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Behaviour analysis of light-duty vehicle drivers using naturalistic driving data collection

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Abstract

It is known that driving patterns have a significant impact on fuel economy. Much fuel is wasted due to unnecessary driving activity, even in the case of highly qualified drivers. This paper examines the driver's behaviour across two sections of the selected routes and quantifies the possible benefits of fuel savings from improvements in driving patterns during transport. Drivers' behaviour on the roadways differs depending on the road condition, and it directly affects fuel consumption. The fuel consumption rate of the vehicle increases with speed but is also dominated by acceleration. During acceleration, fuel consumption rates are excessive even under low-speed conditions, especially in the range of 31-60km/h with 11.57 Liter/100km.

Keywords: Driving behaviour, light-duty vehicle, naturalistic driving

Introduction

Vehicle driving characteristics and experimental data on fuel usage and are critical in assessing the transportation sector's environmental effects. The real-time measurement data of fuel usage is an important requirement parameter to identify the vehicle's fuel consumption. The vehicle's fuel consumption can be estimated using direct or indirect calculation instruments or by the use of fuel consumption models. Direct or indirect calculation procedures can be conducted in laboratories by testing the engine on a chassis dynamometer or the road [1]. However, the recent findings have shown that the laboratory test fuel usage effects are different from those obtained from real-world driving environments [2]. According to Ferreira and Rodrigues, to improve the accuracy of the expected fuel consumption in fuel consumption models, it is important to integrate traffic simulation models like Simulation of Urban Mobility (SUMO) with fuel usage and pollution models such as Passenger Car and Heavy Duty Emission Model (PHEM). Then, because of the complex models discovered by them, that combination of models will be difficult to use by the consumer in real life. [3]. In addition, Franco and Kousoulidou suggested that all vehicle emissions and fuel consumption models are mainly built based on comprehensive data collection of experiments obtained on the vehicle, such as pollution and fuel consumption measurements under some conditions [4]. To ensure high precision of the anticipated performance, it is also important to change the model parameters, particularly when adapting the models of developed countries to developing countries, where there is a significant gap in the degree of technology, the nature of fuels and driving behaviour. The reality is that the adaptation of the model parameters includes measurement data under real-world conditions [4]. After all the above, there is a need to reflect better the diversity of driving trends in real-world around various areas with a number of driving cycles, appropriate for analysis in the simulation.

The methods of calculating the vehicle's instantaneous speed are quite simple, determined by calculating the distances of the vehicle travelled regarding the time taken. As technology grows, Global Positioning System (GPS) equipment is widely used by researchers to capture the vehicles speed profile [5][6]. Although the built on-board instruments usage to calculate vehicle speed has become more preferable for researchers to determine the vehicle's speed. Meanwhile, Satiennam and Seedam have used a non-contact sensor, such as an inductor or magnetic one, to calculate speed by calculating the rotational speed of the wheel [7].

Other than that, the fuel consumption of vehicles depends on the human driving behaviour (i.e. driving profile) as well as on environmental conditions, auxiliary loads, fuel type, and vehicle characteristics. The drive profile is the speed-time profile of the normal vehicle operation. It depends on both the driver's actions, such as the aggressiveness of the acceleration and the on-road environment. For research and simulation purposes, driving periods should describe driving activities in the real world and on-road environments. The previous researcher shows how changes in the on-road driving environment generate different representative driving periods as driving patterns and, subsequently, different measures of fuel consumption [8]. They notice that two additional variables: atmospheric conditions, and vehicle thermal conditions, are the subjects of complementary studies.

Legislative driving cycles (i.e., cycles used in uniform fuel economy and pollution monitoring procedures) are most commonly developed independently of the on-road driving environment. These strategies neglect differences in the road, traffic conditions, and topography that differ geographically. Environmental factors have been shown to influence observable driving trends by Brundell-Freij and Ericsson [9]. As discovered by Arun et al., many researchers have built their driving cycles where legislative cycles do not reflect local driving conditions. Local representative driving cycles illustrate spatial variations in driving habits frequently ignored in legislative cycles, which must be standardized and repeatable for research. However, these cycles are expensive to create and do not generalize well beyond the particular study field [10]. Furthermore, parameters in real-world driving such as driver behaviour, driving climate, environmental conditions have been seen to cause significant variations in mark forecasts as discovered by Greene et al. [11]. Research on the diversity of real-world driving trends is needed across regions with few driving styles. The purpose of this paper is to explore variations in real-world traffic habits associated with various on-road driving conditions such as driving behaviour (acceleration, deceleration and cruising) and road designation (urban, rural, highway road region) on differences in vehicle speed condition.

Methodology

Vehicle test specification

The vehicle tested is a 2.5-liter, four-cylinder light-duty vehicle with four-stroke engines. This model of the vehicle was selected because of its success as the main fleet as proven with higher selling units compared with other manufacturers [12]. A description of the specification of the vehicle is presented in

Table . It uses a diesel direct injection rail system. The vehicle was fueled with EURO 5 B30 diesel. Such a form of the engine has a wide demand in Malaysia, where this research is taking place. Therefore the light-duty vehicle selected for this study would be beneficial to such a population [13].

Table 1 Specification of the engine [12]

Type	Description

Engine	2.5-liter D-4D Diesel
No. of cylinders	4 cylinders
Engine capacity	2494cc
Stroke	93.8mm
Bore	92mm
Connecting rod	158.5mm
Compression ratio	18.5:1
No. of valves	16 valves
Exhaust valve open	30º BBDC
Exhaust valve close	0º BTDC
Intake valve open	2º BTDC
Intake valve close	31º ABDC

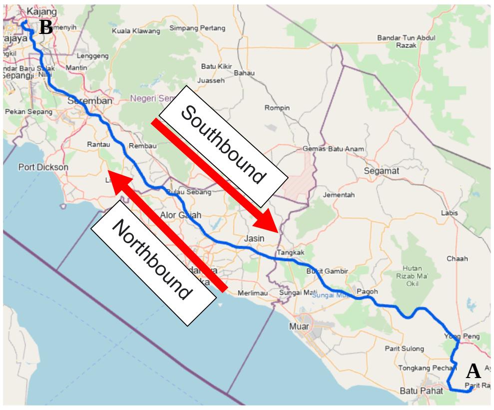
Test Route

The route chosen is a section of the high-frequency route, which has a length of 263 km. The route is long enough to measure the effects of accurate fuel efficiency

The explanation that this route section was analyzed is; this route of the line is the longest part of this dedicated route with different operating characteristics and since the selected route (i.e., the Northbound route) belongs to a road connecting the downtown and suburban residential areas, the traffic has obviously related characteristics, which facilitates subsequent analysis of peak and off-peak hours.

The experiments were carried out during the daytime. This data collection is adequate to produce accurate performance. The same driver drove the vehicle during all the experiments. The location of the vehicle throughout the field trial was tracked by GPS equipment.

Figure 1 Selected experimental route for field data collection



Naturalistic Driving Data Collection

Naturalistic driving refers to participants who drive according to their everyday needs and driving behaviours. On-board data collection systems track and report driving information for the driver as discovered by Holden et al. [14]. This data collection process is relatively expensive, and the data screening process is complicated, but natural driving data will show the real driving behaviour of drivers under current traffic conditions. Therefore, to ensure the reliability and representativeness of our research findings, we used naturalistic driving data in this research.

The approach listed here only addresses variations of the on-road driving condition. It does not include external variables that can impact on-road fuel consumption, including the thermal status of powertrain components, vehicle dynamics and environmental conditions.

Result and Discussion

This section discusses the impact of vehicle speed on fuel consumption, the effect of acceleration on fuel consumption and the contribution of various driving modes on fuel consumption.

The impact of vehicle speed on fuel consumption

Along the test route, the vehicle travelled at different road designation such as rural-urban, highway, and rural roads. Vehicle speed and acceleration rates are reported for vehicle tests on both routes, as seen in **Figure 2** and **Figure 3**. The vehicle starts from point A to B for the Northbound route. Meanwhile, for the Southbound route, the vehicle travelled from point B to A as shown in Figure 1, which ensures the study of the effect speed category in terms of impact on fuel economy. The vehicle begun at a slightly low speed, and then speed changed at the beginning through huge fluctuations in the speed-up process. There were sections where the speed of the vehicle suddenly changed, indicating the brake cases caused by traffic disturbances, several aggressive decelerations followed by a constant speed, except for some small undulations at the center caused by heavy traffic and road construction during the tests. As the speed decreases nearly to zero, tailed by a sharp rise in the vehicle speed due to acceleration. This causes higher average fuel usage rates on the Southbound route.

Vehicle acceleration causes most vehicle speeds, which means that the vehicle's fuel consumption is driven by acceleration. Rapid deceleration occurs due to the brake pedal usage, which creates a lot of energy loss if no energy recovery system exists. As described above, fuel consumption rates are substantially dependent on acceleration, reflecting the driver’s habits in a given situation. It almost displays normal distributions for both routes, with peaks being roughly ±1 ms^{-2}.

During the driving phase, various driving styles can be related to vehicle acceleration, where different driving patterns are linked to vehicle acceleration, which significantly affects fuel consumption. The average fuel savings of 16% was accomplished by supplying the driver with guidance to accelerate/decelerate the car when it was discovered by Gao et al. [15]. They also discovered that fuel consumption was closely related to vehicle acceleration, and drivers' actions also shifted slightly under different driving routes as discovered in the driving pattern between **Figure 2** and **Figure 3**.

Figure 2 Variation of the instantaneous vehicle speed regarding distance at the Northbound route

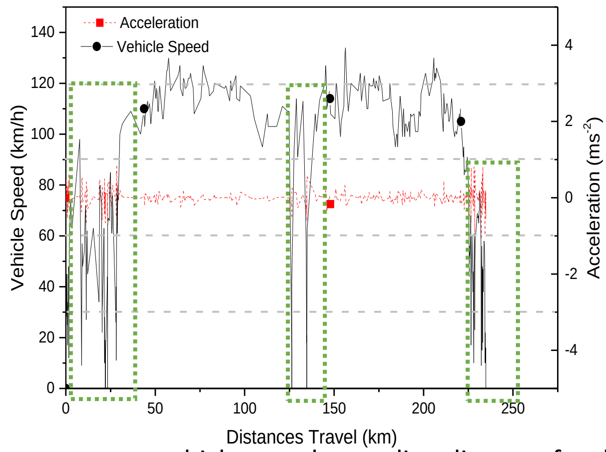
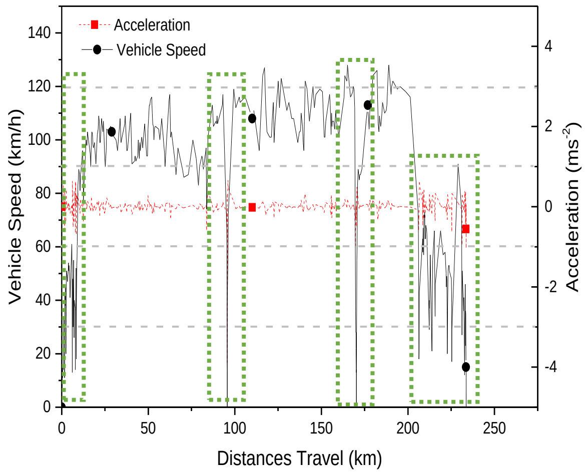


Figure 3 Variation of the instantaneous vehicle speed regarding distance for the Southbound route



From **Figure 4**, the Northbound route showed the majority of the distances travel at vehicle speed 91-120 km/h along 161.00 km (68.55% to whole travel distances) and travel in 5372 seconds with 49.92% to whole travel on that route. Next, for the Southbound route, the maximum distances travelled in the real world are shown at speed category 91-120 km/h with 161.88 km (69.29% to whole travel distances) and contributed about 5528 seconds which is 49.24% of the whole travel time. While the lowest distances travel at speed category 1-30 km/h with only 6.63 km contribute 2.84% to whole distances travel and take 1190 second in the duration of travel (10.60% to whole travel time).

A summary of duration travel for the Northbound route is shown in **Figure 5**. The longest duration travel is with 91-120km/h vehicle speeds for 5372 seconds (49.92% along with the whole route travel). Then followed with speeds 1-30km/h, 31-60km/h, 61-90km/h, and 121-150km/h with durations of 1429 seconds (13.27%), 1092 seconds (10.14%), 985 seconds (9.15%), and 972 seconds (9.03%), respectively. Meanwhile for the Southbound route, the longest duration is with 91-120km/h vehicle speed in 5528 seconds (49.24% of the whole travel time). It is then followed with 61-90km/h, 31-60km/h, 1-30km/h and 121-150km/h with 1653 seconds (14.72%), 1342 seconds (11.95%), 1190 seconds (10.60%), and 406 seconds (3.62%) respectively.

Figure 6 represents the actual amount of total fuel used in respect of five-speed ranges for the actual driving of the vehicle. It is clearly shown the highest fuel use in the vehicle speed of range 91-120km/h with 10.75 liters at the Southbound route, while, in the range 0.51-0.60 liters for the vehicle travelled at speed

1 km/h to 30 km/h, 1.58-1.95 liters from 31 km/h to 60 km/h, respectively. Then for the speed range 61-90 km/h, it consumed 1.77-3.02 liter, and for 91-120km/h, it consumed 10.16-10.75 liter. Then for 121-250km/h, it consumed 0.57-0.94 liters.

The highest fuel consumption is in the range 91-120km/h was consumed in a long period during and travel distance of the entire trip, 105.91-142.28 km (45.11-60.63 % to the whole travel distance) and 3379-5372second (32.56-49.92 % to the whole travel time). Based on real-world fuel consumption, we expect real-world fuel consumption to be normalized to standard driving habits for each vehicle. For the Southbound route, increasing vehicle speed in highway cruising from 61-90km/h to 90-120km/h can raise fuel consumption by 20%.

Figure 4 Overall distances travelled along both routes

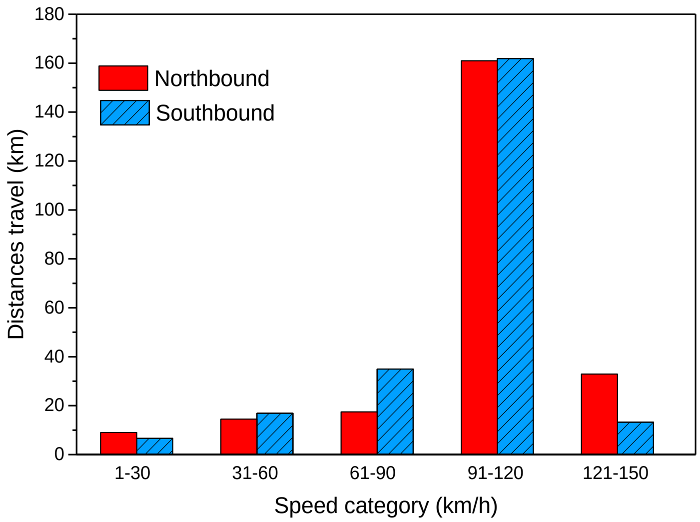


Figure 5 Overall duration travelled along both route

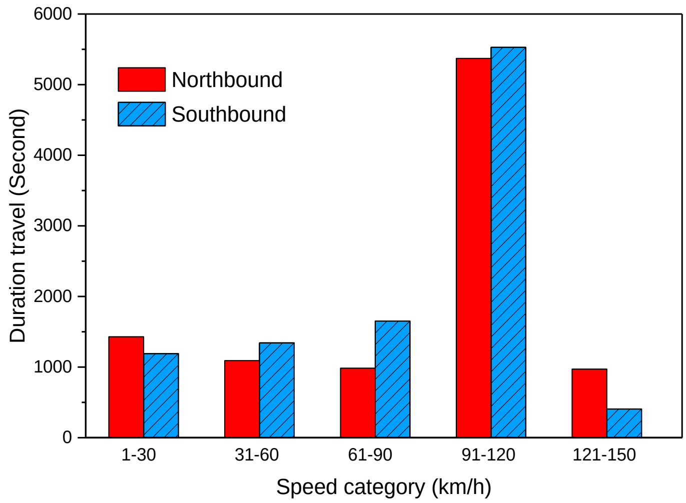


Figure 6 Overall fuel usage along both routes

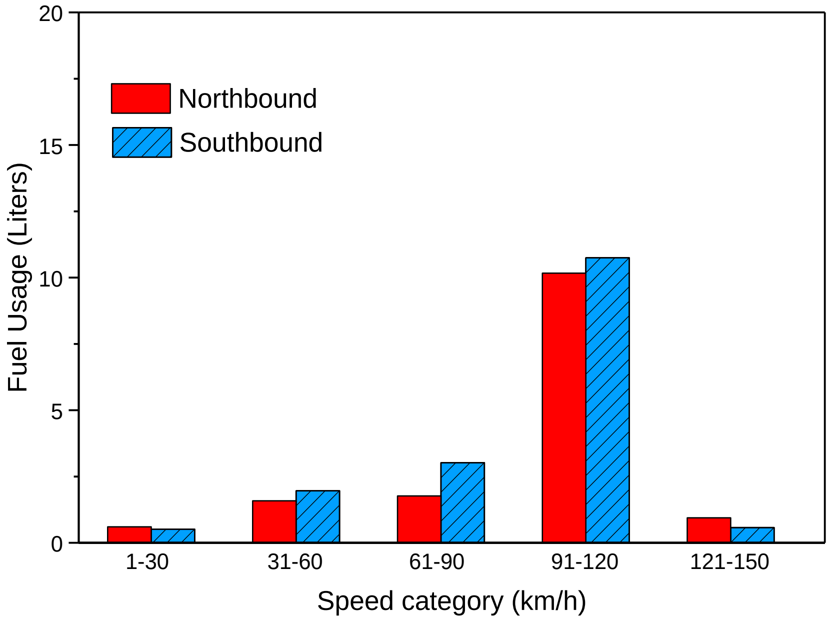
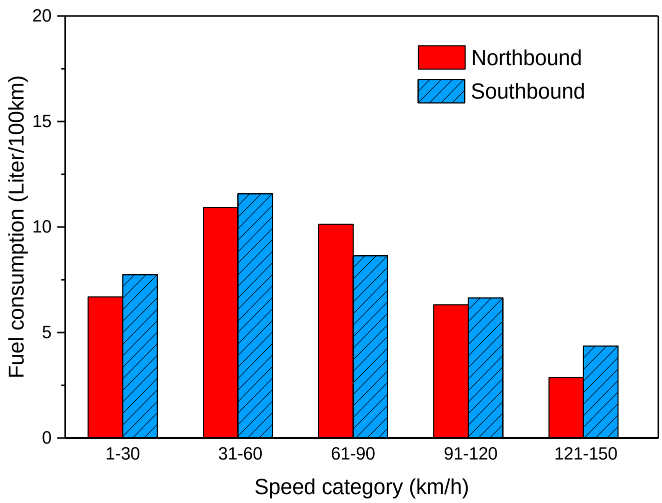


Figure 7 Fuel consumption along both routes



Error! Reference source not found. shows the fuel consumption values of each route. The findings have shown that fuel usage in the Northbound route is lower than the Southbound route fuel usage and that the higher differences with 0.77 ratios of both route fuel usage under 61-90km/h vehicle speed. Meanwhile, under conditions, 91-120 km/h road speed shows the lowest ratio of 0.05 differences in fuel usage between both routes. After normalization, the fuel consumption for the Northbound route is 6.68 L/100 km for speed 1-30km/h, 10.92 L/100 km for speed 31-60km/h, 10.13 L/100 km for 61-90km/h, 6.31 L/100 km for 91-120km/h, and 2.88 L/100 km for 120-150km/h. Meanwhile for the Southbound route, there are 7.74 L/100 km for speed 1-30km/h, 11.57 L/100 km for speed 31-60km/h, 8.63 L/100 km for 61-90km/h, 6.63L/100 km for 91-120km/h, and 4.35 L/100 km for 120-150km/h. The maximum fuel consumption is recorded at speed category 31-60km/h with 11.57 L/100km for the Northbound route, with 5.61% higher than the Southbound route in the same category. The difference in fuel consumption between the two routes can be due to different reasons. Firstly, the Northbound route vehicle speed is a transient mode (rapid changing vehicle speed from 5km/h to 86km/h for the first 30km) in which conditions such as relative positive acceleration as shown in **Figure 3** were more aggressively related to those in the Southbound route. However, the vehicle's average speed on the Southbound route is higher, which means that the total level of fuel consumption is lower, as stated in the previous segment. Finally, the Southbound route's travel duration is longer than that of the Northbound route, and a greater proportion of the driving time happens before the engine is completely warmed up [16]. High fuel consumption in the range of 1-30 km/h was recorded over a short distance and an average duration of the entire journey, 5.29 km (2.26 % of the total distance travelled) and 919 sec (9.38 % of the total journey time) over the Southbound route.

The effect of acceleration on fuel consumption

For both directions, Northbound and Southbound route test data are post-processed and the results are averaged to give normal fuel consumption values. The fuel consumption is given in **Figure 7** and **Figure 8**. It is shown that the average results are slightly higher for the Southbound direction because of having more changes in acceleration and deceleration region. The maximum acceleration has been recorded for Northbound is 0.66 ms^{-2} and for deceleration is at -1.0 ms^{-2}. Meanwhile, the Northbound route showed 0.83 ms^{-2} for maximum acceleration, and maximum deceleration was recorded at -1.2 ms^{-2}. From **Figure 7**, two higher region fuel consumption was observed for the Northbound route with 0.175 liter/s in acceleration region -0.2 ms^{-2} to 0.2 ms^{-2} at 60-80 km/h and 85-100 km/h which the contribution of higher of fuel consumption of the Northbound route compared with the Southbound route in 61-90 km/h vehicle speed Meanwhile for the Southbound route; there are regions that contribute to high fuel consumption, which is at acceleration range -0.2 to 0.2ms^{-2} under vehicle speed 90-100km/h. This can be the cause of the higher contribution fuel usage of the Southbound route under the 91-120km/h speed category compared to the Northbound route.

Figure 7 Fuel consumption contour maps by acceleration and vehicle speed along the Northbound route

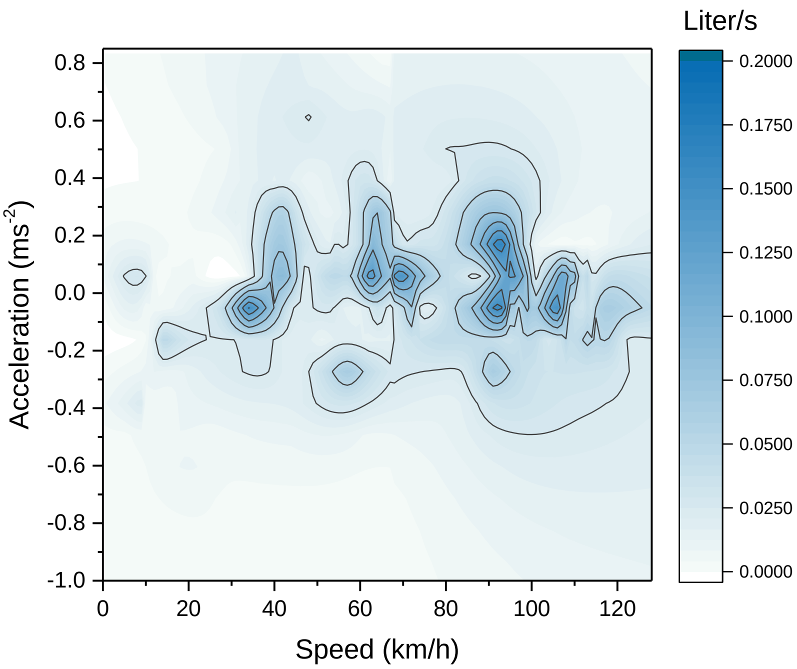
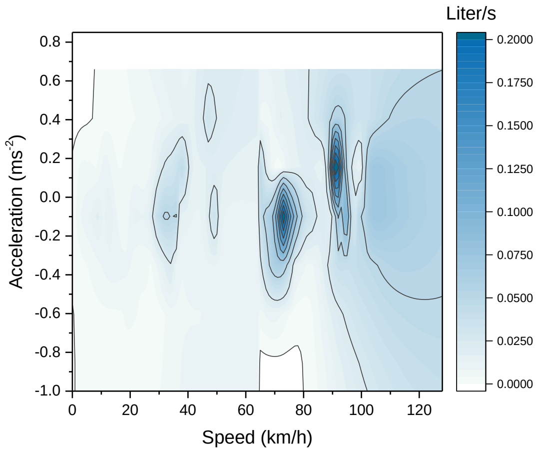


Figure 8 Fuel consumption contour maps by acceleration and vehicle speed along the Southbound route



As described above, fuel consumption rates are substantially dependent on acceleration, which can, to some point, reflect the driver's habits in a given situation. Extended testing speed/speed and acceleration are separated into modes to study the impact of driving style on all fuel consumption. A speed category (S) was defined in increments of 30 km/h starting from the stop conditions. The acceleration ranges were also separated by 0.2 ms^{-2} increments of acceleration (A) modes. The detail of driving modes as shown in **Table** and **Table**. In this context, the variances acceleration for the test as shown in **Figure 9**. With its number, the corresponding mode is indicated.

The percent (%) share value of the contour maps (specific acceleration mode count/total acceleration mode count x 100 percent) variance of the acceleration from the driver as seen in **Figure 9**. The acceleration from -0.2 ms^{-2} to 0 ms^{-2} (A5) at speeds between 91 km/h and 120 km/h (S4) was established as the dominant fuel consumption zone for the Northbound route. The largest share was received at 24.32 % regularly at and followed by 15.41 % at A6. Also, the same contribution of the frequency of negative acceleration A4 for the Southbound route of 22.62 %. The higher frequency of the Southbound route of the A5 and S4 regions with 23.63 %. According to factor analysis by Coloma, García, and Wang; high acceleration variation and high average acceleration/deceleration also have a negative effect on fuel efficiency in a congested environment, which explains why ordinary drivers with moderate speed yet high-speed variance and acceleration have low fuel efficiency [8]. As discussed above, this can be viewed as the higher-speed acceleration of the driver's demand as higher fuel consumption.

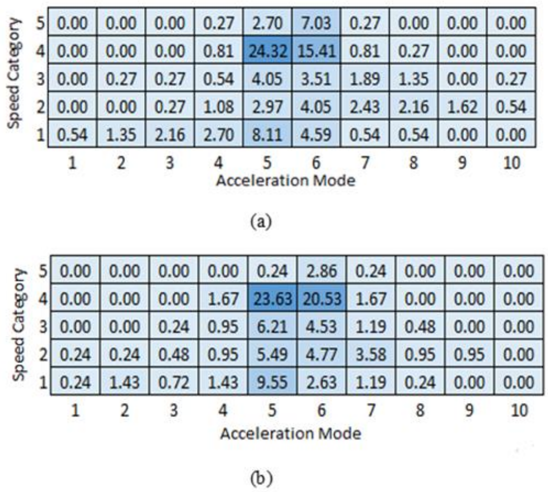
Table 2 Vehicle Speed Category

	Category	Lower Limit (km/h)	Upper Limit (km/h)
Speed Category	S1	0	30
	S2	31	60
	S3	61	90
	S4	91	120
	S5	121	150

Table 3 Acceleration Mode

	Modes	Lower Limit (ms^{-2})	Upper Limit (ms^{-2})
Acceleration	A1	-1	-0.8
	A2	-0.8	-0.6
	A3	-0.6	-0.4
	A4	-0.4	-0.2
	A5	-0.2	0
	A6	0	0.2
	A7	0.2	0.4
	A8	0.4	0.6
	A9	0.6	0.8
	A10	0.8	1

Figure 9 Variation of acceleration mode regarding the vehicle speed for both routes (a) Northbound and (b) Southbound.



The contribution of various driving modes on fuel consumption

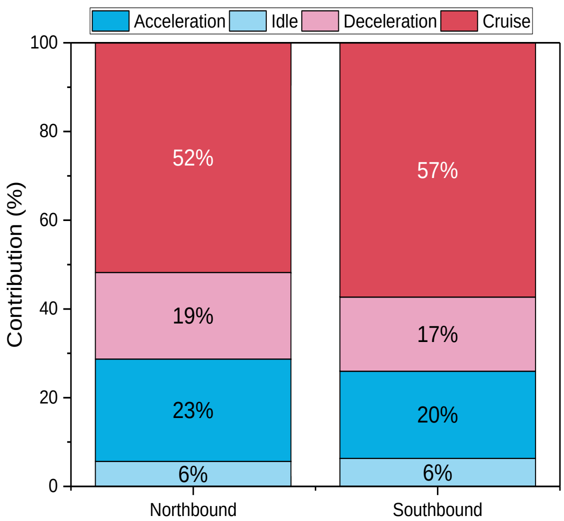
The contribution of driving modes, including idle, deceleration, acceleration and cruising, to a standard efficient journey and fuel consumption is shown in **Figure 10**. The fuel consumption was calculated, and then the contribution of the different driving modes to the average accumulated fuel consumption was calculated. The percentage of each segment was also calculated to confirm traffic congestion, stop and cruise (vehicle speed ≥ 5 km/h and acceleration from -0.1 ms^{-2} to +0.1 ms^{-2}). Different driving modes were defined according to **Table** .

Figure 9 shows that cruise, deceleration and acceleration have almost similar contributions to the duration of the journey, while the idling mode of driving has the smallest contribution among the others. For the Northbound and Southbound routes, most of the trip is in cruising mode, with a contribution of almost half for both routes of 52 % and 57 %, respectively. Meanwhile, the Northbound route contribution is followed by acceleration and deceleration at 23 % and 19 %, respectively. Then for the Southbound route contribution followed in deceleration and acceleration mode with 22 % and 21 %. However, the lower contribution of driving modes to the test route appears to be the idling mode (6 % and 7 %), respectively. The results of this study have shown that occasional stoppages have a significant effect on total fuel consumption.

Table 4 Specification contribution driving mode

Driving mode	Description
Idling	zero speed
Acceleration	a> 0.1 ms^{-2}
Deceleration	a> -0.1 ms^{-2}
Cruising	-0.1 ms^{-2}≤ a ≤0.1 ms^{-2}

Figure 10 The contribution of different driving modes to fuel consumption Vehicle



Conclusion

In this analysis, onboard fuel consumption tests were carried out on two public trips to examine and address the fuel consumption of the light-duty vehicle in real-world conditions. In addition, the relationship between driving behaviour and fuel consumption has been investigated. It can be summarized as:

1. Light duty diesel vehicle speed has a significant impact on fuel economy in a given situation; the fuel consumption rate of the vehicle depends more on acceleration than on speed.
2. Accelerations are in normal distributions for the light-duty vehicle on all road trips which aggressive acceleration contributes in part to higher fuel consumption.
3. The variable-speed drive, impact acceleration and speed are considered. When driving at a low speed (average speed: 31-60km/h), the acceleration increases fuel consumption. The average

speed plays a significant role in this style of driving. In high-speed driving (average speed of more than 90 km/h), all parameters (i.e. speed and acceleration) effectively fuel consumption.

This research is the first step in the complete investigation of the effect of the vehicle driving component on fuel consumption. Real-world vehicle performance monitoring has certain drawbacks since topography and slope conditions are not controllable in real-world scenarios. This analysis would then be carried out on the other side of the real-world test, such as the impact of the topography factor on fuel consumption and vehicle efficiency.

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