Driving style and energy consumption with everyday use of a plug-in hybrid electric vehicle

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ABSTRACT: Chargeable vehicles with focus on plug-in hybrid vehicles have become common. The impact PHEVs have on the energy consumption significantly varies with driving behaviour, charging possibilities, and the driving mission. This study investigates how PHEVs function during real driving. Questionnaires, interviews, and measurement vehicle data are evaluated. Key findings is that the fuel consumption decreases significantly at low speeds compared to a combustion engine vehicle, and that the drivers believe that they adopt the driving to the characteristics of the PHEV, but this is not found in the measurement data. The vehicle is behavious in the way the driver wants without any adaptation required.

KEY WORDS: *Plug-in Hybrid electric vehicles, Driver behaviour, Fuel reduction, Field study*

1 INTRODUCTION

Governments across the world are implementing policies to promote electric vehicles to reduce dependence on oil, decrease greenhouse gas emissions, and improve air quality. In the past few years, global electric vehicle sales have risen, from just hundreds in 2010 to 2 million in January 2017 (Jin & Slowik, 2017). Electrification of vehicles clearly have the potential to increase energy efficiency and decrease local emissions. Chargeable vehicles, such as pure electric vehicles (EV) and plug-in hybrid vehicles (PHEV), have greater potential than non-chargeable vehicles such as hybrid electric vehicle (HEV), even though the latter vehicle category shows benefits compared to internal combustion engine (ICE) vehicles when driving in city traffic. Common arguments against pure electric vehicles are limited range, charger availability, and high purchase cost (Axsen & Kurani, 2013). PHEVs have the benefit of managing most of the daily driving on electricity, but with the fuel tank and ICE to increase the range and reduce the necessity of finding chargers during longer trips.

There is uncertainty in how much the electrification of the powertrain affect the energy consumption of the vehicle as this is dependent on vehicle technology, driving patterns, and charging behaviour (Kurani, Axsen, Caperello, Davies, & Stillwater, 2013). For example, the energy consumption per travelled distance is most likely more decreased when the daily driving distance is within the electric range compared to a vehicle driving long daily distances (Vyas, Santini, & Johnson, 2009). Furthermore, the combustion engine is started in a PHEV when the driver demands more power than the electric machine can deliver. The driving behaviour thereby affects how much the ICE is used even when energy remains in the battery. In a simulation study, based on driving patterns in USDOT's National Household Travel Survey database, Kelly, MacDonald, and Keoleian (2012) found that the percentage of travel driven electrically (Utility Factor, UF) was about 70 %. In another simulation study, Karabasoglu and Michalek (2013) found that drivers who travel in urban conditions cut lifetime costs by up to 20% and greenhouse gas emissions by 60 % when using a PHEV compared to a conventional vehicle. It was also concluded that for motorway driving, conventional vehicles provide a lower cost option with a much smaller greenhouse gas penalty. A sufficient charging infrastructure, for example with charging opportunities at the workplace, is essential to improve the UF for PHEVs (Wu, Aviquzzaman, & Lin, 2015). Since PHEV fuel and electricity usage rates are sensitive to both driving distance and drive cycle, it is important to consider real-world conditions when investigating their potential to save fuel (Carlson, Lohse-Busch, Duoba, & Shidore, 2009; Lee, Adornato, & Filipi, 2011; Marshall, Kelly, Lee, Keoleian, & Filipi, 2013; Patil, Adornato, & Filipi, 2009).

There are several barriers that prevent a more widespread uptake of electrified vehicles in general (Jin & Slowik, 2017). As already mentioned, these barriers include the additional cost of the new technology and the relative convenience of the technology considering range and charge times. Drivers often prefers the PHEV over the electric vehicle due to the extended autonomy and fuel flexibility. However, a common concern is the life expectancy of the batteries, charging behaviour and charging infrastructure. In order to increase the share of PHEVs in the vehicle fleet, information campaigns and governmental subsidies may be necessary to motivate purchases (Baptista et al., 2012; Jin & Slowik, 2017).

There are different discharging strategies of the battery in a PHEV. The most common is to discharge the battery as long as there is energy stored in the battery. This mode is called charge depletion (CD). When there is only a small amount of energy stored in the battery, the state-of-charge (SoC) of the battery is fluctuating but the mean value is constant over time. This mode is called charge sustain (CS). If the destination of the trip is known to the vehicle, for example via a navigation system, there are possibilities to use a blended strategy where the CS and CD modes are combined in order to optimise the use of the electric propulsion (Larsson, 2014). Other possibilities to achieve this is to make the driver actively change driving modes of the vehicle. One example would be to only use the combustion engine when driving in high speeds in order to save electric energy to be used later in the driving mission where the benefits are greater. However, this requires that the driver has a very good understanding of the powertrain.

Since the impact PHEVs have on the energy consumption significantly varies with driving behaviour, charging possibilities, and the driving mission (Wu et al., 2015), this study investigates how PHEVs function during real driving conditions with drivers in everyday use. The results are compared to ICEs and EVs in terms of use, energy use and fuel consumption.

2 METHODOLOGY

To investigate how the drivers believe they use the vehicles and how the vehicles are actually used, three related parts in terms of study procedure, design, logged data, participants, and vehicles are included in the paper. To include seldom drivers to the PHEVs, one part studies data and user behaviour in a car rental service at Linköping University. The second part investigates how PHEVs are used as a commuter vehicle. The drivers replaced their ordinary vehicle for a total time of five weeks to investigate if driving behaviour changed over time using a PHEV. Finally, to include pure EV as a reference in the study, data was collected from company cars that were available for data collection.

2.1 Vehicles

Seven vehicles are included in the study. The main focus of the study is on PHEV, and this vehicle configuration is handled by four Volvo V60 D6 with an electric rear axle and the combustion engine connected to the front wheels. For reference, a VW Passat multi fuel petrol/biogas vehicle is used as part of the car rental service at Linköping University, as well as two Mitsubishi i-Miev that are pure electric vehicles.

The Volvo V60 PHEV has five driving modes that the driver can select via buttons on the dash. The default mode is called *Hybrid* and in this mode the electric machine is prioritised for the propulsion of the vehicle as long as there is energy stored in the battery (CD mode). When the battery is depleted the vehicle is operating as a HEV, and the battery state-of-charge (SoC) level is constant over time (CS mode). In *Power* mode, the engine is always running and the gear shift strategy is tuned to increase the performance of the vehicle. In *Pure* mode, electric driving is further prioritized compared to the hybrid mode, i.e. the driver needs to request a larger torque for the ICE to start. Furthermore, e.g. the climate system functions are reduced. The fourth mode achieves all-wheel-drive (*AWD*) and the final mode is denoted *Save* that saves energy in the battery even if the battery is not depleted.

2.2 Design, procedure and participants

When a customer rented one of the three cars included in the study (two Volvo V60 and one VW Passat), the driver was asked to participate in the study. This involved filling in a web questionnaire. The period for this part of the study lasted from February 2014 to August 2015. Of the 179 drivers who agreed to participate in the study, 171 (49 women and 122 men) completed the first questionnaire which included background questions besides questions about the driving experience. The mean age of these drivers were 39 years (21 – 67 years), they had had their driving license for about 20 years (2 – 50 years), and they drove on average 16 000 km per year. The questionnaire was sent out by email directly after the vehicle was returned. In total, data are available from 256 of the 278 rentals (92 %). Vehicle data from the vehicles was acquired and used in the analyses in combination with the data from the questionnaires.

To investigate how a private person use a PHEV, two Volvo V60 were lent out to 10 participants with no previous experience from driving electrified vehicles. The vehicles were mainly used for commuting to work, but also for private errands and other trips. Each driver used a PHEV for in total five weeks divided in three periods; two weeks in autumn 2014, two weeks in spring 2015, and one week in autumn 2015. All participants had charging possibilities both at work and at home. One participant dropped out for personal reasons, so 9 drivers (6 women and 3 men) completed this part of the study. Their mean age was 45 years (31-63 years) and their yearly mileage was on average 17000 km (10000 – 30000 km). The participants signed an informed consent form and filled in the same questionnaire as the rental service group. They also participated in a focus group after the three trials were completed. Vehicle data from the vehicles was acquired and used in the analyses in combination with the data from the questionnaires and the focus groups.

The two pure EVs (Mitsubishi i-Miev), operated as service cars within a local company with several users per vehicle. Vehicle data was acquired from November 2014 to September 2015. The cars were typically used for shorter trips and an employee were free to use the vehicles if they were available. Unfortunately, it was not possible to connect a specific employee to a specific trip. Therefore, only vehicle data is available for this part of the study.

The study was approved by the regional ethics committee in Linköping (Dnr 2013/468-31).

2.3 Instrumented vehicle and log data

Data from the VW Passat and the Mitsubishi i-Miev were collected with Controller Area Network (CAN) data logger (CTAG, Porriño, Spain) storing data from the on-board diagnostics (OBD) port and from a GPS sensor (Navilock 302U, Tragant Handels- und Beteiligungs GmbH, Berlin, Germany). CAN and GPS data from the Volvo V60 were logged using an in-house acquisition unit developed at Volvo. Available vehicle data from the different vehicles is summarized in Table *1*.

Table 1 Available signals from the different vehicles.

	Volvo V60	VW Passat	Mitsubishi i-Miev
Speed	X	X	X
Odometer	X		X
Acceleration	X	X	
Fuel rate	X		
Battery current	X		X
Battery voltage	X		X
State of Charge	X		X
Engine revolutions	X	X	
Drive mode	X		
Gear	X		
Intake manifold pressure		X	
Engine coolant temperature		X	
Pedal positions	X	X	X
GPS coordinates	X	X	X

2.4 Questionnaire

The questionnaire consisted of 11 questions about travel habits, the participants' attitudes regarding the environmental effects of driving, and regarding their attitude towards driving in general. This was followed by 10 questions about properties and features of a car. Finally, two questions were included about how environmentally aware the participants were. All included questions were answered on a scale from 1 – 7, ranging from "Not important at all" to "Very important", or from "Totally disagree" to "Fully agree". In this paper, the questionnaire data are used to categorize the drivers, see Section 2.5.4.

2.5 Pre-processing and data analysis

Results are presented separately either per study group (rental, commuter, company) or per vehicle type. To investigate if the vehicle is driven in a different way when the battery is used for propulsion compared to when the charging level is constant, the PHEVs are separated into CS mode and CD mode based on the SOC and the driving mode. The battery is fully charged when SOC = 100 % and fully depleted when SOC = 0 %. However, the lowest SOC value encountered in practise is 15 – 20 %. CS is here defined as SOC < 25 % or driving in power, AWD or save battery mode. The save mode is included in the CS mode due to that the most common usage of the save mode is to save the energy in the battery and the mode is thereby not often used to store energy in the battery. CD is defined as SOC > 50 % and driving in either hybrid or pure mode.

2.5.1 Map data

The dataset was enriched with *road type* and *speed limit* using map data from OpenStreetMap®. Queries were made to the database to fetch the map object with the minimum 2-dimensional Cartesian distance to each recorded GPS coordinate.

2.5.2 Energy consumption

Energy consumption was measured or computed differently for all vehicle types based on available information. The total energy consumption for a trip was obtained by integrating the power. Since the different vehicle types used different powertrains, all consumption rates were converted to energy to get comparable results, instead of e.g. amount of diesel or gasoline.

For the Volvo V60, the fuel rate was directly available on CAN. Electric energy was obtained by multiplying the battery current with the battery voltage. For the VW Passat, where only OBD signals were available, the fuel rate, $\dot{m}_f$, was computed based on the volumetric efficiency, η_{vol}. The influence of the inlet manifold was included in the expression of the volumetric efficiency (Eriksson & Nielsen, 2014):

$$\eta_{vol} = c_0 + c_1\sqrt{p_{im}}$$

where c_0 and c_1 are constants, and p_{im} the inlet manifold pressure. The fuel rate was computed as (Heywood, 1988):

$$\dot{m}_f = \eta_{vol}(p_{im})\frac{V_D N p_{im}}{2RT_{im}}\frac{1}{AF_s\lambda}$$

where λ is the air-to-fuel ratio, N the engine speed, V_D the engine displacement, R the gas constant, T_{im} the temperature in the inlet manifold, and AF_s the stoichiometric air-to-fuel ratio. The temperature in the inlet manifold is not available and is assumed as a constant. Finally, the energy rate from the Mitsubishi i-Miev was computed by multiplying the battery current and voltage.

2.5.3 Data segmentation

To investigate how driving behaviour depend on vehicle type, the vehicle data was divided into short homogenous time segments. Two different approaches were used, one dataset based on the posted speed limit and one dataset based on whether the vehicle was accelerating, decelerating or driving with constant speed.

Speed limit segments: In this case, the speed limit was used to create homogenous segments. Another possibility would have been to segment the data based on road type, but due to the correlation between road type and speed limit, it is not feasible to use both criteria at the same time. A segment is thus a sequence of consecutive time series values wherein the posted speed limit is constant, see Fig. *1*. The reason for using the speed limit and not the actual speed, is that it may be of interest to analyse how fast different vehicles are driven.

5-second segments: To investigate how the energy consumption varies for the different vehicles at different driving modes, the data was also segmented as constant speed, acceleration and deceleration. In the analyses, the data segments have a fix duration of 5 seconds. Shorter segments are removed and longer segments are divided into several 5-second segments. Constant speed is defined as a segment where the speed fluctuates with less than 0.2 km/h. Acceleration is defined as a segment where the speed is continuously increasing, and deceleration is defined as when the speed is continually decreasing. Acceleration/deceleration data are smoothed with a Savitzky-Golay filter with polynomial order 2 and window size of 5 seconds. The acceleration signal for the Mitsubishi i-Miev was derived by differentiation of speed using the same Savitzky-Golay filter. These segments will be referred to as 5-second segments.

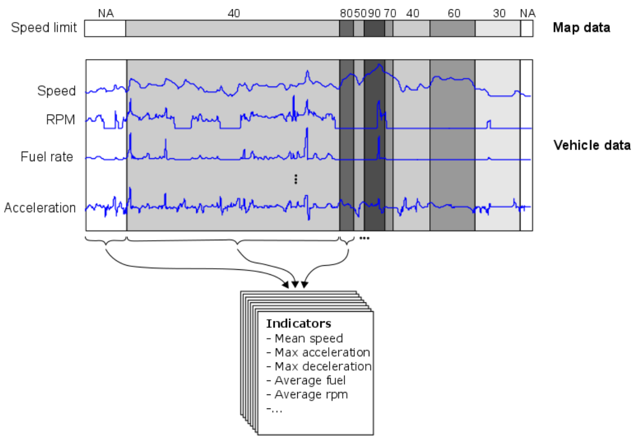

Fig. 1 Illustration of the segmentation process. The posted speed limit defines the segment boundaries. Based on available data in each segment, various performance indicators are calculated for subsequent statistical analysis.

2.5.4 Driver categorization

The drivers were categorized based on a factor analysis of the questionnaire data, resulting in six easily interpretable factors with an eigenvalue greater than 1. The factors are labelled (1) environmentally oriented, (2) Powerful and nice design, (3) Safe and secure, (4) Car oriented, (5) Practical and (6) Alternative travel modes. Based on the factors, six new index variables are calculated by averaging across participants. The index variables are used as input to a cluster analysis to subdivide the participants into two groups. The output is presented in Table 3. Cluster 1 comprise individuals who like powerful engines and cars with good design. They are also generally interested in cars and their technology. This cluster will be referred to as the car-oriented group. The other cluster can be described as more eco-oriented and more practical. These drivers are also more willing to use other transportation modes than car. This cluster will be referred to as the eco-oriented group. Both clusters are highly concerned about safety and security issues when driving.

3 Results and Discussion

3.1 Description of dataset

The number of unique drivers, the number of trips and the distance driven during the field test are summarized in Table 3. In total, 180 drivers drove 3045 trips (84151 km). The two Mitsubishi i-Miev were company cars which were mainly used during office hours, and the usage profile of the Volvo V60, especially for the commuter group, has clear peaks in the morning and in the afternoon, see *Fig. 2a*. The distances of the trips are provided in *Fig. 2b*. The proportion of trips below 5 km are 37 %, 38 %, 67 % and 57 % for the Volvo V60 Commuter, Volvo V60 Rental, VW Passat and Mitsubishi i-Miev, respectively. Corresponding percentages for trips below 35 km, roughly the range of a fully charged battery in the Volvo V60, are 96 %, 97 %, 78 % and 100 %.

Table 2: Results from cluster analyses, with number of participants in each cluster, average ± standard deviation of the index variables.

	Car-oriented (N=100)	Eco-oriented (N=81)
Environmental oriented	4.21 ± 1.05	5.40 ± 0.69
Powerful and nice design	4.76 ± 1.18	3.45 ± 1.04
Safe and secure	6.01 ± 0.87	6.01 ± 0.59
Car oriented	4.01 1.45	2.73 ± 1.03
Practical	3.83 ± 1.41	4.61 ± 0.94
Alternative travel modes	3.36 ± 1.46	5.18 ± 1.17

Table 3: Amount of collected data. The number of drivers is not available for the Mitsubishi i-Miev since no questionnaire data were collected.

Vehicle type	Vehicle Id	Number of drivers	Number of trips	Distance driven (km)
Volvo V60	1	5	453	5665
Commuters	2	4	247	3432
Volvo V60	3	67	684	27589
Rentals	4	56	422	15977
VW Passat	5	48	499	26463
Mitsubishi	6	-	607	4178
i-Miev	7	-	133	847

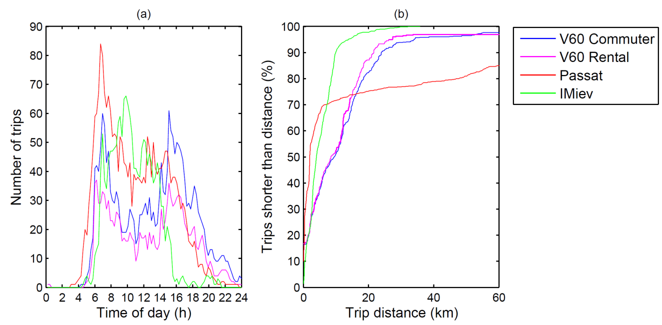

Fig. 2 Number of trips when the vehicles are in motion as a function of time of day (a), and the cumulative percentage of trips below a certain distance (b).

For the PHEVs, UF (defined as the ratio of miles driven in CD mode to total miles travelled) was 65 % and 70 % for the two cars used for commuting, and 28 % and 27 % for the two rental cars. There is a qualitative difference between the commuting cars and the rental cars. The commuting cars were borrowed for an extended period of time with the main purpose of going back and forth between the participants' home and work place, where it was possible to charge the battery. This is close to an ideal situation for a PHEV. For the rental car drivers, who probably just wanted to get from A to B with as little inconvenience as possible, it is likely that they just didn't bother to charge the vehicle. The distances of the trips are similar between the commuter and rental cars (Fig.

2b), but it is likely that each rental consisted of several trips, without recharging along the road. This would explain the large difference in UF.

3.2 Energy consumption

The energy consumption for the different vehicles are presented in Fig. *3*. The figure presents the energy consumption grouped as a function of the vehicle speed, calculated from the speed limit segments. The upper plot in the figure presents the total energy consumption, i.e. the total of electric energy and fuel energy. Note that, as stated above, the size of the different vehicles varies, leading to that the energy consumption cannot be compared between the vehicles. However, how the energy consumption varies as function of for example speed can be compared. In the upper plot in Fig. *3*, it is shown that the energy consumption increases more for the VW Passat than for the other vehicles at low speeds. The main reason for this is the decreased efficiency at low power demand. The minimum energy usage is found to be at about 70 km/h, which is higher compared to the optimal speed computed in Llamas and Eriksson (2014) but still reasonable since the engine speed is allowed to be very low in that study. The energy consumption is increased also in the electrified vehicles at lower speeds, but not as much as in the ICE case. One explanation for the increased energy consumption at the lower speed in the electrified vehicles is that the power for climate control of the compartment is almost independent on the vehicle speed. When the speed is low, the energy consumption per travelled distance for temperature control of the compartment thereby increases, and can be a significant part of the energy consumption.

The middle plot in in Fig. *3* presents the electric energy consumption and the lower plot the fuel energy consumption, i.e. diesel or petrol. The advantage of hybrid vehicles (V60 in CS mode) is recognised by the absence of increased fuel consumption for lower speeds compared to the ICE vehicle. The advantage of PHEV (V60 in CD mode) is also evident – the fuel consumption when driving below 50 km/h is practically zero.

The energy consumption, calculated from the 5-second segments, while driving at constant speed, while accelerating and while decelerating is shown in *Fig. 4*.. The decrease in energy consumption and fuel reduction, using the PHEV compared to the HEV, when driving at constant speed, is clearly shown. The fuel consumption is close to zero for V60 in CD mode for speeds up to 100 km/h. During accelerations the difference is not as clear for the two cases where the battery is charged or depleted. One reason for this is that the combustion engine is started at accelerations where the power from electric motor is non-sufficient to deliver the power required by the driver, even though there is energy stored in the battery. Even though, the fuel consumption for the V60 in CD mode is approximately halved at accelerations for speeds between 20-70 km/h compared to when operating in CS mode. All vehicles recuperate energy during braking. The V60 recuperates more energy when the battery is almost empty, i.e. in CS mode, compared to when the battery has a higher SoC. This is because it is easier to charge a battery with low SoC. The characteristic of energy recuperated in the i-Miev is similar to the corresponding signal for the V60. The i-Miev is a much smaller vehicle than the V60, resulting in that the kinetic energy that is possible to recuperate is smaller for that vehicle compared to the V60.

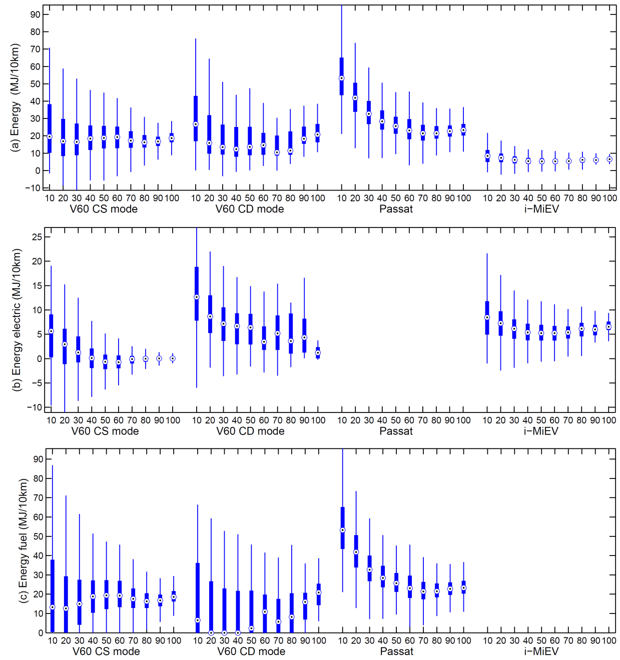

Fig. 3 Boxplots of total (top), electric (middle) and fuel (bottom) energy consumption grouped by vehicle type and vehicle speed (km/h). Outliers (outside of 2.7 standard deviations) are not shown.

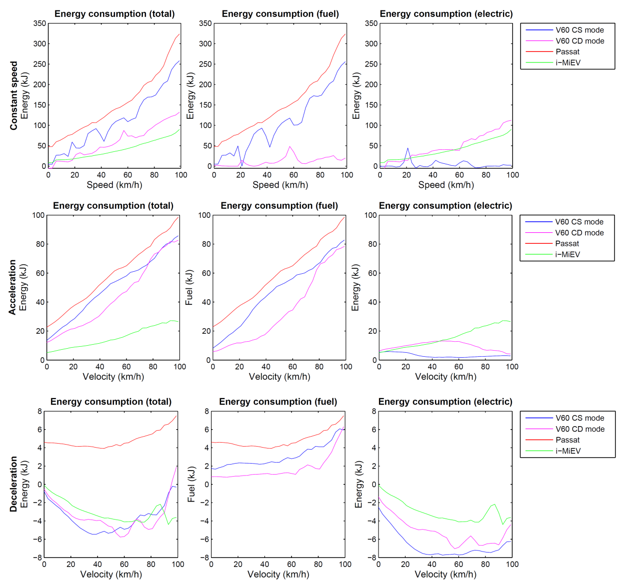

Fig. 4 Mean total (left), electric (middle) and fuel (right) energy consumption across all 5-second segments as a function of vehicle speed.

3.3 Driver behavior and choice of driving mode

The accelerations and accelerator pedal positions for the different vehicles are presented in Fig. *5* as a function of the vehicle speed. In each five second segment fulfilling the criteria for being categorized as acceleration (section 2.5.3), the maximum acceleration within the segment is computed. In the left plot in Fig. *5* the mean of these maximal accelerations in every segment is presented as a function of the vehicle mean speed in the segment. It is shown that the electrified vehicles accelerate harder at speeds up to 20 km/h compared to the ICE vehicle. This is because electric machines deliver high torque even at low speeds, which is not the case for the ICE. The V60 in CS mode performs similarly to the V60 in CD mode since there is most likely some energy stored in the battery that is used at accelerations at low speeds also in the CS mode. In Fig. *5*b, it is shown that the accelerator pedal position has a clear offset for the different vehicles, but the general appearance of the accelerator pedal position is the same for all vehicles. The pedal position is high at take-off, and then decreases to increase in an affine shape with the speed of the vehicle. There is no difference for the V60 whether the vehicle is operated in CS or CD mode. The accelerator pedal position, as a function of speed, increases somewhat faster for the VW Passat and the Mitsubishi i-Miev compared to the Volvo V60. A figure for the deceleration behaviour is not included in the paper, but there are no clear differences between vehicle types regarding braking.

When asked about their driver behaviour when driving the Volvo V60, more than half of the drivers (53%) from the rental service vehicles stated that they had adapted their behaviour to fit the car. They claimed that they accelerated less hard so that the diesel engine did not start (27%). Some also claimed that they generally drove more calmly since it was an eco-friendly car (19%), while some in contrast claimed that they accelerated harder since it was a powerful car (17%). The focus group interviews confirmed this, where all drivers believed that they adapted their driving to fit the car. None of this is however shown in the data (see e.g. Fig. *5*), which implies that they believed they had adapted, or had the intention to adapt their behaviour, but this did not result in any actual change.

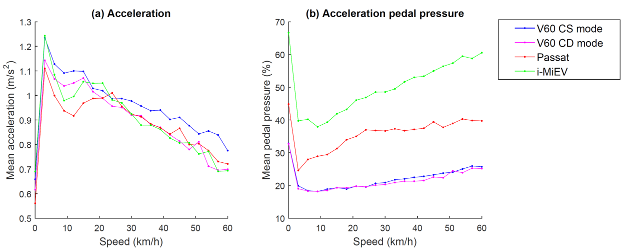

Fig. 5 The mean value, across all 5-second acceleration segments and as a function of speed, of the maximum acceleration and max accelerator pedal position within each segment.

As stated in section 2.1, the V60 PHEV has five different driving modes. The time distribution of what mode the car-oriented and the eco-oriented groups have engaged is presented in Fig. *6*. The default mode at every start of the vehicle is Hybrid, which also is the most commonly used mode for both categories of drivers. There are no large differences between the two groups of drivers, but the car-oriented group is more likely to drive in the pure mode. Since this group has stated that they are more prone to explore technology and test all systems in a new car, this is most likely due to interest in the new technology rather than concern for the environment.

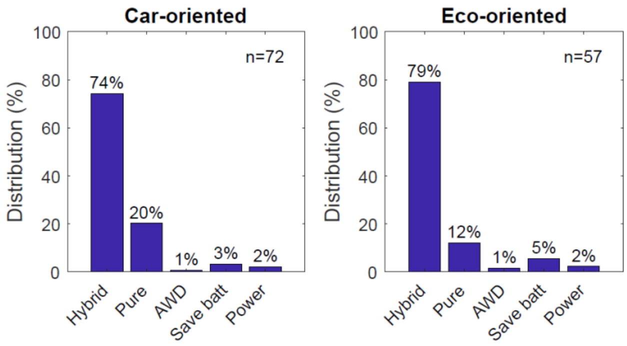

Fig. 6 The percentage distribution of selected driving mode for the two clusters of drivers.

4 FINAL DISCUSSION AND CONCLUSIONS

All in all, PHEVs are more energy efficient than both ICEs and HEVs. They are also relatively easy to use and do not require any changes in driving behaviour. This make PHEVs a good solution to reduce the use of energy while still having the flexibility of an ICE vehicle, without the disturbance of range anxiety. To a large extent, the daily commute can be covered by only using the electric motor. This, however, requires that the battery can be charged when parked at the workplace.

The questionnaire results show that many drivers believe they adapt their behaviour to the vehicle, e.g. by accelerating smoother or taking care to accelerate in such a way that the ICE does not start. However, a comparison with the collected vehicle data shows that they do not adapt their driving at all. Instead it seems that their normal driving style will fulfil their intentions anyway, and there is no difference between the V60 in CS or CD mode regarding pedal position and acceleration. There is a difference in accelerations at low speeds where the electric vehicles have a higher acceleration, but this is more likely due to the different characteristics of the vehicles. Even though drivers have the intention to adapt their driving, and they think that they do, the powertrain of the PHEV is adapted in such a way that it corresponds naturally to a large proportion of the driving. So, the drivers adapt but without actually changing their behaviour. This is also confirmed by the fact that they do not change their behaviour, neither initially, nor over time, which would be expected if behavioural adaptation had occurred, as shown by Lai, Hjälmdahl, Chorlton, and Wiklund (2010).

There are some limitations in this study. Even though the vehicles used for comparison in this study are paired as much as possible within the available fleet of cars, they have different models, different powertrains and, for the EV, different size. On top of that, the energy consumption calculations differ between vehicle types. Absolute levels of energy consumption should therefore not be compared. Instead, relative and qualitative differences between vehicle types are the main foci in this paper. In future studies, it would be interesting to compare identical vehicles with different powertrains.

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