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An Investigation of Fuel Economy Potential of Hybrid Vehicles under Real-World Driving Conditions in Bangkok

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Abstract

This study attempted to investigate fuel economy performance of hybrid vehicles under real-world driving conditions in Bangkok. The effect of traffic conditions and driving styles were taken into account. To cover the variations in traffic conditions, city, suburban and highway traffic were selected to represent the variety of traffic flow. For the effect of driving styles, the experiment was conducted by four experienced drivers, two aggressive and two normal-calm drivers. Statistical parameters, average speed and acceleration noise, were employed to quantify and analyse the impact of Bangkok traffic conditions and driving styles on both vehicles' fuel consumption. This study integrated microtrip segmentation technique into the data analysis. Experimental results illustrated that HVs were capable of reducing fuel consumption of CVs in all traffic conditions and driving styles covered by this study. Particularly in the congested traffic in Bangkok, HVs potentially decreased the fuel consumption by a maximum of 47.3%. More importantly, HVs greatly mitigated the effect of aggressiveness on excessive fuel consumption in practical driving habits, although they appeared to be more sensitive to aggressiveness than CVs.

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Keywords: hybrid vehicle, conventional vehicle, fuel consumption reduction, traffic condition, driving style

1. Introduction

Globally, the transportation sector has contributed to one-third of overall energy consumption; however, in metropolitan areas, the transportation energy consumption has critically increased due to a large amount of vehicle intensity [1]. In metropolitan Bangkok, the statistics from the past five years have shown that the consumption level has dramatically risen to approximately 70%, which has caused more than 90% of the overall city's Greenhouse gas (GHG) emissions [2]. Over the past decades, several academic studies have showed that powertrain technologies, traffic conditions, and driving styles were fundamental causes of excessive fuel consumption and emissions [3,4]. Still, a number of papers have

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shown that electrified vehicles have a potential to decrease and manage the on-road energy consumption and GHG emissions of conventional vehicles (CVs), especially in city drives [3, 5, 6]. In Thailand, there are only hybrid vehicles (HVs) available in the car market, and the number of HVs is still in small demand.Thus, this study attempted to investigate the fuel consumption reduction potential of HVs under real-world Bangkok conditions which included the impact of local traffic conditions and driving styles. Bangkok conditions and presented the fuel consumption characteristics analysis.

In 2012, Raykin et al. attempted to evaluate the impact of traffic conditions, city, suburban, highway, in Toronto on tank-to-wheel energy. This study generated the representative city, suburban, and highway driving cycles from real-world driving data. Then Autonomie software was used to simulate fuel consumptions of HVs and CVs. As a result, the fuel consumption of HVs was lower in all traffic conditions. For HVs, the best fuel economy was in city traffic, and the worst fuel consumption was in highway traffic, which was the opposite of CVs' fuel consumption trend. In 2007, Sharer et al. studied the impact of aggressive driving on CVs and HVs' fuel consumption sensitivity. The study utilized UDDS and HWFET which were well-known standard driving cycles. To adjust driving aggressiveness, the driving cycle speed profiles were multiplied by scaling factors, 0.8, 1, 1.2, 1.4 and 1.6. Then the adjusted driving cycles were imported to PSAT vehicle simulation to calculate the fuel consumption. The result showed that the aggressiveness directly had an effect on the vehicles fuel consumption, and HVs were more sensitive to the variation of aggressiveness than CVs. In 2013, Neubauer and Wood took traffic conditions and driving styles into account. This study obtained real-world driving data from the NERL Secure Transportation Data Center. However, the energy consumption of CVs, HVs, plug-in hybrid and electric vehicles were calculated by ADVISOR vehicle simulator. The initial powertrain specification parameters were iteratively simulated, such as engine, motor, and battery. For analysis, the fuel consumption results were shown in scatter plots of average speed and average acceleration with a color gradient of percentage of energy consumption. However, while the method of analysis meant that it was simple to understand the energy consumption characteristics, using the percentage of energy consumption meant that it was not possible to compare the results of CVs and HVs. In order to improve the results of the former studies to become more realistic, many researchers included the effect of traffic conditions and driving styles in the analysis [5, 7- 9] and conducted the tests based on the real-world traffic and fuel consumption measurement [7-10]. Therefore, this study attempted to (1) investigate the fuel saving potential of HVs compared to CVs under traffic conditions and driving styles in Bangkok, and (2) compare the fuel consumption characteristics of CVs and HVs at similar driving conditions and provide explanations of operation fundamentals of HVs' powertrain.

2. Methodology

3.1. Route and driver selection

To capture the variety of driving situations in Bangkok, average speed, number of vehicles at peak hours, and locations were taken into account [6, 13, 14]. All the major routes in Bangkok were clustered into three traffic conditions, city, suburban and highway, by the average speed based on Bangkok transportation statistics 2012 [15]. The routes in which the average speeds less than 20 km/h, between 20-60 km/h, and above 60 km/h were clustered in city, suburban and highway traffic conditions respectively. Then, in each traffic condition, the routes that had the highest utilization were selected. In Fig.1., the representative routes were Silom and Sathon Nuea, Rama 3, and Motorway 7 of which the orientations covered three different major areas. The red and blue areas indicated the inner city and downtown business zones. The brown, orange and yellow classified the density of inhabited areas varying from densely to sparsely, respectively [16].

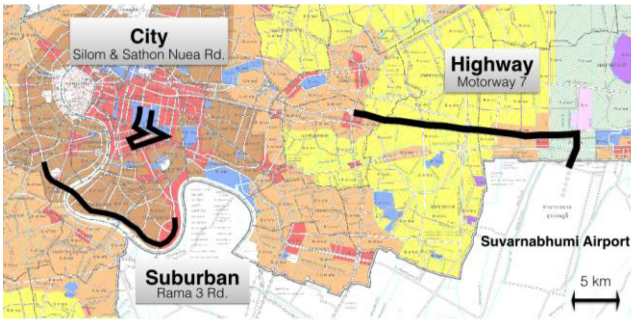


Fig.1. Representative routes' orientation. [16]

For traffic conditions of the representative routes, the nature of traffic usually has high stop/km and long idling duration at low speed. On the other hand, stop/km and idling duration become lower when average speed increases [4]. Therefore, average speed, stop/km and %idling were used to indicate traffic conditions in this study, which are described in Table 1.

Table 1. Traffic conditions' characteristics [based on normal-calm driving style]

Route	V_{avg} *(km/h)*	*Stop/km*	*%idle*
City	*5-10*	*7-10*	*37-46%*
Suburban	*35-39*	*0.17-0.39*	*11-18%*
Highway	*65-76*	*0*	*0*

Four experienced drivers were employed for the experiment, two aggressive drivers and two normal-calm drivers, in order to capture the impact of aggressive and normal-calm driving on fuel consumption. Table 2. describes the characteristics of the drivers in the three traffic conditions by using the maximum acceleration and the maximum speed [7].

Table 2. Drivers' characteristics

Traffic conditions	*Normal-calm*		*Aggressive*	
	A_{max} *(g)*	V_{max} *(km/h)*	A_{max} *(g)*	V_{max} *(km/h)*
City	*0.13-0.16*	*37-45*	*0.18-0.38*	*39-75*
Suburban	*0.13-0.17*	*79-90*	*0.28-0.37*	*131-169*
Highway	*0.04-0.16*	*97-115*	*0.16-0.25*	*159-167*

3.2. Experimental set-up

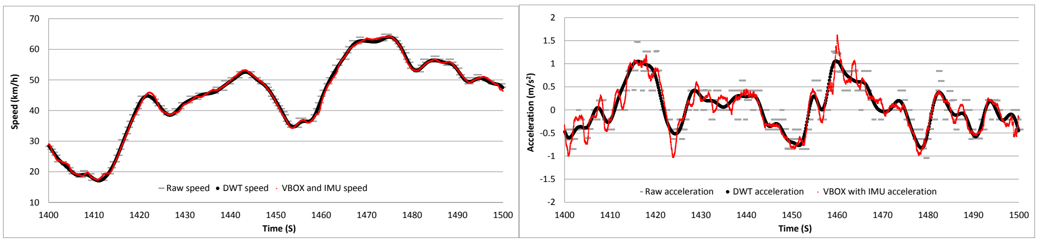
For the test vehicles, 2014 Toyota Prius and 2015 Toyota Corolla Altis were selected to represent HVs and CVs respectively. Both vehicles had engine size of 1,789 cc, and were the dominant vehicle size in Bangkok. The Prius weight was 120 kg more than the Altis weight due to the additional 60 kW electric motor and 1.31kW Ni-MH battery. For the vehicles initial preparations, the air conditioners of both vehicles were set to automatic mode at 25°C. The tires were inflated at the recommended specifications in order to avoid speed-measurement error. For the carry-on load, passengers were limited to 2 persons per vehicle including the driver. The test started when Prius' battery reached 51% state of charge and the driving mode was selected to normal. The two vehicles were released simultaneously on the same route. To avoid negative effects of car-following method, the drivers were assigned to keep the vehicles flowing along the traffic naturally. The test was conducted 12 times for each vehicle. The drivers who had the same driving style were asked to switch the vehicles in order to compensate for the effect of different acceleration response between the vehicles. The test distance covered more than 400 km.

3.3. Data acquisition and processing

Vehicle Interface Module (VIM) and Global Tech Stream (GTS) software were installed to record vehicle data, such as vehicle speed, engine revolution, fuel injection amount, and engine on-off condition. The data recorder was connected via on-board diagnostics (OBD) port with sampling rate at 8.5 Hz.

One of the most important primary data is velocity and its corresponding acceleration. An option to obtain more accurate vehicle speed is to use VBOX integrated with Inertia Measurement Unit (IMU). However, for the study that covered city and suburban areas, such as the present study, the obstruction of the satellite signal from tall buildings, bridges, trees, or tool ways was found to be too frequent for efficient and accurate data gathering, and the roughness of the routes' surface in Bangkok also caused undetectable random noise to the IMU signal. Thus, the decision was made to determine if the use of vehicle speed from OBD provides sufficient accuracy for the present study.

Fig.2. (a) shows that the vehicle speed from OBD (raw speed) was quite accurate compared to the vehicle speed from VBOX and IMU. Note that the speed sensors in the vehicles came with 1km/h resolution. This discrete nature of the OBD speed data incurred significant errors in the acceleration calculation process. To improve quality of the data, Discrete Wavelet Transform (DWT) was implemented to OBD speed data to decrease the discreteness. DWT is developed based on Fourier transform technique. [17] Wang and Zhang (2009) suggested that DWT was more flexible to apply to non-uniform signal, such as real-world driving data, and effective in magnetic pick-up speed sensor. In this study, Daubechies number 5 at the 4th level was the initial set-up for the vehicles speed DWT. Fig.2. (a) and (b) show the improvement of speed and acceleration data respectively after applying DWT. Moreover, average speed and acceleration noise were calculated from DWT speed and acceleration in order to find the correlation between the data from DWT and VBOX integrated with IMU. The correlation was found at 0.97.



(a) (b)

Fig.2. (a) The comparison among DWT speed and raw speed, and VBOX and IMU speed data; (b) The comparison among DWT acceleration and raw acceleration, and VBOX and IMU speed data

3.4. Data interpretation

This study introduced microtrip segmentation technique. Microtrip is defined as a series of speed data between start and stop points, which is commonly used in driving cycle construction and driving pattern recognition [8, 10]. Decomposing data length allows statistical parameters to identify the core characteristics of a mocrotrip more precisely than a long trip, and also increases the statistic data.

To understand HVs and CVs' fuel consumption characteristic under local traffic conditions in Bangkok, average speed was selected to indicate the congestion level as a conventional parameter due to its strong correlation with fuel consumption. To quantify the aggressiveness in driving styles, most of the parameters are mainly related to vehicle's acceleration, such as maximum acceleration, average acceleration, standard deviation of acceleration, and others. However, Ding and Rakha (2002)[9] introduced a concept of comparing aggressive driving styles to noise of a traffic flow. They utilized acceleration noise parameter, which is a combination of speed and acceleration as shown in equation (1). Thus, acceleration noise tends to dramatically increase when a driver applies high acceleration at high speed, which corresponds to fuel consumption. This parameter has become more acceptable in quantifying the aggressiveness of drivers and evaluating the stability of driving. [12] Therefore, the driving aggressiveness in this study was quantified by acceleration noise. Fig.3. illustrates the meaning of acceleration noise. The graph shows an example of microtrips which have similar average speed (km/h) but at different acceleration noise (m/s^2). The blue solid line and green dash line are speed and acceleration of the vehicle. It is noticeable that microtrips with higher acceleration noise tended to have longer time-spent on higher speed and harder acceleration.

$$A_{noise} = \sqrt{\frac{\sum_{i=1}^{n} a_i^2 v_i}{\sum_{i=1}^{n} v_i}} \qquad (1)$$

where A_{noise} and a_i are acceleration noise and instantaneous acceleration in a unit of m/s^2, v_i is instantaneous speed in a unit of km/h.

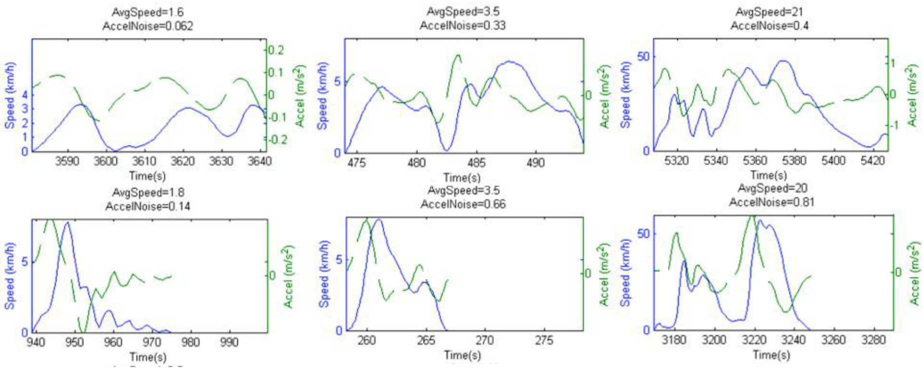
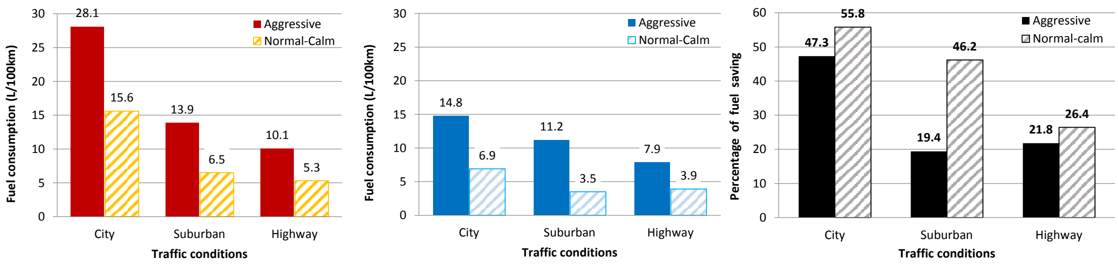


Fig.3. The comparison of microtrips at similar average speed but different acceleration noise

3. Results and discussion

Fig.4, comparing between (a) and (b), shows that HVs were capable of reducing fuel consumption from CVs in all tested traffic conditions and driving styles. However, the trend of HVs' fuel consumption in all traffic was different from Raykin et al. (2013)'s study. HVs consumed highest fuel consumption for city traffic, and lowest for highway traffic, which was consistent to CVs' fuel consumption trend. For the driving styles, aggressiveness significantly increased fuel consumption of both vehicles about 100% in all traffic except for HVs suburban's fuel consumption. The aggressiveness significantly increased HVs' fuel consumption in suburban to approximately 220% compared to normal-calm driving. HVs appeared to be slightly more sensitive to driver's aggressiveness in terms of fuel consumption than CVs. Fig.4. (c) showed the percentage of fuel saving potential of HVs based on CVs' fuel consumption, which varied between 55.8% to 19.4% depending on traffic conditions and driving styles. For normal-calm driving style, HVs reached the highest potential to reduce fuel consumption of CVs for city traffic at 55.8% and slightly decreased for suburban and highway traffic to 46.2% and 26.4% respectively. For aggressive driving, fuel saving potential of HVs dropped to 47.3%, 19.4% and 21.8% for city, suburban and highway respectively, because HVs were more sensitive to aggressive driving.



(a) *(b)* *(c)*

Fig. 4. (a) CVs' fuel consumption comparison between aggressive and normal-calm driving styles in the three traffic conditions; (b) HVs' fuel consumption comparison between aggressive and normal-calm driving styles in the three traffic conditions; (c) The percent of fuel saving of HVs over CVs in all driving conditions

To illustrate CVs and HVs fuel consumption characteristics in more detail, Fig.6. shows the relationship between fuel consumption, traffic conditions and driving styles. Each data point represents data of a microtrip that was segmented from the representative routes. The overall fuel consumption of HVs at the same average speed and acceleration noise levels appeared to consume less fuel than CVs; however, both vehicles still shared several similar trends. According to the results from Fig.6., average speed tended to have a strong impact of fuel consumption on both vehicles; the fuel consumption dramatically increased as the average speed decreased. As well as driving styles, the impact of aggressive driving also presented on both vehicles' fuel consumption as rising trends, which could be seen clearly only in CVs and HVs at average speeds higher than 15 km/h.

Focusing on the low average speed data, HVs' data points in Fig.6 (b) aligned differently from CVs, which were more densely grouped in every average speed interval. HVs' data points spread vertically all over the region from zero to maximum fuel consumption rates. This characteristic of HVs occurred due to the variation of the HVs' motors and the engine proportion. The proportion of electrical and petrol drives depended on operation fundamentals of HVs' powertrain, which could be determined by the instantaneous vehicle speed, the percent stage of charge (SOC) of the high voltage battery and the position of the acceleration pedal. From the observation, the vehicle speed was the primary factor which could be used to separate the HVs' powertrain operation to two conditions, which were speed approximately below 60 km/h (low speed condition) and speed approximately above 60 km/h (high speed condition).

In the low speed condition, such as low average speed microtrip and idling, the proportion of electric and petrol drives were determined by %SOC and the position of the acceleration pedal. %SOC always fluctuated between 39% to 51%, approximately. When %SOC was lower than 39%, the engine was started to generate electricity, and when %SOC reached 51%, the engine was shut down. In the meantime, the position of the acceleration pedal was detected. It was found that when the driver pressed the pedal harder than 20-30% of the stroke (The position depended on the current speed corresponding to the current vehicle's power demand), the engine was started to respond the desired power. Moreover, during the engine was on, when the required propulsion power was lower than the operating engine power, the excess energy was stored in the high voltage battery. On the other hand, when the required propulsion power was greater than the operating engine power, the motor assisted the engine instead. It was essential to note that the concept of operation fundamentals of HVs' powertrain does not attempt to prolong electric driving range as much as possible, but it attempts to operate the motors and the engine in their most efficient regions, and to compensate for each other's shortcomes while maintaining its performance.

The fuel consumption of HVs in the low speed condition is showed in Fig.6. (b). It was found that the microtrips for which average speeds were below 15 km/h usually had maximum speeds lower than 60 km/h. Therefore, all the microtrip data for which average speeds were below 15km/h could be determined in the low speed condition. The variation of HVs' fuel consumption characteristics was presented in the Fig.6. (b) at the average speed less than 15 km/h. The percentage of pure-electric drives at average speeds less than 3 km/h to between 10-15 km/h were found to be 34.5%, 31.8%, 48.0%, 11.1% respectively. As a result, these pure-electric microtrips significantly decreased fuel consumption in city traffic, where the data usually consisted of several low average speed microtrips. The scattered data above the zero fuel consumption line occurred due to the random start of HVs' engine. The variation in fuel consumption of the data occurred because of the variety of the motors and engine proportion, which were subjected to %SOC and the acceleration pedal position at each moment.

For the microtrips at average speed higher than 15km/h, the driving speed frequently exceeded 60km/h, which caused the HVs' engine to start and operate mainly during the high speed drives. As a result, the HVs' data shared similar rising trends to CVs', and the percentage of fuel saving on suburban and highway in Fig.5. decreased from 47.3% to 19.4% and 21.8% respectively. In addition, while the engine was running at the high speed condition, the battery was charged until %SOC reach up to 70-75% on the highway tests.

For driving styles, there was some evidence showing that driving styles also had a major impact on vehicle fuel consumption. In Fig.6., at the same speed range, as the acceleration noise increased, the fuel consumption also increased with a constant slope. This characteristic occurred with both vehicles except for HVs at speeds less than 15km/h.

At the low average speed microtrips, aggressive drivers tended to press the acceleration pedal harder than normal-calm drivers, so the engine started more frequently. As a result, this behaviour caused the data points of microtrips at average speeds less than 15 km/h to separate into two clusters, which were pure electric drive and petrol drive clusters. It was found that all pure-electric microtrips belonged to normal-calm drivers. The petrol drive clusters which were in microtrips' average speed less than 3 km/h to 10-15 km/h had average fuel consumption at 49 l/100km, 35 l/100km, 16 l/100km, 9.4 l/100km respectively, which were slightly lower than CVs' fuel consumption levels, 50.3 l/100km, 36.9 l/100km, 24.5 l/100km and 17.2 l/100km respectively. It meant that HVs had the ability to maintain pure-electric drive during low average speed trips, which was the key to fuel saving; however, aggressive driving should be avoided in these low speed driving patterns due to excessive fuel consumption from engine start. For the overall data range, it was noted that the boundaries of HVs' acceleration noise in all average speed ranges were lower than CVs, which explained Fig.5. that HVs had not only higher fuel efficiency but also ability to alleviate driving aggressiveness levels. The result also corresponded to HVs' acceleration pedal characteristic that was intentionally designed to have lower sensitivity than normal vehicles.

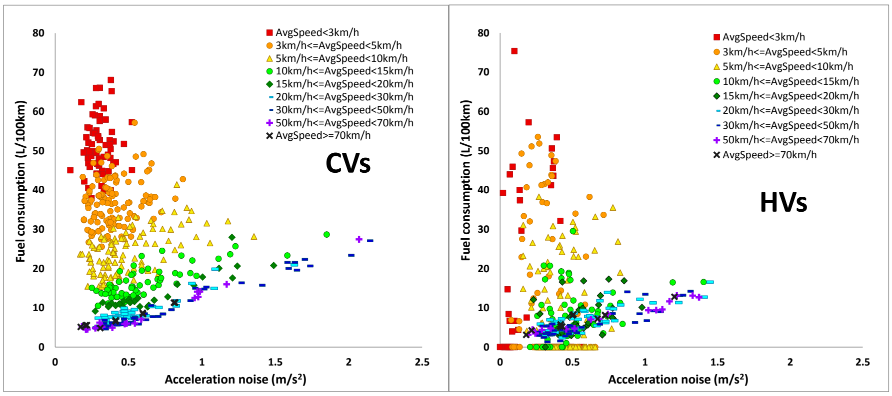


Fig.5. (a) CVs fuel consumption characteristics; (b) HVs fuel consumption characteristics

4. Conclusion

HVs were capable of reducing fuel consumption of CVs in all tested traffic conditions and driving styles in Bangkok. In city traffic with normal-calm driving styles, HVs achieved the greatest fuel consumption reduction, almost 56%, from CVs in city traffic and approximately 46% and 26% in suburban and highway traffic respectively. It was important to note that aggressive driving should be avoided in all traffic conditions, because it significantly increased fuel consumption up to 100% for CVs and 200% for HVs. For driving styles, HVs appeared to be more sensitive to aggressive driving in terms of percentage of excessive fuel consumption compared to CVs.

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