IMPACTS ON CO2 EMISSION REDUCTION BY INTRODUCING HYBRID CARS IN A DEVELOPING CITY BASED ON PROBE INFORMATION AND MOBILE FUEL CONSUMPTION MEASURSMENT

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Since hybrid cars consume less gasoline, especially under traffic congestion situation, it is expect to reduce fuel consumption and CO2 emission from vehicles in developing cities. Those reductions should be estimated to understand more of its impacts of introducing hybrid cars, particularly in developing cities. As fuel consumption and CO2 reduction basically depend on driving patterns of vehicles, which locally fluctuate and unstable, the estimation method is difficult. Therefore, estimation method by using data from a lot of probe vehicles operated over the Bangkok Metropolitan and Region (BMR), which can reflect more accurately traffic conditions, is considered and applied in this study. The method to estimate CO2 emission is proposed based on probe information and mobile fuel consumption measurement by tested hybrid cars under the assumption that all probe vehicles be replaced by the hybrid ones. The fraction of duration in each driving mode is defined as "Time Sharing of Driving Modes" calculated as an input variable. As a result, CO2 emission rate increases by high stopping and crawling percentages caused by traffic congestion, and CO2 emission reduction impacts are clearly observed in congestion periods.

Key Words : *CO2 Emission, Time Sharing of Driving Modes, Hybrid Cars, Probe Vehicles*

1. INTRODUCTION

Carbon dioxide (CO2) is the essential part of greenhouse gas (GHG) emitted through human activities in many sectors such as power generation, industry, agriculture, as well as transportation. CO2 emissions from fossil fuel combustion in the transportation sector have received much attention[1)], especially road transportation accounted for 74% of the total emission, and they are continuously rising[2)]. Much or less CO2 emission in road transportation depends on activity rate investigated by distance traveled or fuel consumption of vehicles at that period[3)]. Then, CO2 emission can be calculated by multiplying these activity rates to emission factor of each vehicle and fuel type.

In addition, traffic congestion, as indicated by low average speed and non-smooth traffic flow by stopping/idling and moving behavior of vehicles, increase fuel consumption and CO2 emission[4), 5), 6)] because each vehicle is basically kept in idle and is still burning fuel even if it is not moving. Thus, these problems are necessary to concern for solving and reducing of fuel consumption and CO2 emission.

There are many countermeasures for low-carbon emission in transportation 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.

According to solving IMPROVE countermeasures, the auto industry has tried to develop a new generation of fuel saving and environmentally friendly vehicles. “Hybrid Vehicle” is one such vehicle and it has been brought to the auto market. Since a hybrid car consumes less gasoline, especially under traffic congestion, as the electric power can support during accelerating and cruising mode and its engine can stop operation when stopping/idling. Therefore, it is expected to reduce fuel consumption and CO2 emission by vehicles in developing cities, and amount of their reduction by introducing hybrid car should be estimated to understand its impacts. However, fuel consumption and emission rate, based on vehicle movement including hybrid cars, are deeply depended on driving situations.

Probe data are one of the real-world data, providing location, speed, direction, and time stamp, and can reflect the driving situations that locally fluctuate and are unstable depending on traffic conditions, especially in the metropolitan like Bangkok, Thailand. Traffic conditions in Bangkok vary by periods (peak, and off peak hours), by days (weekdays and weekends), by sub-area (inner and outer area), and by road categories (highways, arterials, and minor roads). Thus, field fuel consumption and CO2 emission are not easy to estimate.

Some research studied on implementing probe data to estimate fuel consumption and GHG emission by specifying driving patterns. Li et al.[8)] and Chang et al.[9)] applied the International Vehicle Emission (IVE) model to estimate real-time traffic CO2 emission based on probe data and road detectors in Beijing, China. There were findings of the impacts of using alternative energy based on probe data such as comparison of probe vehicle emissions and fuel consumption using diesel and 5% biodiesel (B5) blend[10)]. In these defined studies, speed and acceleration from probe data were used for separating into the bins/ranges and considering each separate case into the models. These studies could report fuel consumption and GHG emission in real-time in each roadway and period, and determine which speed range and acceleration is the most fuel consumed or reduced. However, from these literature, driving patterns or modes were not analyzed as to which one had the most impact, and they did not analyze the indicators of traffic congestion, such as % of idling or number of stops, affecting GHG emission in different conditions.

There are previous research conducting driving patterns to study their impacts on fuel consumption and GHG emision. Song et al.[6)] proposed the emission models by the relationship between emission factors, delay, and number stops at intersections on arterials. This study collected tested buses based on vehicle specific power (VSP) method that collected GHG emission and delay in to the bin in each 1 Kilowatt/ton, and considered GHG emission at mid-block arterial sections and minor road crossings. These parameters together with emission rate could be used to estimate emission factor based on samples of buses.

Smit et al.[11)] implemented traffic data from average speed received on each section to develop speed distribution method to predict GHG emissions. Speed distributions could help to predict more detail speed data affecting more accurate emission estimation.

Virginia Tech (VT) Models can predict fuel consumptions and GHG emission rates based on instantaneous speed and acceleration reflecting driving pattern by collecting field test data in each vehicle and fuel type. Rakha and Ding[12)] and Rakha et al.[13), 14)] also applied these models to study the impacts of stops and to estimate hot stabilized light-duty vehicles and trucks.

These studies by applying VSP, speed distributions, as well as VT Models could determine fuel consumptions and GHG emission rates varied by speed in different acceleration curves. Nevertheless, they considered only tested vehicles in the fields without sufficient data reflecting activity rates or driving patterns of all traffic system like probe data.

The Comprehensive Model Estimation (CHEM) was applied to the research of Zhang et al.[15)] to estimate vehicle emissions in work zone and rush hour congestion along freeway segment. Speed, acceleration, and location were collected by probe data, which were used for separating into the bins/ranges and considering each separate case into the models. This research could indicate fuel consumption and GHG emission in different vehicle operation modes but, it only focused on one freeway section without other types of roadways.

Recently, probe information detected by a lot of vehicles has been commercialized and operated every day and on every road category over Bangkok area. More details of this probe data can estimate fuel consumption and CO2 emission by vehicle acceleration from speed transition, which can be divided into 5 driving modes consisting of stopping, crawling, cruising, accelerating, and decelerating. In this study, the fraction of duration of each driving mode is defined as "Time Sharing of Driving Modes." Therefore, fuel consumption and CO2 emission estimation based on probe data, which is the representative of all vehicles in Bangkok, is possible to be studied and analyzed.

Although there was study on fuel consumption estimation based on time sharing of driving modes from probe data in Bangkok[16)], the scope of the study was limited to the central area. It did not consider crawling behavior of vehicles, considered only fuel consumption estimation. Also, there were using data in which time intervals are longer than 5 seconds affecting excessive cruising mode percentages.

By the gaps indicated by literatures, the objective of this study is to estimate CO2 emission by using time sharing of driving modes in various conditions based on probe data, and determine its reduction by the impacts of using hybrid vehicles in Bangkok Metropolitan and Region (BMR).

The structure of this paper is divided into 5 sections. After introduction, study design is the next section that explains study site and data collection. Then, time sharing calculations of probe data are presented. After that, estimation of CO2 reduction by hybrid vehicles is summarized. And, the final section is the conclusion.

2. STUDY DESIGN

(1) Study Site

Bangkok Metropolitan and Region (BMR), Thailand, was selected as the study site. BMR was divided into inner and outer BMR by differences in population and road network density, and land-use, as shown in Figure 1 (Above). Also, Figure 1 (Below) shows selected section on arterial, called Asokemontree road, for sectional emission estimation. This section is located between the Asoke Sukhumvit and Asoke Petchaburi intersection.

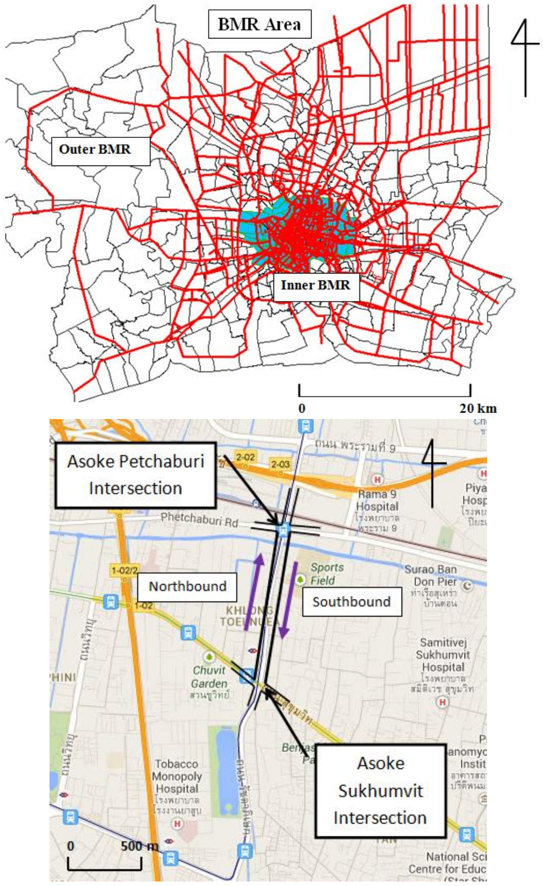


Fig.1 Study Site (Above), and Asoke Montree road (Below)

Different cases or 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[17)] and road categories (highways, arterials, and minor roads). Regarding road category, highways are motorways, expressways, and main highways where traffic flow is uninterrupted. Arterials are main roadways where traffic flow is interrupted by road crossings and signalized intersections. And minor roads are roadways that are the branches or minor roads of each arterial roadway.

(2) Data Collection

Probe vehicles was collected in 30 days during September to October, 2013 (21 days on weekdays and 9 days on weekends). In this study, speeds obtained from probe data, were separated into 7 ranges from 0, 1-10, …., to 51-60, and > 61 km/hr. These data were used to calculate time sharing of driving modes.

Mobile fuel consumption of hybrid cars was measured by using two tested vehicles in the field in order to represent fuel consumption under proposed driving modes. These data were collected on selected roadways from 13:00 to 19:00 on October 22nd (weekday) and 23rd (weekend), 2013. In addition, those two cars (TOYOTA PRIUS and TOYOTA CAMRY HYBRID), which had installed controller area network (CAN) interface, were run to collect the status of the vehicle and engine on selected road sections[18]. Then, mobile fuel consumption measurements obtained from CAN, together with GPS data, were recorded by data logger.

Finally, CO2 emission estimation, calculated from fuel consumption based on time sharing of driving modes from probe data, together with mobile fuel consumption measurement from CAN data in an ordinary case, was compared to the case in which all probe vehicles, assumed to be replaced by hybrid vehicles. Then, emission reductions in both cases were determined and discussed.

3. TIME SHARING OF DRIVING MODES CALCULATIONS

Time sharing diagrams of 5 driving modes, consisting of stopping/idling, crawling, accelerating, cruising, and decelerating between inner and outer areas, can be represented in **Fig.2** as examples on arterials on weekdays. Especially crawling mode, it is defined when (1) speed fluctuates in the range from 1 to around 10 km/h (speed can be more than 10 km/h, but previous and beyond speed collections are lower than 10 km/h), and (2) speed continuously increases, maintains, and decreases within 10 km/h at least 5 second intervals. This definition of vehicle crawling can represent the traffic congestion affecting increased fuel consumption, not only for stopping vehicles.

From the results in **Fig.2**, after considering crawling mode, increased percentages of congestion are readily seen that they account for almost 30% on arterials. If only stopping/idling percentages are considered, only a few impacts of congestion are seen in which its percentages are not greater than 10%.

For more understanding of the results, distributions (percentages) of driving modes among road categories and days are compared and determined which driving mode is the highest or most affected in evening peak, as the example shows in **Fig.3**. The results indicate that decelerating mode is the greatest percentage in most cases, while cruising mode is the second. Meanwhile, stopping and crawling mode increase in inner areas on weekdays and only on minor roads on weekends.

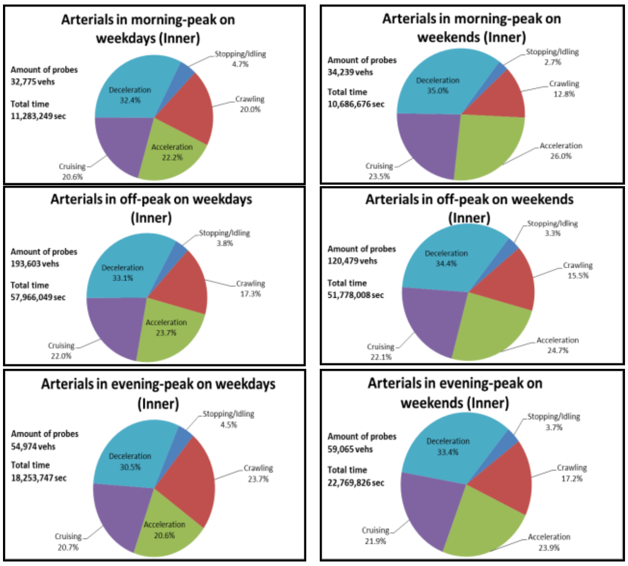


Fig.2 Time sharing diagrams between inner and outer BMR on weekdays on arterials

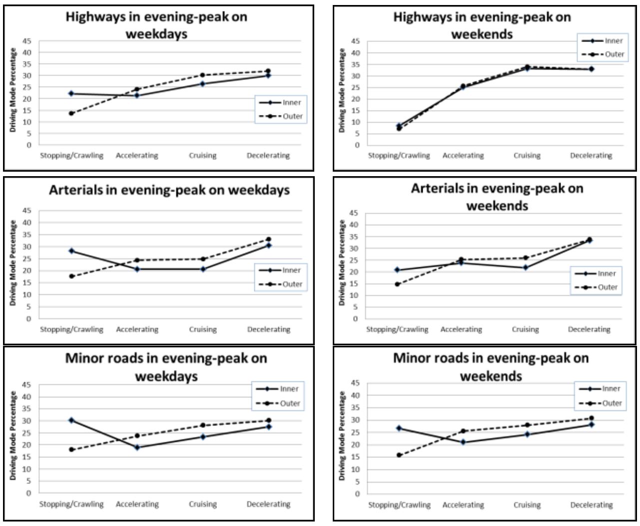
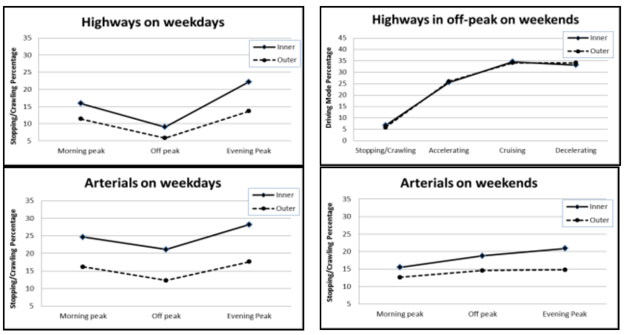


Fig.3 Driving mode percentages on each road category and days during evening peak

Furthermore, stopping and crawling mode affecting traffic congestion and fuel consumption can be represented in **Fig.4**, which shows the comparison of its percentage between the inner and outer areas in each case.



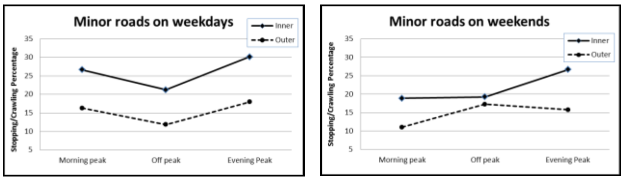


Fig.4 Stopping/Crawling percentages on each road category and days

From the results in **Fig.4**, stopping and crawling percentages in the inner areas are greater than in the outer areas in all cases. In addition, on weekdays, evening peaks are at the highest percentage of stopping and crawling, and the trend lines of its percentages look like a V-shape from in the morning to evening peak in all cases, except on highways in the outer area in which the morning peak is the lowest. Meanwhile on weekends, stopping/crawling percentage in the morning peaks are lower than those in the off-peak and evening peak, except on highways in the inner area in which the morning peak is the highest.

4. CO2 EMISSION ESTIMATION AND REDUCTION BY THE IMPACTS OF USING HYBRID VEHICLES

(1) Estimation Process

Before CO2 emission estimation, fuel consumption as the activity rate is calculated in the first step. By collecting mobile measurement by CAN data, fuel consumption wastes (CC/sec) can be calculated in different days of week (weekday and weekend), and periods (peak hours and off-peak). Fuel consumption wastes of 2 types of tested hybrid cars (TOYOTA PRIUS and CAMRY HYBRID) in each driving mode, speed range, and indicated time frequency (sec), in case of hybrid system operated (ON) or in-operated (OFF), during peak hours on weekday, are summarized as examples in **Table 1.** and **2.**.

Based on the **Table 1.** and **2.**, fuel consumption from probe data on each driving mode can be estimated by Equation (1) with hybrid system and Equation (2) without hybrid system.

Table 1 Fuel consumption waste results of TOYOTA PIRUS HYBRID from CAN data

Driving Modes	Stopping/Idling				Crawling				Accelerating			
Speed Range (km/h)	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec
0	0.25	344	0	1903	-	-	-	-	-	-	-	-
1-10	-	-	-	-	0.89	88	0	311	1.06	16	0	18
11-20	-	-	-	-					1.36	82	0	44
21-30	-	-	-	-	-	-	-	-	1.78	130	0	6
31-40	-	-	-	-	-	-	-	-	2.16	92	0	0
41-50	-	-	-	-	-	-	-	-	2.22	74	0	0
51-60	-	-	-	-	-	-	-	-	2.15	43	0	0
>61	-	-	-	-	-	-	-	-	1.47	15	0	0

Driving Modes	Cruising				Decelerating			
Speed Range (km/h)	ON	sec	OFF	sec	ON	sec	OFF	sec
0	-	-	-	-	-	-	-	-
1-10	0.57	8	0	36	0.62	11	0	52
11-20	0.89	25	0	42	0.53	38	0	89
21-30	0.90	58	0	17	0.53	55	0	55
31-40	0.94	19	0	5	0.54	38	0	35
41-50	0.88	42	0	4	0.51	25	0	32
51-60	1.19	16	0	3	0.49	14	0	21
>61	1.29	16	0	0	0.60	10	0	1

Table 2 Fuel consumption waste results of TOYOTA CAMRY HYBRID from CAN data

Driving Modes	Stopping/Idling				Crawling				Accelerating			
Speed Range (km/h)	ON	sec	OFF	sec	ON	sec	OFF	sec	ON	sec	OFF	sec
0	0.25	688	0	2550	-	-	-	-	-	-	-	-
1-10	-	-	-	-	0.52	281	0	239	1.00	38	0	18
11-20	-	-	-	-					1.14	128	0	36
21-30	-	-	-	-	-	-	-	-	1.39	105	0	18
31-40	-	-	-	-	-	-	-	-	1.71	91	0	6
41-50	-	-	-	-	-	-	-	-	1.90	72	0	6
51-60	-	-	-	-	-	-	-	-	2.20	33	0	3
>61	-	-	-	-	-	-	-	-	2.38	41	0	0

Driving Modes	Cruising				Decelerating			
Speed Range (km/h)	ON	sec	OFF	sec	ON	sec	OFF	sec
0	-	-	-	-	-	-	-	-
1-10	0.46	30	0	25	0.42	46	0	51
11-20	0.67	64	0	35	0.45	56	0	85
21-30	0.76	33	0	27	0.44	45	0	66
31-40	0.81	29	0	13	0.57	34	0	51
41-50	0.88	50	0	14	0.47	40	0	25
51-60	0.93	5	0	3	0.48	16	0	5
>61	1.35	21	0	0	0.65	22	0	0

- For with hybrid system (With HV) and engine ON

$$FC_{ON}^{WithHV} = FC_{Speed\ and\ Mode\ (ON)} \times TS \times \frac{Freq_{on}}{Freq_{on} + Freq_{off}} \tag{1}$$

- For without hybrid system (Without HV)

$$FC_{OFF}^{WithoutHV} = FC_{Speed\ and\ Mode\ (ON)} \times TS \tag{2}$$

Where

FC_{ON}^{WithHV} = total fuel consumption for With HV during engine ON (CC)

$FC_{WithoutHV}$ = total fuel consumption for Without HV (CC)

$FC_{Speed\ and\ Mode\ (ON)}$ = fuel wasted for each speed range and driving mode during engine ON (CC/sec)

TS = total time sharing in each driving mode from probe data

$Freq_{on}$ and $Freq_{off}$ = time frequency (sec) of hybrid engine when it is operated (ON and OFF)

From Equation (1) and (2), after total fuel consumption in each type of hybrid cars is estimated in all conditions, the results are calculated in average in order to be the representative value of 2 types.

Then, total CO2 emission can be calculated by multiplying fuel consumption to CO2 emission factor, as shown in Equation (3)[3].

Total CO2 emission = FC x *Emission Factor* (3)

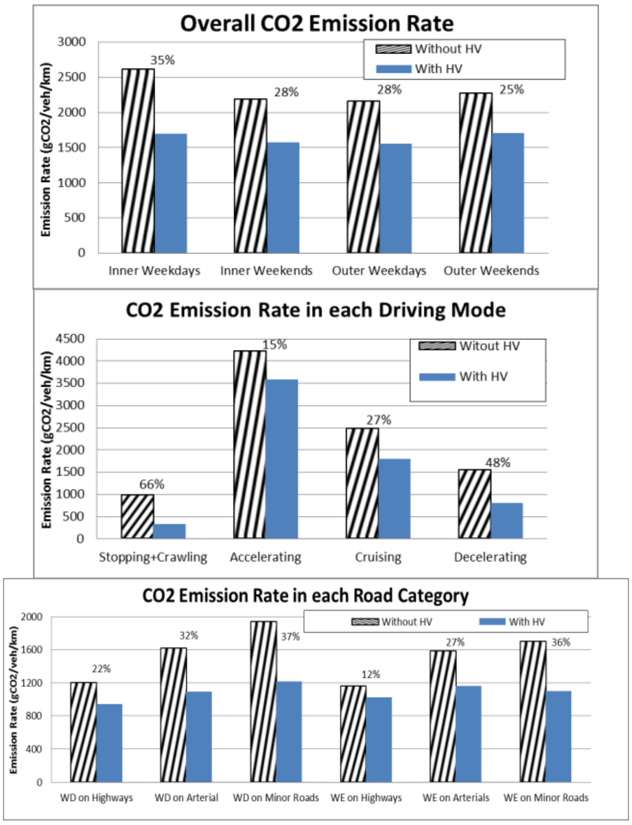
For how to identify emission factor in this study, since tested hybrid cars consume gasoline, default CO2 emission factor of motor gasoline, which is equal to 69,300 kgCO2/TJ[3], is used in this study. However, the unit of fuel consumption calculated in this study is the volume of fuel consumed, not calorific value of fuel consumed. Thus, the value from IPCC[3] should be converted to volume unit. Department of Alternative Energy Development and Efficiency, Ministry of Energy of Thailand indicated that gasoline releases calorific value equals to 7,420 kilocalories (kcal) per 1 liter of fuel consumed[19]. Then, the unit of kcal can be converted into Joule (J). As a result, CO2 emission factor of gasoline equals to 2.18 gCO2/CC of fuel consumed as the multiplier for CO2 estimation in this study.

For effectiveness analysis, total CO2 emission is divided by vehicle kilometer traveled (VKT) of probe vehicles to obtain CO2 emission rate, as shown in Equation (4).

$$CO2\ Emission\ Rate = \frac{Total\ CO2\ emission}{Vehicle\ Kilometer\ traveled\ (VKT)} \qquad (4)$$

(2) CO2 Estimations Results

Emission rates and reduction percentages (difference percentages between without HV and with HV rates) are summarized in 3 cases (overall, road category, and driving mode), as shown in **Fig.5**.



Note: WD = weekdays, WE = weekends

Fig. 5 CO2 emission rate results in each consideration

From overall results, the greatest emission rate is in the inner area on weekdays in without HV. The second are in inner area on weekends and outer both weekdays and weekends, which are not significantly different. When road category is considered, the greatest emission rate is on minor roads on weekdays in which the average speed is low. The seconds are on minor roads on weekends and arterials on weekdays and weekends. Regarding reduction percentages, they have the most impact on the greatest emission in overall and road category cases.

High emission rates from overall and road category cases correspond to high stopping and crawling percentages from time sharing results. Thus, they can indicate that CO2 emission increases when traffic is congested measured by time sharing of driving modes, as according to previous research[4].

Regarding driving modes, the greatest emission one is during accelerating in without HV and with HV cases. However, in term of emission reduction, stopping and crawling modes are the most effective by 66% reduction.

For more understanding of emission rates in each speed range, **Fig.6** and **Fig.7** represent overall emission rate comparing between inner and outer area and emission rate among road categories in inner area, respectively. Generally, although CO2 emission rates depend on speed and acceleration, fuel consumption, which is the activity rate estimated by time sharing of driving mode in this study, is also an important factor affecting CO2 emission rates depending on traffic conditions in inner and outer area as well as road categories.

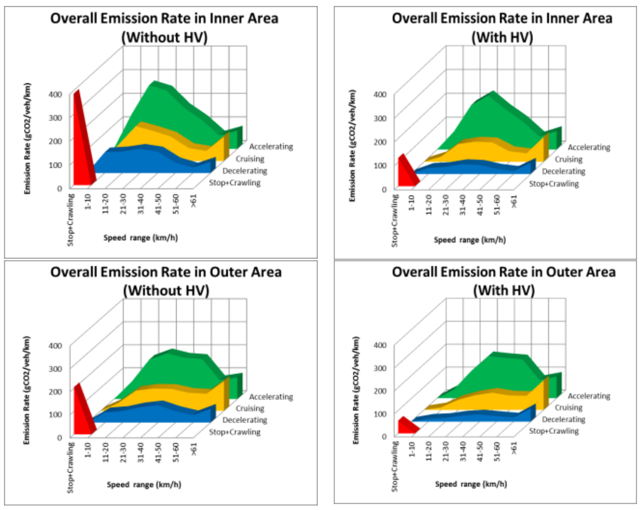


Fig.6 Overall emission rates in each speed range

In **Fig.6**, emission rates in inner area (Above) are greater than in outer area (Below), and With HV case (Right) in inner area can obviously reduce CO2 emission, especially on stopping + crawling mode. Moreover, accelerating mode between 11-30 km/h, and stopping + crawling mode in Without HV cases (Left) emit much CO_2.

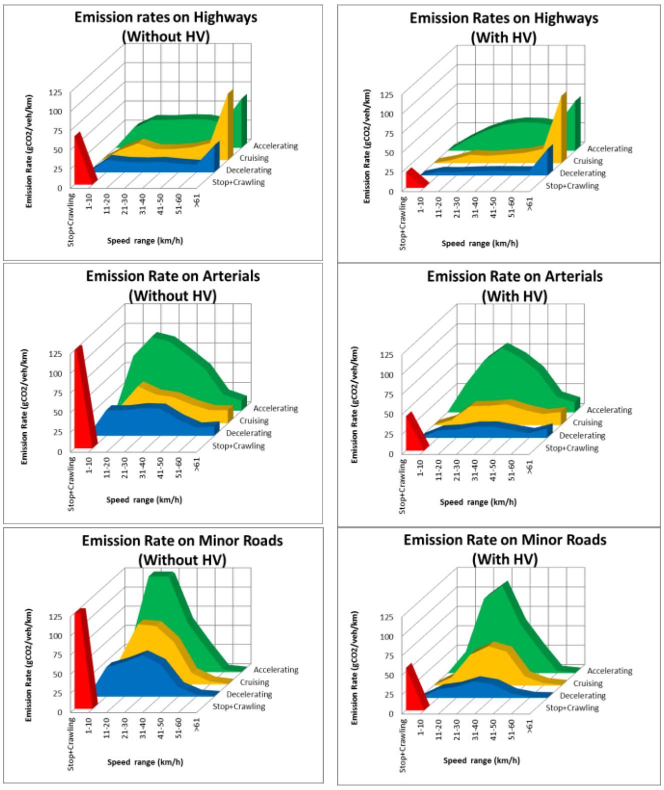


Fig.7 Emission rates in each speed range in each road category

In **Fig.7**, stopping + crawling mode and accelerating mode emit much CO_2 in all road categories, especially in Without HV cases (Left). Regarding accelerating mode, on highways, CO_2 emission rates increase when speed increases. On arterials, emission rates are the highest when speed range is 11-20 km/h. And on minor roads, there are high emission rates in the lowest speed range (1-10 km/h). In With HV cases (Right) and all road categories, CO_2 emission reduction can obviously observed, especially on stopping + crawling mode.

When CO_2 emission is considered within the selected section on arterial, time sharing of driving modes and CO_2 emission rate, divided by distance in each 100 meters, can be shown in **Fig.8**. Sectional emission rates are estimated by 8 probe vehicles moving in northbound direction on 22nd October 2013, during 15:00 - 16:00.

In **Fig.8**, the greatest emission rate occurs in the the first 100 and 200 meters from the stopline of the intersection. More emission rates are related to more stopping and crawling percentages from time sharing results and congestion queue from observation. After hybrid cars are proposed, CO_2 reductions in the ranges of 100 and 200 meters from the intersection are significant. That means if traffic operators can find out suitable solution to relieve traffic congestion or delay near the intersection, CO_2 emission can be reduced significantly.

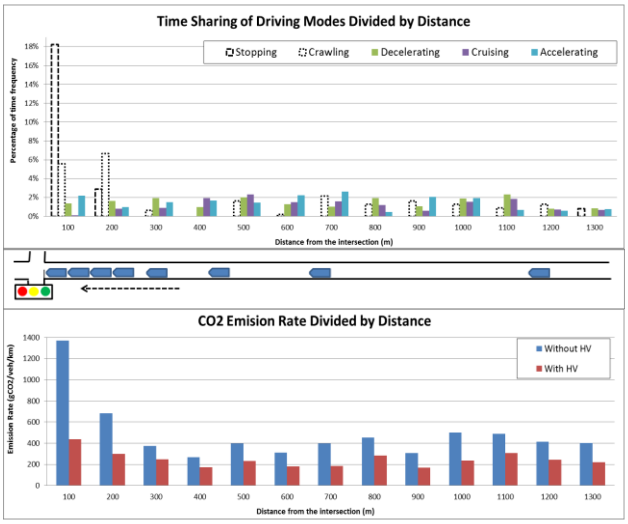


Fig.8 Time sharing of driving modes (Above) and CO_2 emission rate divided by distance (Below)

5. CONCLUSSION

This study aims to estimate CO_2 emission by using time sharing of driving modes in various conditions based on probe data, and determine its reduction by the impacts of using hybrid vehicles in Bangkok Metropolitan and Region (BMR). The method to estimate CO_2 emission is considered from both Business As Usual (BAU) case and replacing hybrid vehicles case in all probe vehicles for finding the emission reduction impacts.

As a result, the greatest emission rate is in the inner area of BMR on weekdays in without hybrid system case. Regarding road category, the greatest emission rate is on minor roads on weekdays. These results correspond to high stopping and crawling percentages from time sharing calculations in the initial analysis. The driving mode affecting high CO_2 emission rate is during accelerating. If hybrid vehicles replace all probe vehicles, emission reduction impacts are clearly observed in the inner area on weekdays, on minor roads, and on stopping/crawling mode. Moreover, when sectional emission on arterial is analyzed, the greatest emission rate occurs in the the first 100 and 200 meters from the stopline of the intersection. Also, CO_2 reductions in the same distances are significant. Consequently, hybrid vehicles can help to reduce CO_2 emission in congestion periods that are high stopping/crawling percentages.

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