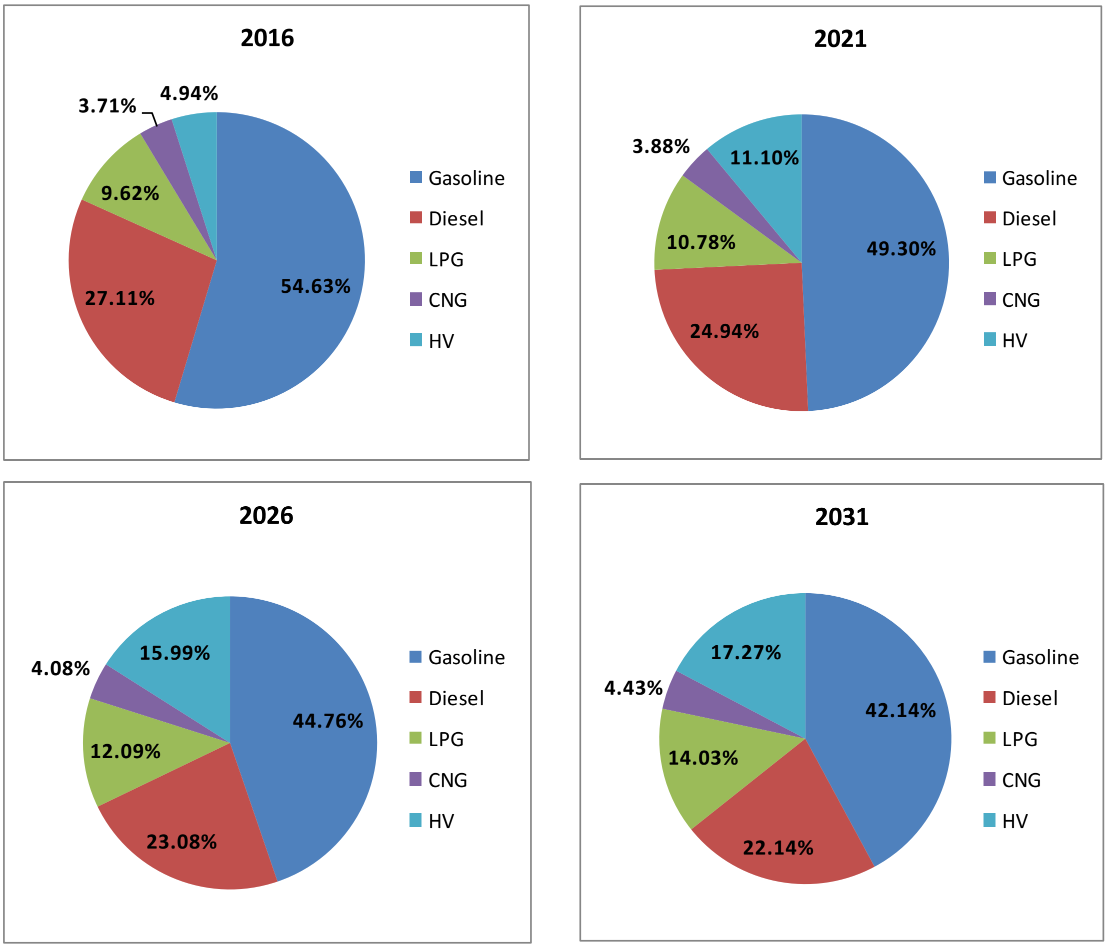


Figure 6.10 Percentage share of fuel during 2016 to 2031 in private cars in case of with HV

From Figure 6.10, the highest percentage share of fuel is still gasoline, which is around 42 - 54% that is less than without HV case. However, the trend of percentage decreases due to increasing of CNG, LPG, and also HV usage. By the policy proposed by EPPO [12], percentages of HV are shared from other four fuel types from 4.94% in 2016 to 17.27% in 2031. The second percentage is still diesel, which is around 22 - 27% that is also less than without HV case due to the same reason as mentioned above.

(3) Estimation of fuel consumption and its reduction

Since there are many types of fuel for estimation of fuel consumption in this study, the standard unit of energy consumed that can be inducated and compared for different fuel type should be conducted. Thus, the unit of kiloton oil equivalent (ktoe), in which volumes or weights of many fuel types, can be converted into the same volumes of clude oils considerd from oil refinery that there are differences of amount of fuel types released. The results of estimation of fuel consumption during 2016 to 2031 and its reduction percentages can be shown in Figure 6.11 both in comparison of all vehicles in BMR and only private cars.

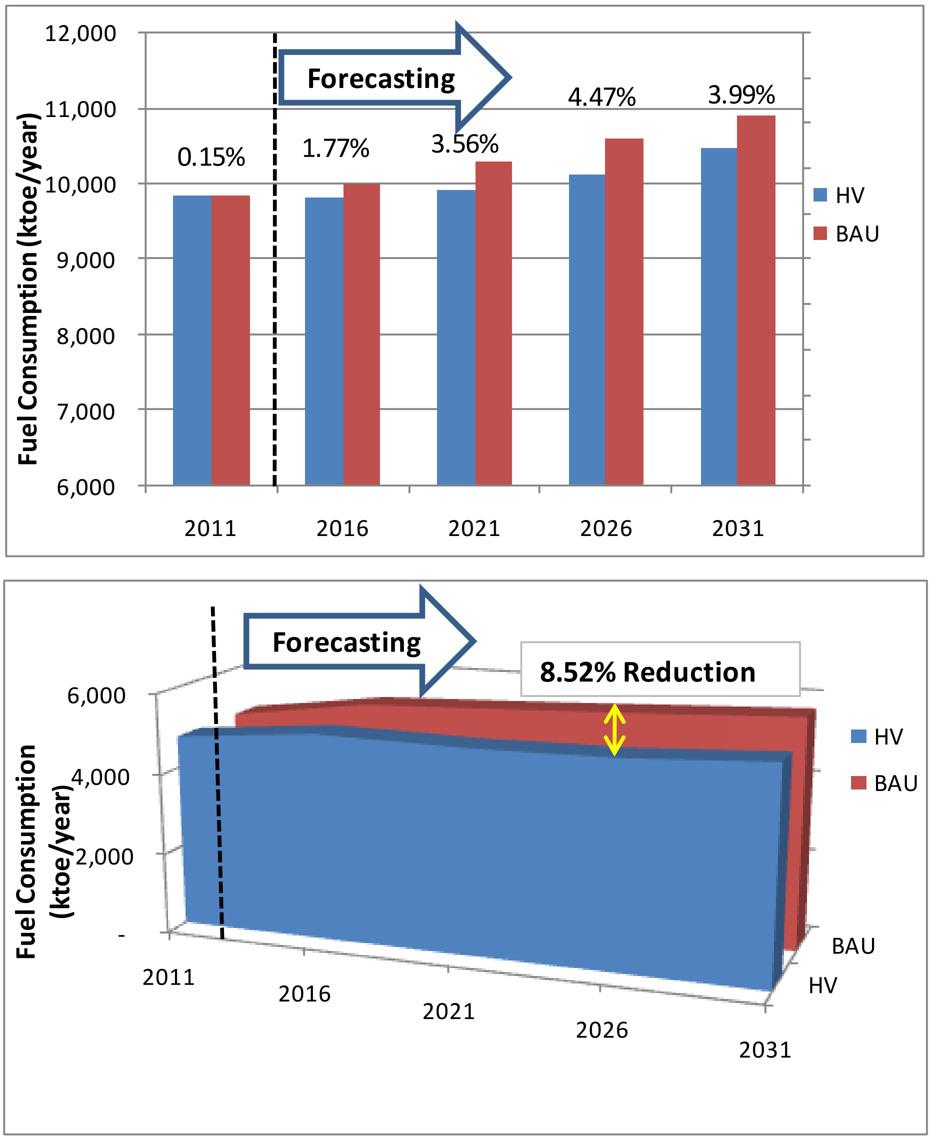


Figure 6.11 Fuel consumption and its reductions both in comparison of all vehicles in BMR (above) and only private cars (below)

It was found that with HV can reduce fuel consumption from 2016 to 2031. The highest redution percentages are in 2026, calculated to 4.47 % in comparison with all vehicles in BMR and 8.52% in comparison with only private cars.

6.4 Verification of Reliability of Estimation of Fuel Consumption and Its Reduction

Reliability in this study, fuel consumption and its reduction by estimation from probe data is compared with the actual fuel consumption measured by fuel consumption from field test and observed fuel consumption in transport sector obtained from Department of Alternative Energy Development and Efficiency, Ministry of energy of Thailand (DEDE) [13].

The results of estimation of fuel consumption based on proposed equations are compared with observed fuel consumption in transport sector during 2011 to 2015 obtained from (DEDE) [13]. Since data of fuel consumption is all provinces in Thailand, in this study, observed fuel consumption can be obtained from percentage of registered vehicles in BMR compared with all registered vehicles in Thailand, which is around 30% in each year. Comparison of 2 sources of fuel consumption during 2011 to 2015 can be shown in Table 6.6.

Table 6.6 Fuel consumption between estimation and observation from DEDE [13]

Year	Fuel Consumption (ktoe)		Difference Percentage
	Estimation	Observation	
2011	9,847	7,894	25%
2012	9,878	8,131	21%
2013	9,908	8,352	19%
2014	9,939	8,308	20%
2015	9,969	8,835	13%

From Table 6.6, difference percentage between estimation and observation in base year in 2011 is the highest different, accounted to 25%. After that, percentage differences can decrease until in the year of 2015, accounted for 13%, and also have the trend of decreasing for future years. That means, by decreasing of difference percentage, it can be proved that estimation of fuel consumption by proposed equations can be used for estimation of fuel consumption reduction by promoting hybrid cars.

According to proving results of fuel consumption reduction by promoting hybrid cars, Table 6.7 shows the comparison of fuel consumption rates calculation in each road category and days of week in inner areas between estimation from probe data and actual measurement by field test. Probe data in this comparison were brought to collection from 10,000 taxis, but they were selected for each condition in inner area of BMR in different days of week and road categories.

Table 6.7 Fuel consumption rates (cc/veh/km) of conventional and hybrid cars and their reductions between probe taxis and field test

Conditions	Estimation from probe taxis			Actual measurement from field test			Different reduction percentage between 2 data
	Conventional (without HV)	Hybrid (with HV)	% Reduction	Conventional	Hybrid	% Reduction	
WD on Highways	102	40	61%	100	44	56%	5%
WD on Arterial	136	40	70%	161	53	67%	3%
WD on Minor Roads	134	46	65%	156	53	66%	1%
WE on Highways	69	42	39%	65	35	46%	7%
WE on Arterials	119	43	63%	137	44	68%	5%
WE on Minor Roads	94	34	64%	97	35	64%	0%

Note: WD = weekdays, WE = weekends

From Table 6.7, different percentages in most conditions are not much different from each other (< 10%). However, fuel consumption rates by field test are higher than probe data, especially on arterials and minor roads. The possible reason is real running was tested in one of critical area for traffic congestion in inner area of BMR, similar to that shown in a previous study [14] that fuel consumption in downtown is higher than suburb area. Thus, proving reduction percentages are reliable.

6.5 Concluding Remarks

This chapter estimates fuel consumption reduction by two defined scenarios in this study are (1) All probe cars (10,000 taxis) are replaced by hybrid cars and (2) Private cars in BMR are replaced by hybrid cars.

Regarding the first scenario, fuel consumption rates (cc/veh/km) and reduction percentages (difference percentages between without HV and with HV rates) are summarized in 2 types of considerations (area and days of week, and road category). From area and days of week results, the highest consumption rate is in the inner area on weekdays without HV. When road category is considered, the highest consumption rate is on arterials on weekdays. Regarding reduction percentages, fuel consumption reductions are clearly observed in the inner area on weekdays on arterials.

Regarding the second scenario, fuel consumption can be estiamatd by proposed equations applied from vehicle kilometer traveled (VKT) by using time sharing of driving modes, amount of detected probe cars, and average speed from probe data. Moreover, additional data are used for proposed equations consisting of link traffic volume, 8 types of number of registerd vehicles, and fuel share in BMR from base year in 2011. Then, fuel consumption can be forecasted for future years by calculating growth rate of link traffic volume. The results of estimation of fuel consumption during 2016 to 2031 and its reduction percentages can be estimated in the unit of kiloton oil equivalent (ktoe). As a results, with HV case can reduce fuel consumption by the highest redution percentages in 2026 equal to 474 ktoe, as calculated to 4.47% in comparison with all vehicle types in BMR and 8.52% in comparison with only private cars.

For examination of reliability of estimation, fuel consumption rate and its reduction estimated by probe data was compared with the actual fuel consumption measured by field test and observed fuel consumption in transport sector during 2011 to 2015 obtained from Department of Alternative Energy Development and Efficiency of Thailand (DEDE). The examinations were found that percentage difference between estimation and observation in base year in 2011 is the highest different, accounted to 25%. After that, percentage differences can decrease until in the year of 2015, accounted for 13%. That means it can be proved that estimation of fuel consumption by proposed equations can be used for estimation of fuel consumption reduction by promoting hybrid cars. Regarding fuel consumption reduction, different percentages in most conditions are not very different from each other. That means estimation of fuel consumption reductions from probe data are confirmed in reliability.

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CHAPTER 7

CONCLUSIONS

This chapter summarizes the dissertation's findings, conclusions, and recommendations. Estimation of fuel consumption in road transport sector is important to evaluate policies for reduction of fuel consumption, but it is not easy to estimate due to fluctuation and unstableness of driving patterns depending on traffic conditions. Thus, floating car data or probe data, reflecting well traffic conditions, can be used for estimation of fuel consumption. However, fuel consumption cannot be measured directly from probe cars, because it is not practical to install fuel consumption measurement devices on all probe cars. In addition, devices for fuel consumption measurement require high time resolution, but data from probe cars cannot be obtained at this high time resolution.

Speed data collected from probe cars can help to estimate fuel consumption by using speed profiles. The proportion of accumulated time in each driving mode obtained from speed profiles is applied and defined as "Time Sharing of Driving Modes." Implementing time sharing of driving modes gives clearer explanation of driving patterns than only interpretation of average speed or acceleration data. Thus, it is used for development method to estimate fuel consumption reduction in this dissertation.

Crawling is a behavior of vehicles in traffic stream, which is the transition driving state between stopping/idling and full moving of vehicle normally occurring in congestion, is considered as additional driving mode, because crawling of vehicles can reflect traffic congestion and fuel consumption, not only vehicle stopping.

In this dissertation, promoting hybrid cars in a developing city, "Bangkok Metropolitan and Region area (BMR)," Thailand was selected as case study for estimating fuel consumption reduction.

7.1 Conclusions

- Development of estimation of fuel consumption reduction in this dissertation based on time sharing of driving modes has the great advantage for the future policy implementation to reduce fuel consumption in road transport sector, and can be applied in other cities if probe data are available.

- By determination of time sharing of driving modes based on probe data in this dissertation, decelerating mode spends the greatest time percentage in most cases, cruising mode is the second, and the third is accelerating. Although time percentages of crawling mode are less than first three driving modes, crawling mode can indicate traffic congestion that is readily seen by increased time percentages of stopping and crawling mode. If only stopping mode is considered, traffic congestion impact would not be clearly seen. Stopping and crawling percentages in the inner areas are greater than in the outer areas in all cases, and high percentages of them are readily seen only on minor roads in the inner areas.

- Additional driving mode (crawling) can provide the different results between with and without considering it by indicating traffic congestion and estimating fuel consumption in conventional gasoline car on accelerating mode. Fuel consumption on accelerating mode with crawling in conventional gasoline car is higher than without crawling, because acceleration in low speed ranges is removed from original accelerating mode. The results of hybrid cars are the same as in conventional gasoline car, but fuel consumption on accelerating mode increases less than that in conventional gasoline car. Thus, fuel consumption on crawling mode can be significantly reduced if hybrid car replace conventional gasoline car.

- From the scenario that all probe cars from 10,000 taxis replace by hybrid cars, estimation of fuel consumption in the inner area of BMR on weekdays on arterials are the conditions that have greatest impacts on fuel consumption corresponding with traffic congestion. Reductions of fuel consumption are clearly observed in the inner area on weekdays on arterials.

- From the scenario that private cars in BMR replace by hybrid cars following the policy stated that “Hybrid car sales will be 25 % in 2031 of private cars,” promoting hybrid cars can reduce fuel consumption with the highest reduction percentages in 2026, equal to 474 kiloton of oil equivalent (ktoe), calculated to 4.47 % and 8.52% in comparison with all vehicles in BMR and only private cars, respectively.

- Examination of estimation of fuel consumption and its reductions from probe data are confirmed in reliability by comparing with the actual fuel consumption measured by field test and observed fuel consumption in transport sector during 2011 to 2015 obtained from Department of Alternative

Energy Development and Efficiency of Thailand (DEDE).

7.2 Recommendations

Since CO_2 emission in road transport sector is the problem concerned and fuel consumption is an input of its emission, CO_2 emission reduction by hybrid cars should be estimated for further study.

In addition, since an assumption that time sharing of driving modes is stable for future years is defined in this study, for better estimation, finding method to forecast time sharing of driving modes for future years should also be considered for further study.