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ORIGINAL ARTICLE

Fuel Consumption of Passenger Cars at Different Levels of Traffic Congestion and Traffic Conditions in Urban Cities of Sarawak

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ABSTRACT – The ever-increasing number of road users has caused traffic congestion to become more prominent, especially in urban environments. This is also causing the consumption of fuel to escalate rapidly. Numerous fuel economy studies were undertaken in Malaysia but mainly focused in Peninsular Malaysia region only. The fuel consumption results may not represent the actual fuel consumption in Sarawak due to differences in term of topographical factors between these regions. This paper aims to evaluate the fuel consumption of passenger cars in Sarawak under different congestion levels and traffic conditions. Perodua Bezza and Perodua Myvi were used as test vehicles to collect the speed profiles. The Comprehensive Modal Emissions Model (CMEM) was used to estimate the fuel consumption as well as to evaluate the contribution of specific vehicle operation on the total fuel consumption based on the speed profiles being obtained. It was found that the fuel consumption increased proportionally with the congestion level and the highest consumption occurred during peak-hours for the moderately and severely congested route. Acceleration accounted the largest fraction of fuel consumption, especially as the vehicle starts to accelerate from idling condition or at low vehicle speed of less than 5 km/h.

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INTRODUCTION

The ever-increasing number of vehicles on the road in the world today translates to a great surge in fuel consumption and negatively impact the environment and human health due to increased carbon emissions [1],[2]. It was reported that transportation sector contributes to about 27% of global energy consumption, in which light-duty vehicles that include passenger cars, account to a significant 70% of the consumption of fuel in this sector [3]. In Malaysia, land transportation accounts up to 90% of the total carbon emission from the transportation sector and up to 70% of the emissions is attributable to light-duty vehicles, indicating that such vehicles contribute the most towards the total fuel consumption [4],[5]. This situation will get even worse with increasing levels of traffic congestion as the consumption of fuel will also be increased [6]. Apart from the environmental issue caused by the exhaust emissions that has often been associated with the vehicular consumption of fuel, it can also cause negative impact to the economy. For instance, the cost of congestion in Kuala Lumpur accounted up to 2.2% of Malaysia's GDP in 2016 [5]. This is a significant economic loss to the country which calls for an urgent effort to develop and implement fuel economy regulation in order to reduce the consumption of fuel. This can be achieved by conducting a fuel economy study especially at traffic congested areas. The fuel economy data obtained from such study is very important for developing fuel economy policy and other efforts such as traffic management and planning in that particular area [7].

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In Sarawak, there are several divisions that are densely populated, notably in Kuching, Samarahan, Miri, Sibu and Bintulu. These divisions are located in the urban areas where the traffic congestion is inevitable, particularly during peak-hours when people travel to work in the morning and back home in the evening. However, fuel loss due to traffic congestion in Sarawak is yet to be assessed and quantified and hence, there is little to no information on how much traffic congestion could impact the fuel consumption in the region. Although several studies on fuel economy had been carried out in Peninsular Malaysia [8],[9],[10], it can be expected that the driving characteristics in Peninsular Malaysia are different with that of Sarawak, hence, the data obtained there may not be applicable to be used in Sarawak. This is due to differences in road quality and topography since these factors can produce fuel consumption readings that are unique from one place to another [11],[12].

In this paper, the fuel consumption of passenger cars in Sarawak is evaluated under different congestion levels and traffic conditions (i.e., peak-hour, off-peak-hour and weekend) by characterizing the actual driving behavior. Specifically, the fuel consumption is scrutinized in terms of various vehicle operations such as acceleration, deceleration, idle time and speed. The findings can provide valuable information for traffic planning and management in Sarawak, which include, among others, design of road systems and transportation infrastructure as well as traffic light control. Furthermore, understanding the actual driving behavior allows appropriate policies (e.g., eco-driving) to be implemented. This will, in turn, contribute to the reduction in expenditure on fuel and travel time leading to a positive economic growth [13]. Most importantly, reduction in fuel consumption will lead to less exhaust emissions, which ameliorates environmental and life quality.

MATERIALS AND METHODOLOGY

Route Selection

Route selection is essential to ensure that the driving data being collected can best represent the driving condition at different levels of traffic congestion in Sarawak. In this study, the congestion level is assigned by segregating the level of service (LOS) into three groups, i.e., low congestion (LOS A or B), moderate congestion (LOS C or D) and high congestion (LOS E or F). Three routes were chosen for the data collection based on the information from Road Traffic Volume Malaysia 2018 [14]. The chosen routes are SR404 (LOS A), SR403 (LOS D) and SR106 (LOS F) with the details as given in Table 1. The maps of the chosen routes were obtained from Bing Maps as shown in Figure 1. A field survey was conducted prior to the data collection to ensure that these test routes were free from any damage and construction activities.

Table 1. Details of routes chosen for data collection.

Census Station	**Coordinate**		**City**	**Road Length (km)**	**LOS**	**Peak-Hour**	
	From	To				Morning	Evening
SR404	4.442333, 114.013812	4.502298, 113.995457	Miri	7.8	A	0600–0700	1700–1800
SR403	4.338140, 114.000550	4.399695, 113.996046	Miri	9.0	D	0700–0800	1700–1800
SR106	1.461701, 110.326535	1.567480, 110.321132	Kuching	13.4	F	0700–0800	1700–1800

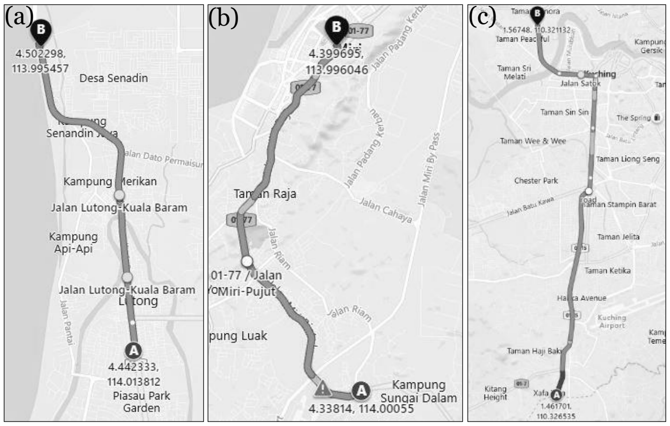

Figure 1. Map view from Bing Maps for (a) SR404, (b) SR403 and (c) SR106.

Data Collection

The speed profiles of the test vehicles at the predetermined routes were collected and recorded in real time in the form of speed-time data by the instrumented test vehicles. The speed-time data were taken during peak-hours, off-peak-hours and weekend for the chosen routes. Six data samples were collected from both traffic direction during peak-hours, off-peak-hours and weekend and each sample was repeated once, resulting in a total of 12 samples for each route.

The two instrumented vehicles employed during the course of data collection were Perodua Myvi and Perodua Bezza and their technical specifications are listed in Table 2. The vehicles and on-board data collection system installed in the vehicles were provided by the Malaysia Automotive, Robotics and IoT Institute (MARii). The schematic diagram of the equipment setup in the test vehicle is illustrated in Figure 2. The data acquisition system was made by Keyence Corporation, Japan and comprises of four modules with varying functions. The modules were powered by an AC power supply (NR-U60) and connected in a way to allow synchronized multi-data collection. The temperature measurement unit (NR-TH08) measures ambient and cabin temperature. Instantaneous vehicle and engine speed were recorded using the Control Area Network (CAN) bus data acquisition unit (NR-C512) through the on-board diagnostics port of the test vehicle. The NR-600 data logger connects the modules to a computer equipped with a proprietary software that allowed user to monitor the entire data collection process in real-time and save the collected data after the completion of a test.

At the starting point of each route, the on-board measurement system was turned on and allowed to stabilize for 30 seconds before the test was started. A co-driver was on-board to monitor the data in real time and to provide extra load on the test vehicle's engine. Auxiliary systems such as air conditioning and radio were turned on throughout the test. A random vehicle was chosen as target to be followed at a safe distance during the test and immediately changed the target to a new vehicle if the former vehicle deviated away from the test route. After reaching the end point of the test route, the data logger was stopped after 30 seconds of data stabilization while idling.

Table 2. Technical specifications of test vehicles.

Technical Data	Perodua Bezza 1.3 Advance (2016)	Perodua Myvi 1.5 Advance (2015)
Cylinder / Capacity (cc)	Inline 4 / 1329 cc	Inline 4 / 1495 cc
Fuel type	Gasoline	Gasoline
Transmission type	4-speed automatic transmission	4-speed automatic transmission
Engine max output	94 hp at 6000 rpm	102 hp at 6000 rpm
Engine max torque	121 Nm at 4000 rpm	136 Nm at 4400 rpm
Engine compression ratio	11.5:1	10:1

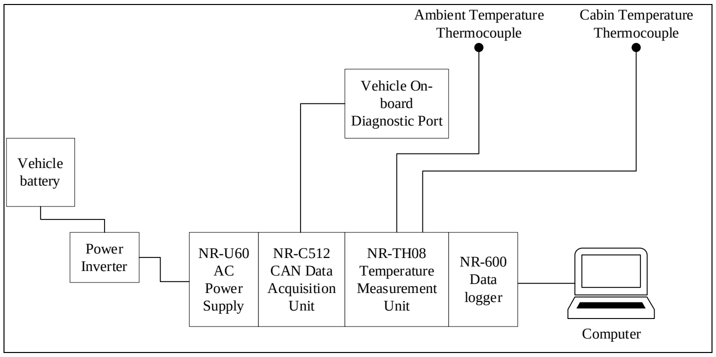

Figure 2. Schematic diagram of data acquisition system.

Estimation of Fuel Consumption

In this study, the Comprehensive Modal Emissions Model (CMEM) was used as the analytical tool to estimate the fuel consumption of the test vehicles. CMEM is a microscopic model developed by the University of California, Riverside [15]. It is a well-established tool for estimating vehicular fuel consumption and has been used in a lot of studies worldwide [16],[17],[18],[19]. CMEM provides second-by-second fuel consumption figures which allow in-depth look at the instantaneous fuel consumption at any given point of a particular trip. Hence, the instantaneous fuel consumption data can be scrutinized in terms of the composition of fuel consumption according to various vehicle operations such as acceleration, deceleration, idle and uniform speed. In this manner, the fuel consumption which corresponds to each of the aforementioned vehicle operations can be assessed accordingly. Table 3 shows some of the important vehicle parameters and operating variables that is required as model input for fuel consumption calculations by CMEM.

Table 3. CMEM model input.

Parameters	Unit
Accessory power	hp
Tractive road load	hp
Vehicle mass	kg
Engine displacement	liter
Engine idle speed	rpm
Engine speed to vehicle speed ratio	rpm/kph
Engine torque at maximum engine power	Nm
Engine speed at maximum engine torque	rpm
Maximum engine power	kW
Engine speed at maximum engine power	rpm
Number of gears	-

Accessory power primarily refers to the power consumption of the air-conditioning system and is relative to the ambient temperature, which can be estimated by [20],

$$P_{\mathrm{AC}} = 0.25T_{\mathrm{out}} - 6 \tag{1}$$

where T_{out} is the ambient temperature (°C). This parameter varies from one trip to another due to variation in ambient temperature during data collection process.

Tractive road load is the load that an engine has to overcome in order to move the vehicle and is trip dependent. Tractive road load or P_{TRL} (W) is estimated by,

$$P_{\mathrm{TRL}} = F_{\mathrm{wheel}}.v \tag{2}$$

where F_{wheel} is the sum of forces acting against the motion of vehicle and v is the vehicle speed (m/s). The sum of these forces is calculated by,

$$F_{\mathrm{wheel}} = F_{\mathrm{acceleration}} + F_{\mathrm{slope}} + F_{\mathrm{air}} + F_{\mathrm{rolling}} \tag{3}$$

where $F_{\mathrm{acceleration}}$ is the force caused by vehicle acceleration, F_{slope} is the force caused by slope or road gradient, F_{air} is the air drag force and F_{rolling} is the force that resist the movement of tires. $F_{\mathrm{acceleration}}$, F_{slope}, F_{air} and F_{rolling} can be calculated using Equation 4, 5, 6 and 7, respectively,

$$F_{\mathrm{acceleration}} = ma \tag{4}$$

$$F_{\mathrm{slope}} = mg \sin\theta \tag{5}$$

$$F_{\mathrm{air}} = \frac{1}{2}\rho v^2 C_d A \tag{6}$$

$$F_{\mathrm{rolling}} = C_r mg \tag{7}$$

where m is the total vehicle mass with one driver and one passenger on board (kg), a is vehicle acceleration (m/s^2), g is gravitational acceleration (m/s^2), θ is angle of road gradient (°), ρ is air density (kg/m^3), v is vehicle speed (m/s), C_d is the air drag coefficient, A is vehicle frontal area (m^2) and C_r is the rolling resistance coefficient.

Engine torque at maximum engine power, $T_{P\max}$ (N·m) can be calculated by,

$$T_{P_{\max}} = \frac{30P_{\max}}{\pi n} \tag{8}$$

where $P_{\max}$ is the maximum engine power (W) and n is engine speed at maximum engine power (rpm).

RESULTS AND DISCUSSION

Table 4 shows the vehicle dynamics such as vehicle average speed, acceleration-deceleration frequency, idle time and stop frequency across various congestion levels and traffic conditions for both test vehicles. These data were extracted from the speed profiles obtained from all the trips. It was found that the acceleration-deceleration and stop frequency are increased with increasing congestion level. These findings show that the vehicles underwent repeated stop-go motions which accurately represent the actual driving characteristics at an increasing level of congestion that will certainly cause a reduction in the average velocity of the vehicles. Furthermore, high idling time which is associated with high traffic congestion is also evidenced from the recorded speed profiles.

The average fuel consumption of the test vehicles across various levels of traffic congestion is illustrated in Figure 3. It is found that the consumption of fuel is increased with increasing level of traffic congestion. The fuel consumption of Perodua Bezza and Perodua Myvi increases by 16.39% and 17.32%, respectively, from low to moderate congestion and a further increase of 20.64% and 11.73%, respectively, were observed at high congestion. It is also observed that the consumption of fuel by Perodua Myvi is higher than that of Perodua Bezza in all the routes. This observation is expected due to the larger engine capacity of Perodua Myvi that will cause more fuel to be burnt and being consumed.

The vehicle dynamics outlined in Table 4 can affect the fuel consumption in numerous ways. For instance, low average speed at high traffic congestion is the result of frequent vehicle interactions. In this situation, the engine will operate below the optimum engine speed for fuel efficiency and thus, consuming more fuel [21]. The engine efficiency is said to be optimum when it operates at maximum mechanical efficiency which is when the optimum operating temperature is achieved that will minimize the frictional forces within the engine component [22]. In addition, frequent vehicle interaction at high traffic congestion also introduces repeated stop-go motions and causes significant velocity fluctuations. This frequent stops subject the engine to a higher frequency of acceleration which is very demanding for the engine, predominantly at low vehicle speed [23]. This causes the engine to consume more fuel to overcome the inertia of the vehicle. Besides, long idle time results in high fuel consumption due to the enrichment of fuel-air mixtures when the engine operates at low speed during vehicle idling [24].

Table 4. Vehicle dynamics at various congestion levels and traffic condition.

Vehicle	Route	Traffic Condition	Vehicle Dynamics			
			Average speed (km/h)	**Acceleration-Deceleration Frequency**	**Idle Time (s)**	**Stop Frequency**
Perodua Bezza	SR404 (LOS A)	Off-peak	43.7	121.0	119.0	3.8
		Peak	35.8	165.0	151.0	5.5
		Weekend	43.5	108.0	124.5	4.0
	SR403 (LOS D)	Off-peak	36.0	124.5	227.3	7.3
		Peak	22.0	226.5	341.3	15.5
		Weekend	35.5	125.0	186.3	5.5
	SR106 (LOS F)	Off-peak	25.4	298.0	706.5	27.3
		Peak	15.7	417.0	1466.5	56.0
		Weekend	28.9	232.5	591.8	17.3
Perodua Myvi	SR404 (LOS A)	Off-peak	41.8	96.5	119.8	4.5
		Peak	38.0	129.5	114.0	9.3
		Weekend	45.4	90.5	93.0	4.0
	SR403 (LOS D)	Off-peak	33.6	136.0	223.3	10.3
		Peak	21.3	263.5	380.8	26.3
		Weekend	35.4	120.0	237.3	6.3
	SR106 (LOS F)	Off-peak	25.1	327.5	651.5	32.5
		Peak	15.9	478.5	1366.0	76.8
		Weekend	27.8	314.0	547.0	25.5

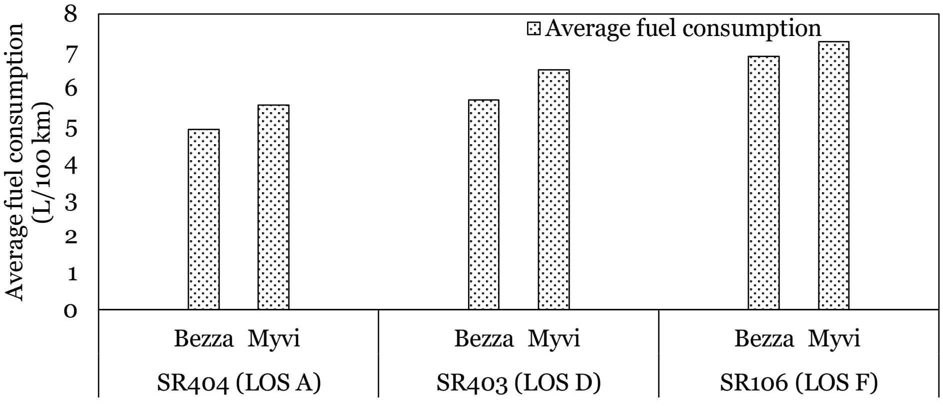

Figure 3. Average fuel consumption at different level of traffic congestion.

Figure 4 shows the consumption of fuel by the vehicles which are separated based on the traffic conditions. It is observed that the highest fuel consumption is recorded during peak-hours of high and moderate congestion levels. However, the fuel consumption during peak-hours in the least congested route is observed to be the lowest among other traffic conditions. In order to further scrutinize the effect of traffic conditions on fuel consumption, the fraction of fuel being consumed with respect to various vehicular operations were examined. Table 5 shows the distribution of fuel consumptions during the acceleration, deceleration, idling and uniform speed of both vehicles at different traffic conditions in all the routes. It is found that the vehicle acceleration consumes the most fuel amongst all of the operations, which is approximately two-thirds of the total fuel being consumed. It is also observed that the fuel consumption due to acceleration is the highest during peak-hours in all the routes, except at SR404 where the effect of acceleration during peak-hours in this route is the lowest as compared to the other traffic conditions. Hence, this finding could explain the reason why the average fuel consumption during peak-hours in SR404 is the lowest as observed in Figure 4.

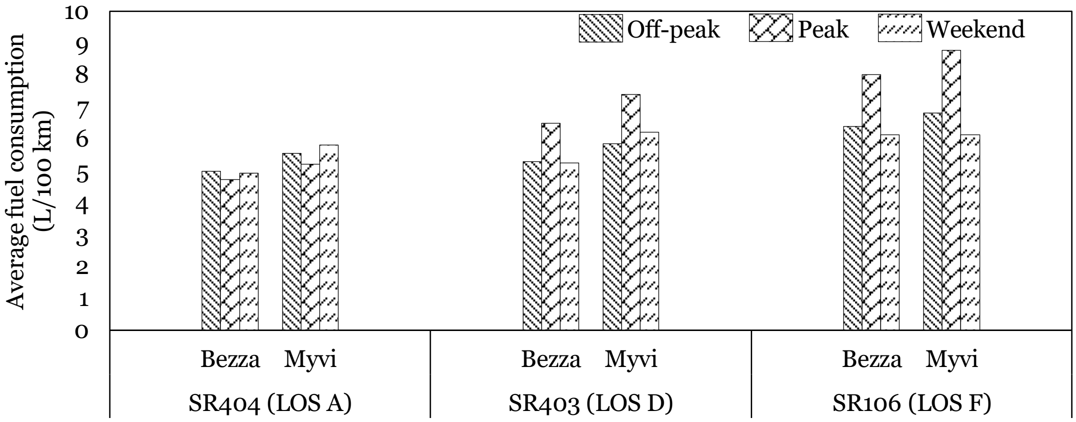

Figure 4. Average fuel consumption of Perodua Bezza and Perodua Myvi across various congestion levels and traffic conditions.

Table 5. Vehicle dynamics at various congestion levels and traffic condition.

Vehicle	Route	Traffic Condition	Vehicle Operation Fuel Consumption (mL/km)			
			Acceleration	Deceleration	Idle	Uniform speed
Perodua Bezza	SR404 (LOS A)	Off-peak	34.390	10.384	3.154	1.868
		Peak	30.720	10.064	3.980	2.389
		Weekend	34.066	9.978	3.297	1.998
	SR403 (LOS D)	Off-peak	36.737	9.525	5.180	1.464
		Peak	39.097	13.403	10.403	2.016
		Weekend	37.005	9.494	4.266	1.675
	SR106 (LOS F)	Off-peak	40.895	11.513	10.215	1.223
		Peak	43.249	14.302	21.055	1.644
		Weekend	41.221	10.169	8.722	1.196
Perodua Myvi	SR404 (LOS A)	Off-peak	38.490	12.013	3.635	1.434
		Peak	35.101	11.843	3.297	1.907
		Weekend	42.225	11.636	2.816	1.396
	SR403 (LOS D)	Off-peak	39.091	11.892	5.793	1.714
		Peak	45.950	16.336	9.650	2.065
		Weekend	43.451	11.188	6.298	1.087
	SR106 (LOS F)	Off-peak	42.267	13.513	10.757	1.628
		Peak	47.226	16.769	22.189	1.649
		Weekend	38.273	12.699	8.849	1.498

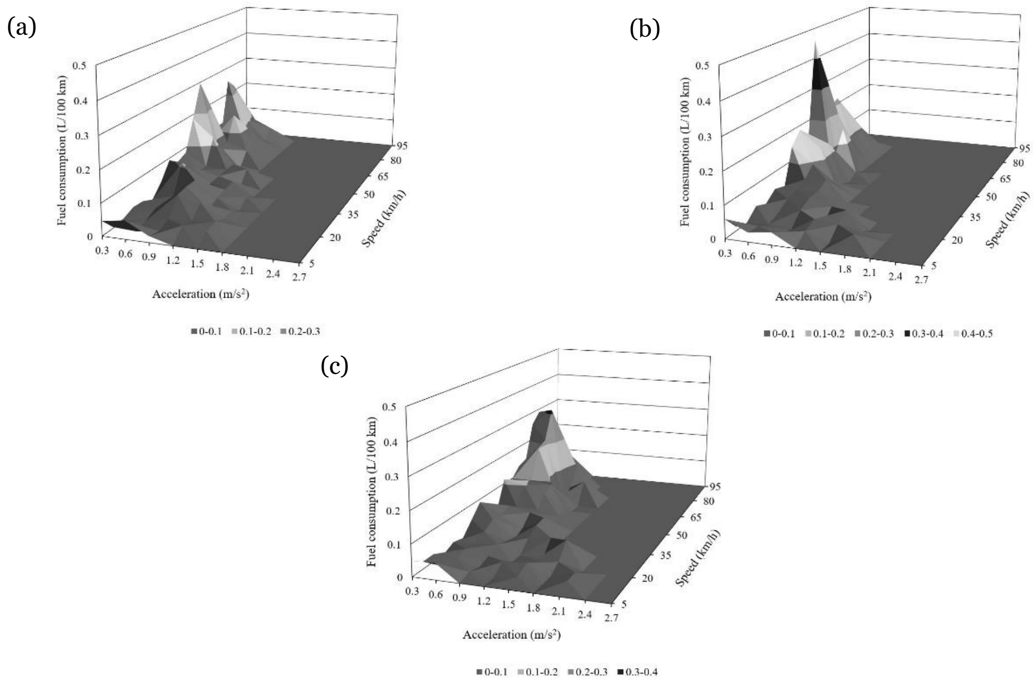

Figure 5. Acceleration-speed-fuel consumption surface graph of Perodua Myvi at SR404 during (a) off-peak-hour (b) peak-hour and (c) weekend.

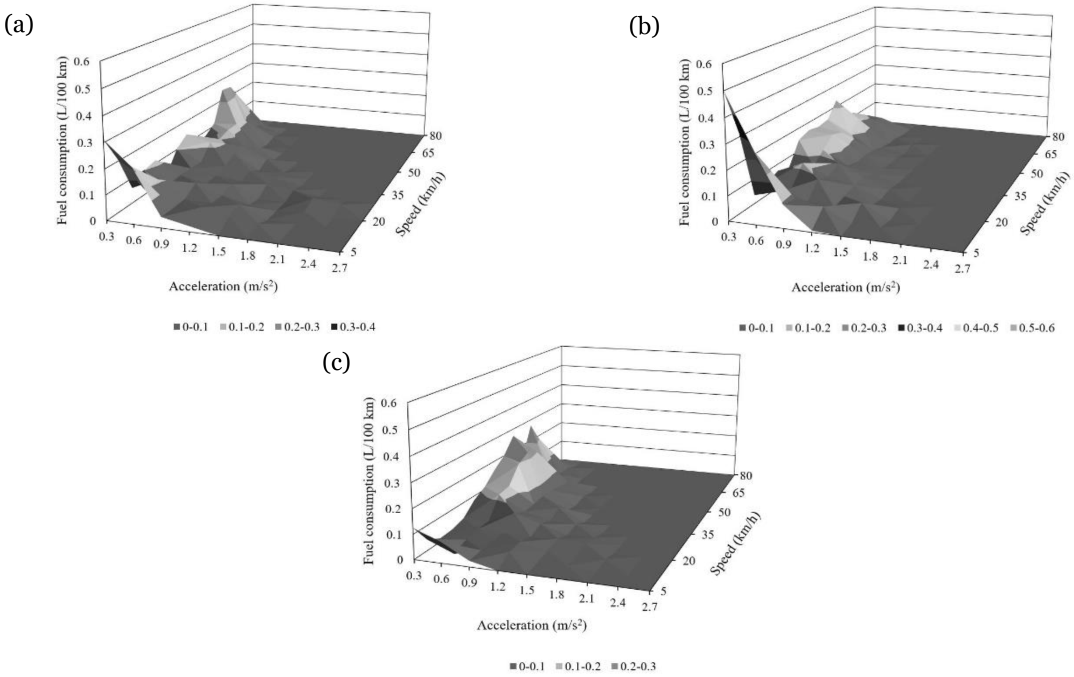

Figure 6. Acceleration-speed-fuel consumption surface graph of Perodua Myvi at SR106 during (a) off-peak-hour (b) peak-hour and (c) weekend.

Since the vehicular acceleration is the highest contributor to the overall fuel consumption, it is necessary to perform further investigation on how the consumption of fuel was being affected by the vehicular acceleration. For this examination, the acceleration-speed-fuel consumption surface graphs were plotted for the least congested SR404 and the most congested route SR106 on selected trips from Perodua Myvi, as shown in Figure 5 and 6, respectively. In the least congested route SR404, high fuel consumption is clearly observed when the vehicle accelerates at less than 0.3 m/s^2 especially at the vehicle speed of 50 km/h and above. In contrast, the fuel consumption is dominant in the low-speed region of less than 5 km/h for the most congested route SR106 at the same acceleration, particularly during peak and off-peak hours. These observations could be due to the different speed profile that can be expected between the two routes. At the least congested route, the occurrence of vehicle travelling at high speed, which is an indication of a free-flowing traffic, is greater compared to that at the most congested route where the vehicle speed would concentrate at the low-speed region, as shown in Figures 7 and 8.

High-speed acceleration has the highest occurrence frequency in the least congested route SR404 regardless of traffic conditions as observed in Figure 7. It is interesting to note that high-speed acceleration is most obvious during peak-hours. In most cases, the traffic flow during peak-hours is the most restrictive and vehicles would normally engage in low-speed acceleration in this condition. However, this finding suggests that at low congestion level, traffic flow does not differ distinguishably across various traffic conditions and the effect of traffic condition on fuel consumption is rather insignificant.

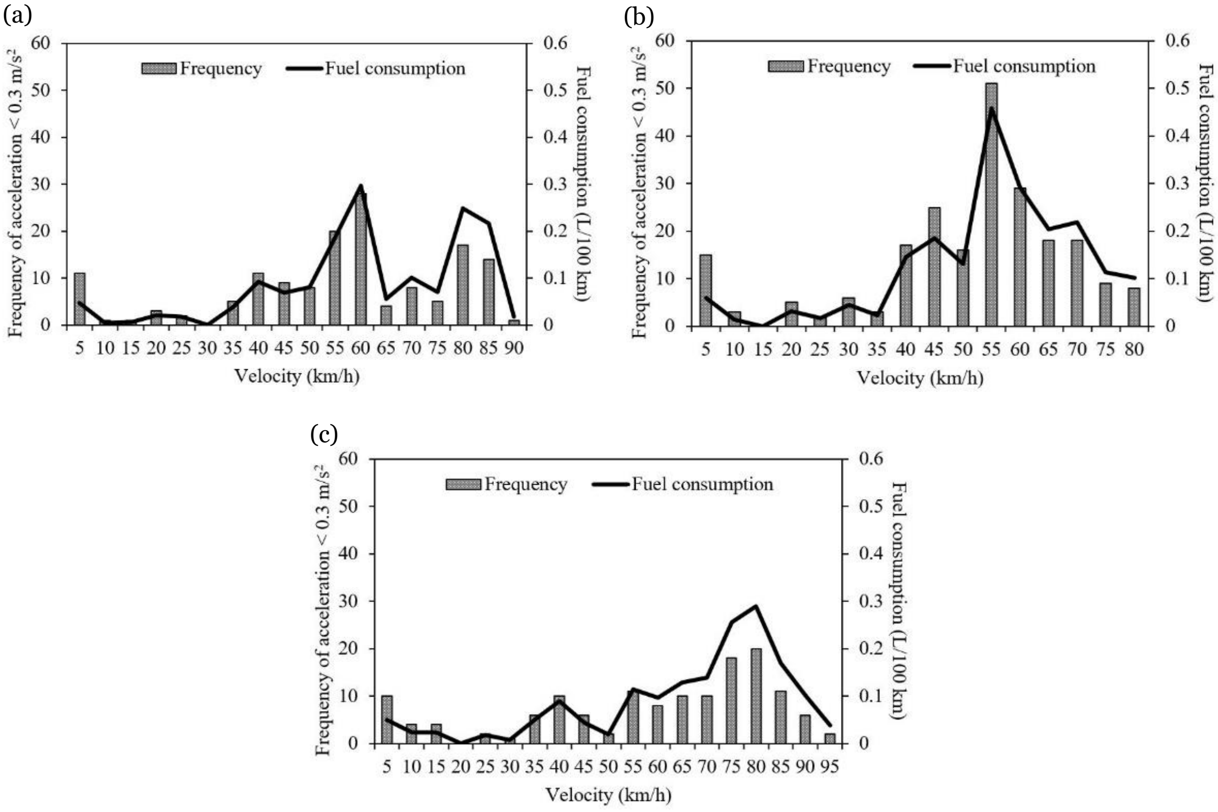

Figure 7. The variation in the fuel consumption that corresponds to the frequency of acceleration less than 0.3 m/s^2 across the velocity of vehicle during (a) off-peak-hour, (b) peak-hour, and (c) weekend at SR404.

From Figure 8, it can be seen that low-speed acceleration has the highest occurrence frequency in the most congested route SR106 especially during off-peak- and peak-hours. This observation indicates that vehicles accelerate at low-speed more frequently than that at SR404 particularly during peak-hours where interactions between vehicles are more prominent. This occurrence can be attributed to repeated acceleration and braking operations at low-speed, which result in high fuel consumption. It can also be seen that the effect of acceleration on fuel consumption is greater at a higher speed as compared to that at lower speed even though the occurrence frequency of high-speed acceleration is lower than that of low-speed acceleration. This can be attributed to the greater engine loads when the vehicle operates at high-speed acceleration as observed in other study [25]. In that study, high-speed operation causes the wheel work to increase dramatically and it becomes more significant during high-speed acceleration. At high-speed operation, vehicle speed primarily affects the engine load due to aerodynamic resistance [23]. A mild acceleration at high vehicle speed can increase aerodynamic resistance and thus, increasing wheel work and ultimately, increasing fuel consumption.

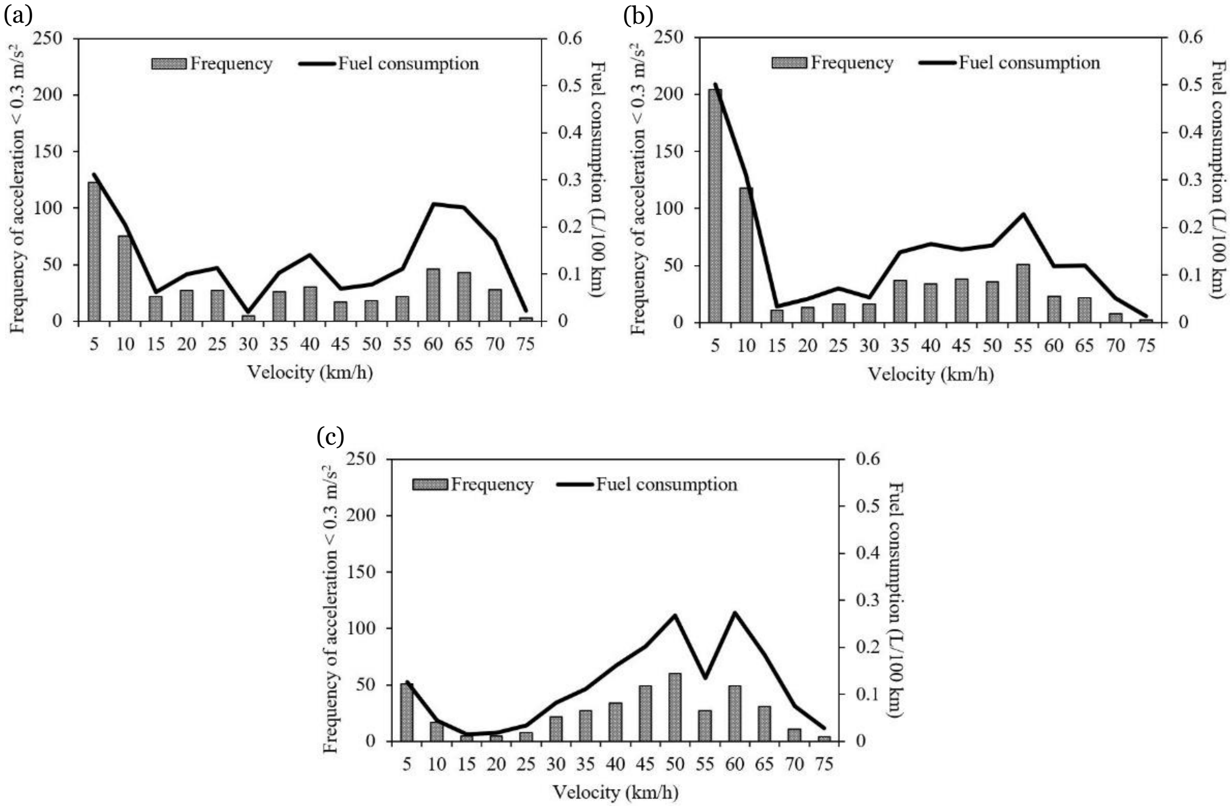

Figure 8. The variation in the fuel consumption that corresponds to the frequency of acceleration less than 0.3 m/s² across the velocity of vehicle during (a) off-peak-hour, (b) peak-hour, and (c) weekend at SR106.

CONCLUSION

The driving behavior of passenger cars at various congestion levels and traffic conditions in the selected urban routes of Sarawak were measured and the fuel consumption was analyzed using CMEM. High acceleration-deceleration and stop frequencies as well as long idling are evident with increasing levels of traffic congestion, resulting to a reduction in the average velocity of the vehicles. The consumption of fuel is found to increase with increasing level of traffic congestions. The fuel consumption of Perodua Bezza and Perodua Myvi increases by 16.39% and 17.32%, respectively, from low (LOS A) to moderate (LOS D) congestion and a further increase of 20.64% and 11.73%, respectively, were observed at high congestion (LOS F). The highest fuel consumption is observed at high congestion level (LOS F) and during peak-hours, which is approximately 8.03 L/100 km and 8.78 L/100 km for Perodua Bezza and Perodua Myvi, respectively. It is found that in all the routes, irrespective of the levels of traffic congestion and traffic conditions, the fuel consumptions are mostly contributed by the vehicular acceleration, which is about a two-third of the total fuel being consumed. The high fuel consumption is particularly significant when the vehicular acceleration takes place at an increasing vehicle speed. The findings from this pioneering research could serve as a fundamental guideline for future research regarding fuel economy and urban sustainable development in Sarawak.

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