36th International Electric Vehicle Symposium and Exhibition (EVS36)
Sacramento, California, USA, June 11-14, 2023

Plug-in hybrid electric vehicles fleet penetration issues: empirical results from two Portuguese business fleets

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Executive Summary

Driving behavior and vehicle's fuel type can explain real world fuel consumption values. One common alternative to pure electric vehicles (EV) are the plug-in hybrid vehicles (PHEV). Their standard driving cycles typically report low fuel consumption and low greenhouse gas (GHG) emissions.

This paper shows data on eight PHEV (four distinct models) operated by two different companies and aggregated on Daloop's fleet management platform. Our results show that on average 40% of total distance is done using electricity, fuel consumption is similar to ICE vehicles and charging from grid only happens after travelling 3 times the average distance. Switching to a PHEV must be aligned with new driving and charging behaviors in order to achieve the desired savings. A key takeaway message is that charging from the grid and having fully battery level for every business day increases the share of electric driven distance and decreases total costs.

Keywords: PHEV (plug in hybrid electric vehicle), fleet, telematics, vehicle performance, user behaviour

1 Introduction

Nowadays the world is changing to electric mobility with the goal of reducing pollution and greenhouse gas emissions, both locally and globally. Cars sales of full electric vehicles (FEV) and PHEV have been continously increasing ever since electrification technologies became available in the market [1], [2].

Regarding sales in the European Union (EU) + European Free Trade Association (EFTA) + United Kingdom (UK), and comparing 2022-Q2 versus 2021-Q2, PHEV sales have decreased 12,5% and BEV have increased 11,1% [3]. The PHEV negative trend may be explained by the newest EU commitment to update PHEV carbon dioxide (CO_2) emissions measurement procedures. PHEV official advertised emissions are lower than what real operation shows [4], [5]. The biggest difference between PHEV and FEV is that the first one has both an ICE and an electric motor, while the second has just an electric motor.

Currently PHEV share is one third of the EV market, a number to take into account when discussing electric and fuel efficiency. Before purchasing and to take full advantage of a PHEV, there are some points to consider, i.e., average daily distance, access to electric charging points and charging and driving behavior. Some EU countries have implemented tax benefits and purchase incentives both to private use or company fleets [6]. These incentives have led buyers to believe that their operation costs are lower or that they are being environmentally friendly, which is a topic addressed in this paper.

In addition, we attempt to enrich existing empirical studies about distinct PHEV models regarding their driving/charging patterns focusing on their efficiency and sustainability. The vehicles belong to two different Portuguese business fleets and their data is not for testing purposes, it represents real trips regarding their business and operations. Table 1 presents the literature review and how our analysis fits into the framework.

2 Data and Methods

The data used in this analysis was obtained from eight PHEV (four distinct models), which had installed an internet-of-things (IoT) device, commonly known as telematic device. The telematic device monitors the controller area network (CAN) bus properties, such as, vehicle speed, odometer, fuel level and state of charge (SOC) in addition to other parameters powered by Global Navigation Satellite System (GNSS) technologies such as speed, latitude and longitude. It also allows a high-resolution data, i.e., each change in a property (vehicle speed as an example) is saved in a packet and every six seconds this same packet is sent to the big data platform. Then the data is retrieved by a software analysis tool and data cleaning techniques are applied (e.g., hampel filter on fuel level and SOC).

The advantages of the study dataset are a) communication frequency, i.e, real raw data every six seconds (when driving or plug-in charging) and every hour while stopped and b) the PHEV models covered, which are new to the market and belong to different businesses/companies (named as A and B for privacy reasons). The disadvantages are a) the small sample size (i.e., just eight vehicles) and b) short data collection period.

Vehicles metadata and data collection period are on Table 2. One of the columns displays *Electric autonomy*, based on Worldwide harmonized Light-duty vehicles Test Procedure (WLTP). We have found minor differences in different data sources about *Battery capacity* (Total vs Usable) and *Electric autonomy* and the ones we chose are presented on the table. Regarding the data collection period, for company A it is equal to 165 unique consecutive days (approximately 6 months) and for company B it is 362 unique consecutive days (almost one year).

Table 1: Literature review

Reference	Paper year	Data source	Number of vehicles	Distinct PHEV models	Private or Business	Country
[5]	2022	Survey and data logger	9,000	100	Private and Business	EU
[7]	2022	On-board diagnostics (OBD)	10,488	1	Almost private	United States of America (USA), Canada
[8]	2012	GPS tracking * different from telematic	229	0	Private	USA
[9]	2019	OBD	1,768	1	Private	USA
[10]	2015	GPS tracking	432	0	Private	Sweden
[11]	2020	Survey	5,418	17	Private	USA
[12]	2020	Survey and data logger	153	4	Private	USA
[13]	2019	GPS tracking	49	1	Not Availabe	China
[14]	2018	GPS tracking and manual input	1,831	5	Almost private	USA, Canada and Germany
[15]	2021	GPS tracking and manual input	>100,000	66	Private and Business	USA, Canada, China and EU
Current paper	**2023**	**Telematics**	**8**	**4**	**Business**	**Portugal**

Table 2: Vehicles metadata

Company	User type	Vehicle brand & model	Engine type	Quantity	Battery capacity (kWh)	Electric autonomy WLTP (km)	Data collection period (y/m/d)
A	Administrative	Peugeot 3008 SUV Hybrid	Gasoline	4	11.8 [16]	59 [17]	2022/05/01 to 2022/10/12
B	Administrative	BMW 330e	Gasoline	2	10.4 [18]	59 [18]	2021/10/15 to 2022/10/12
		Mercedes E300 DE	Diesel	1	13.5 [19]	50 [19]	
		Mercedes A250e	Gasoline	1	15.6 [20]	68 [20]	

In this paper whenever electric distance is meant as distance travelled when electricity was being consumed by its battery pack and used as unique source to power the vehicle movement no matter how the battery was charged (if from the grid or the ICE), except in cases where explicitly explained. Energy used for auxiliary systems such as Air conditioning, if used, is included in vehicle consumption data as we do not have enough detail to separate it.

We have also calculated the *Electric driving share (%)*, i.e., the percentage of total distance only consuming electricity from the battery (charge-depleting mode); this does not follow the WLTP utility factor (UF), which states that ICE can also be working at the same time.

Concerning CO_2 emissions, which are on Results and Discussion section, they are calculated using standard CO_2 factors equal to 2.67455 $kgCO_2$eq. per liter and 2.421 $kgCO_2$eq. per liter (according to DIN 16258/KS2050), for diesel and gasoline respectively [5]. The method used is explained via equation (1),

$$Company\ CO_2\ emissions = \left(\sum_{i=1}^{n} fuel\ consumed_{i,j}\right) \times CO_2\ factor_j\ , \qquad (1)$$

$$where\ n\ is\ the\ total\ number\ of\ days\ and\ j\ the\ fuel\ type$$

In order to calculate costs and financial savings we have taken into account market average prices, in this case, for gasoline and diesel (E5 and B7, respectively, according to NP EN 16942:2017) in the Portuguese market. For year 2022 the average price for gasoline was 1.851 €/liter and for diesel 1.796 €/liter [21]. Regarding electricity prices each company operated with its own electricity tariff, 0.179€/kWh and 0.133€/kWh, for company A and B respectively.

3 Results and Discussion

Table 3 presents the main aggregated outputs for each company. The *Total distance* is based on odometer values, *Median distance / vehicle / day* and *Median electric distance (ED) / vehicle / day* are based on the days the vehicles were driven, i.e., if in a specific day a vehicle was not driven it is not considered to the median. Concerning *Electric driving share*, *CO_2 emissions / distance* the figures are also based on the days the vehicles were driven and *Average fuel consumed* takes into account the *Total distance*. On the other hand, *Electricity charged grid* and *Electricity consumed battery,* consider all the days within the data collection period because even if the vehicles were stopped (i.e., no distance travelled), the battery could still be charged or discharged.

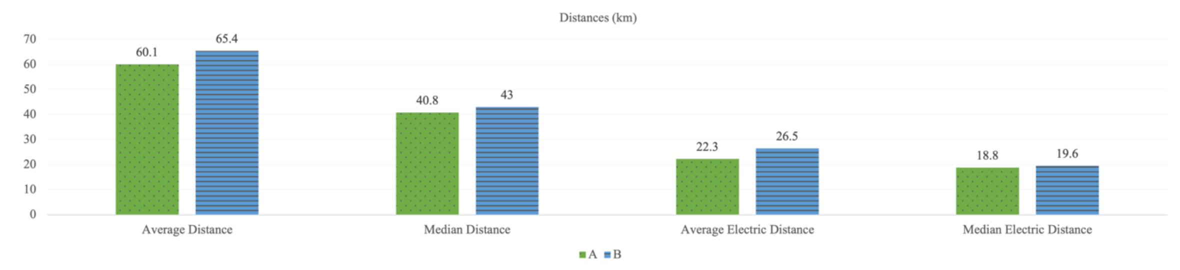

Figure 2: Comparison of average and median distance / vehicle / day and average and median electric distance /vehicle / day between companies A and B (from left to right)

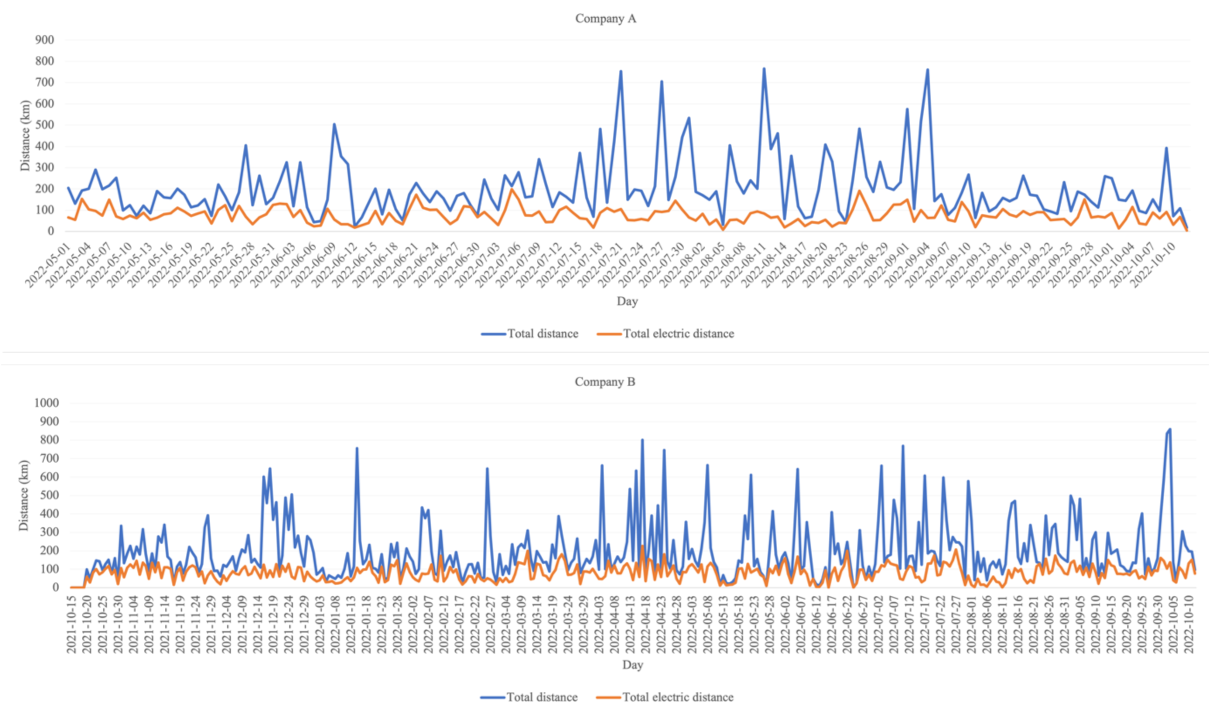

Figure 1: Total distance (blue line), in km, and total electric distance (orange line), in km, per day and per company (top company A, bottom company B)

Table 3: Results of PHEV data analysis

Company	Total distance (km)	Median distance (km) / vehicle / day	Median ED (km) / vehicle / day	Electric driving share (%)	CO_2 emissions / distance (kg CO_2/km)	Average fuel consumed (l/100 km)	Electricity charged grid (kWh)	Electricity consumed battery (kWh)
A	33,613	41	19	37	0.162	6.7	1,758	3,258
B	71,628	43	20	40	0.129	5.3	4,643	9,006

Table 4: Total distance (km) per vehicle

Distance (km) company A				Distance (km) company B			
Peugeot 3008 Hyb.	Peugeot 3008 Hyb.	Peugeot 3008 Hyb.	Peugeot 3008 Hyb.	BMW 330e	BMW 330e	Mercedes A250e	Mercedes E300 DE
10,914.3	6,848.2	7,876.2	7,974.7	16,850	12,957	22,750	19,071.6

Distances

The *Median distance / vehicle / day* is quite similar between companies and an interesting point about it is both are smaller than their EVs batteries autonomies (Table 2), so the full battery capacity is being neglected. *Electric driving share (%)* was 37%, for company A, and 40%, for company B. Thus the global share of electric mode is not even 50%.

Figure 2 compares the average and median values of *distance travelled / vehicle / day* and *electric distance travelled / vehicle / day* on each company. Figure 1 shows the total distance travelled per day by company and the same for total electric distance. In summary, for company A total electric distance is 12,485.8 km and total ICE distance is 21,127.2 km; about company B, total electric distance is 28,996.2 km and total ICE distance is 42,631.8 km. By total ICE distance we mean distance travelled when the engine was working.

Table 4 shows the total distance (km) per vehicle during the data collection period.

Energy consumption and charging behaviour

Taking into account Table 3 data it is possible to calculate the total energy charged (ECE) by the ICE, per company, according to (2),

$$Total\ ECE\ ICE[kWh] = Electricity\ consumed\ battery - Electricity\ charged\ grid \quad (2)$$

Company A *Total ECE ICE* is 1500 kWh and company B *Total ECE ICE* is 4363 kWh. Company A charged 54% of its energy from the grid while company B charged 52%. This also means that 46% of the electricity used by vehicles was produced by the internal combustion engine for company A and 48% for company B.

One question raised was: how many kilometers, on average, do the vehicles of each company travel before plugging-in again? In short, the distance travelled between charging frequency. For this purpose, we define "charging" as a) plugging-in a charging cable and b) a minimum increase of 20% SOC. The method used is shown by equation (3). Let us consider the average distance travelled by the vehicles before plugging-in the vehicle again as "Y":

$$Y = average\ daily\ distance\ \times\ average\ days\ without\ plugging\ cable \quad (3)$$

For company A, $average\ daily\ distance = 60.1$ and $average\ days\ without\ plugging\ cable = 2.9$; for company B, $average\ daily\ distance = 65.4$ and $average\ days\ without\ plugging\ cable = 3$.

The final results are shown on equation (4):

$$Y = \begin{cases} \sim 174\ km, company\ A \\ \sim 196\ km, company\ B \end{cases} \quad (4)$$

There is also another important metric to observe, which is the median energy charged, 8.1 kWh and 8 kWh, for company A and B, respectively. The average values are 7.2 kWh and 7.6 kWh respectively. For charging times, the median and average values for company A are quite similar, around 1h55minutes, and for company B are 2h26minutes and 3h08minutes, respectively. Both companies take similar energy values per charge, on median and average, but company A takes less time to do it.

In the Table 5 we provide the average energy consumption (AEC) per vehicle. This value was obtained dividing total energy consumption (kWh) of each vehicle per electric distance (km).

Table 5: Average energy consumption (AEC), in kWh/km, by vehicle

AEC company A				AEC company B			
Peugeot 3008 Hyb.	Peugeot 3008 Hyb.	Peugeot 3008 Hyb.	Peugeot 3008 Hyb.	BMW 330e	BMW 330e	Mercedes A250e	Mercedes E300 DE
0.32	0.30	0.21	0.26	0.25	0.28	0.25	0.51

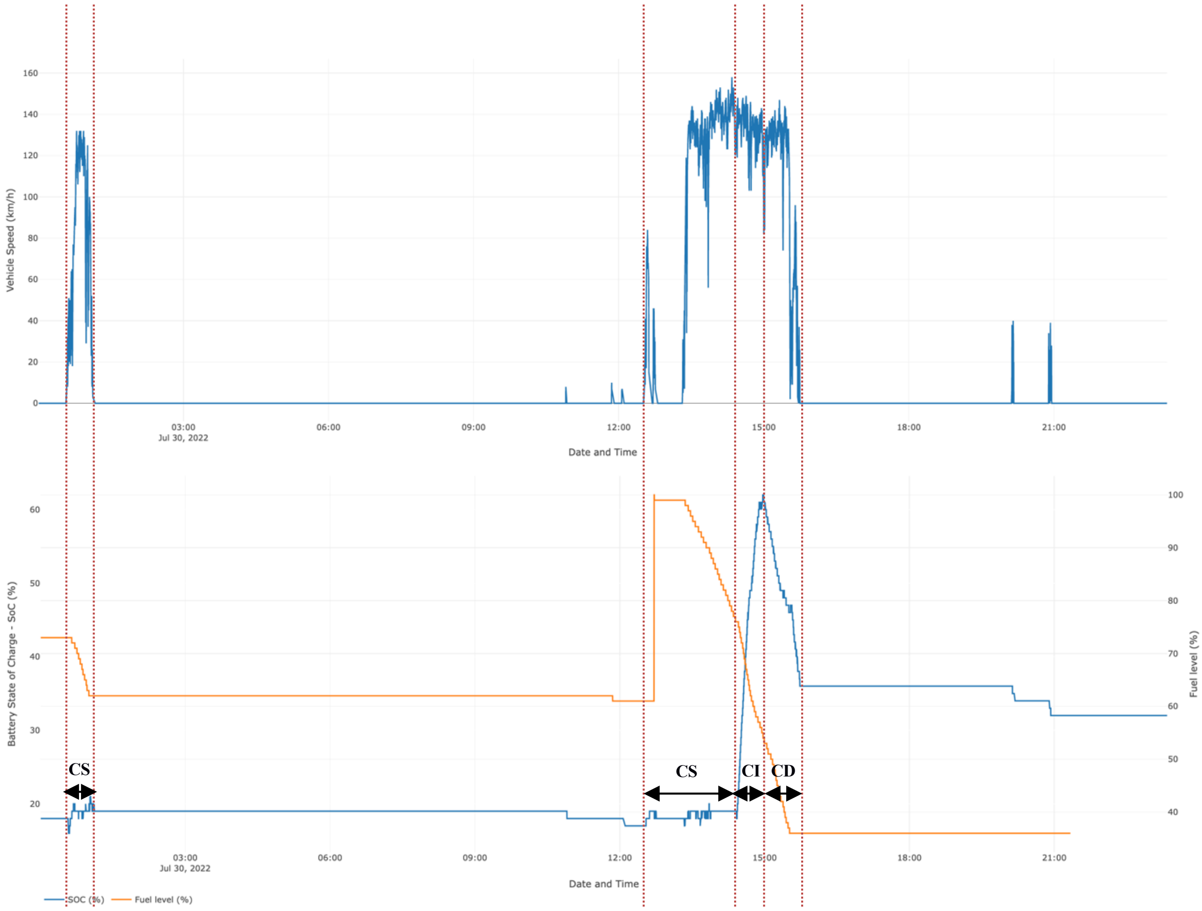

Figure 3: Example of different charging modes while driving, on a vehicle of company A; first plot is vehicle speed, then SOC (%) and fuel level (%) are on the same plot (top-down view); the red dot vertical lines emphasize the multiple charging modes

Figure 3 shows three different properties, vehicle speed (km/h), SOC (%) and fuel level (l) of a vehicle belonging to company A on July 30, 2022. We can identify three charging modes: charge-depleting (CD), charge-increasing (CI) and charge-sustaining (CS). CI started at 2:25 p.m. and ended at 2:58 p.m., with SOC increasing from 18% to 62%, thus 44% of the battery recharged by ICE. On the same period, the fuel level decreased from 76% to 55%, which means 9.7 liter of fuel consumed travelling 73km. The average fuel consumption only for CI period is equal to 13.8 l/100km. CI mode is equivalent to run on fuel (diesel or gasoline) both to move the vehicle and to recharge the battery pack.

Fuel consumption and GHG emissions

For fuel consumption, companies A and B consumed a total of 2252 liters and 3820 liters, respectively. On average, they show similar values as typical ICE passenger vehicles, with average fuel consumptions per company between 5 and 7 l/100km (results on Table 3). Figure 5 and Figure 4 show the daily fuel consumptions distribution (l/100km) per company and vehicle model, through a boxplot, and Table 6 explains the mean and median values of these boxplots. We compare the fuel consumption of all daily distances versus daily distances less than 60 km in order to match with the average electric range metadata (Table 2). The formula used to plot Figure 5 and Figure 4 is given by equation (5),

$$fuel\ consumption_{i,j}\left[\frac{l}{100km}\right] = \frac{fuel\ consumed_{i,j}\ [km]}{total\ daily\ distance_{i,j}\ [km]},\quad (5)$$

$$where\ i\ is\ the\ day, j\ the\ vehicle$$

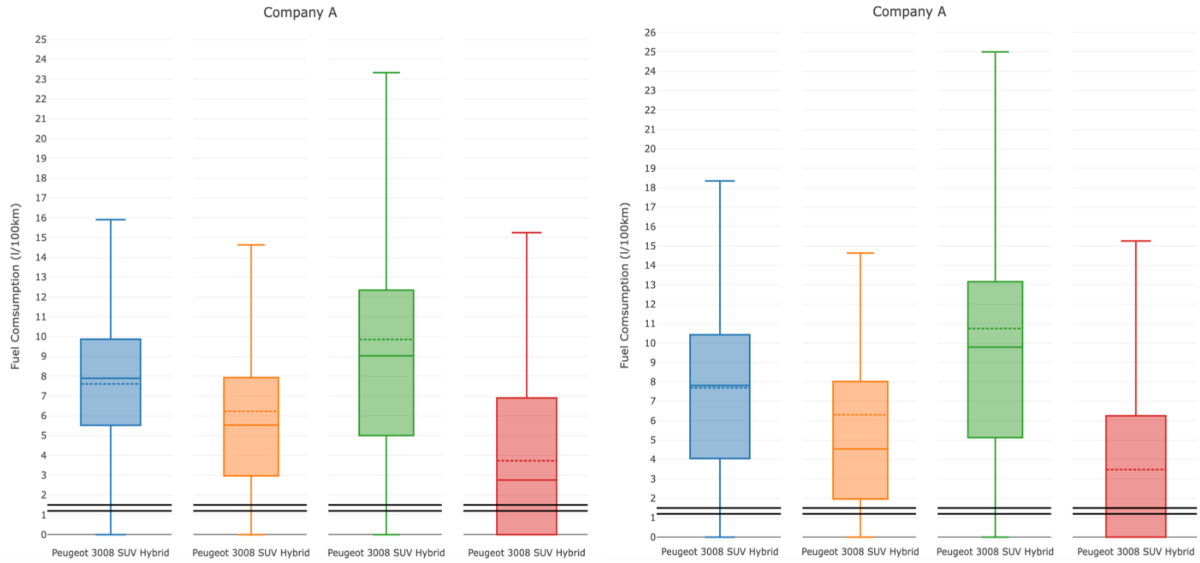

Figure 5: Boxplots of fuel consumption (l/100km) per vehicle for company A. On the left it is plotted for every daily distances travelled and on the right for distances smaller than 60km; the black horizontal lines match the WLTP min and max values of each model; the median is represented by a solid dash and the mean by a dash, all coloured. Y-axis scale does not necessarily match between the plots.

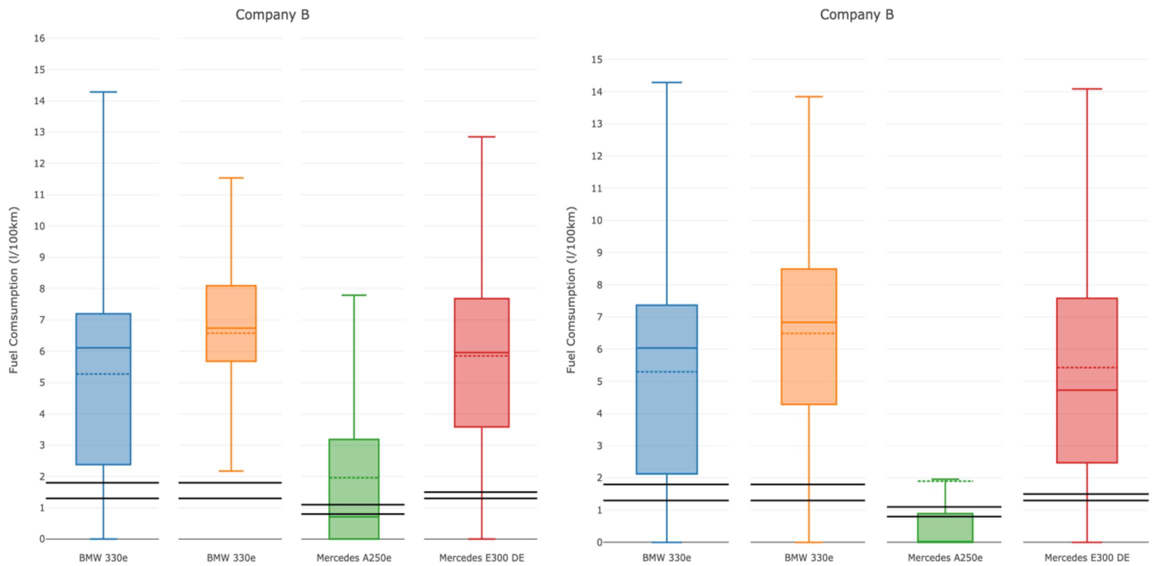

Figure 4: Boxplots of fuel consumption (l/100km) per vehicle for company B. On the left it is plotted for every daily distances travelled and on the right for distances smaller than 60km; the black horizontal lines match the WLTP min and max values of each model; the median is represented by a solid dash and the mean by a dash, all coloured. Y-axis scale does not necessarily match between the plots.

IWhen comparing with WLTP values (Table 6), the real fuel consumptions are higher, e.g., on company A the WLTP max is 1.5 and only one vehicle achieves this value; the others have fuel consumptions from 1.87 to 7.13 times higher than WLTP max. Company B has also deviations from WLTP max about 3 to 5 times, except for one vehicle, with its mean fuel consumption just 1.8 times higher than WLTP max and the median even lower that WLTP min; this vehicle is also the one with high electric autonomy according to Table 2.

Regarding CI mode, the only vehicle that did not show this behaviour is the one resulting in least fuel consumed on company B and on the overall analysis.

Table 6: Explanation of mean fuel consumption values of Figure 5 and Figure 4, following the same vehicles order on each chart, from left to the right

Company	Car model	WLTP (l/100km)		Mean fuel consumption (l/100km)		Median fuel consumption (l/100km)	
		Min	Max	All distances	Distances < 60km	All distances	Distances < 60km
A	Peugeot 3008 SUV Hybrid	1.2	1.5	7.6	7.7	7.9	7.8
				6.2	6.3	5.5	4.5
				9.9	10.7	9	9.8
				3.7	3.5	2.8	**1.5**
B	BMW 330e	1.3	1.8	5.3	5.3	6.1	6
				6.6	6.5	6.7	6.8
	Mercedes A250e	**0.8**	**1.1**	**2**	**1.9**	**0.7**	**0**
	Mercedes E300 DE	1.3	1.5	5.8	5.4	5.9	4.7

For CO_2 emissions they are very close to a standard ICE vehicle. This may be explained by 1) low electric driving share and 2) the PHEV operation modes being used (especially CI and CS). Table 3 shows an average emission of 0.162 $kgCO_2/km$ and 0.129 $kgCO_2/km$ for company A and B, respectively. On Figure 6 the same metric is shown, average CO_2 emissions, this time per vehicle, and its comparison with WLTP standards, using the same data sources on Table 2; in the cases where no data was available for WLTP emission values, the study either used fixed values or an average between the max and min [22], [23].

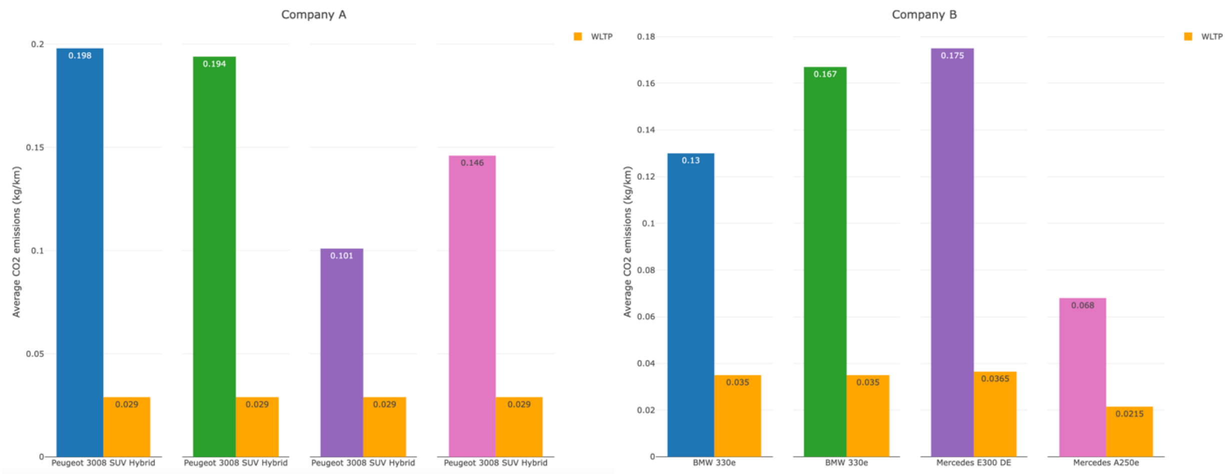

Figure 6: Comparison of real average CO_2 emissions versus WLTP (orange bar, always the one sticked to the right) per vehicle; left chart is for company A and right chart for company B. For company A it follows the same vehicle order as in previous tables and charts.

Based on the results of Figure 6 all the vehicles of both companies show much higher real values than those stated by WLTP tests. They are 3.2 to 6.8 higher than WLTP values.

Costs and financial savings

Table 7 presents a simplifed cost analysis for each company including the current status costs (CSC) and three future scenarios. There are 4 rows per company: first row represents the CSC, i.e., the costs each company had based on their usage, and then three future scenarios costs (FSC1, FSC2 and FSC3); for simplification, “blended-mode” is not considered on future scenario costs, e.g., engine and electic motor working simultaneously to run the vehicle.

Error! Reference source not found. it summarises the definition of the different scenarios in order to understand the whole cost pipeline. The financial savings per company, in €, are calculated following the order of equations (6) to (10).

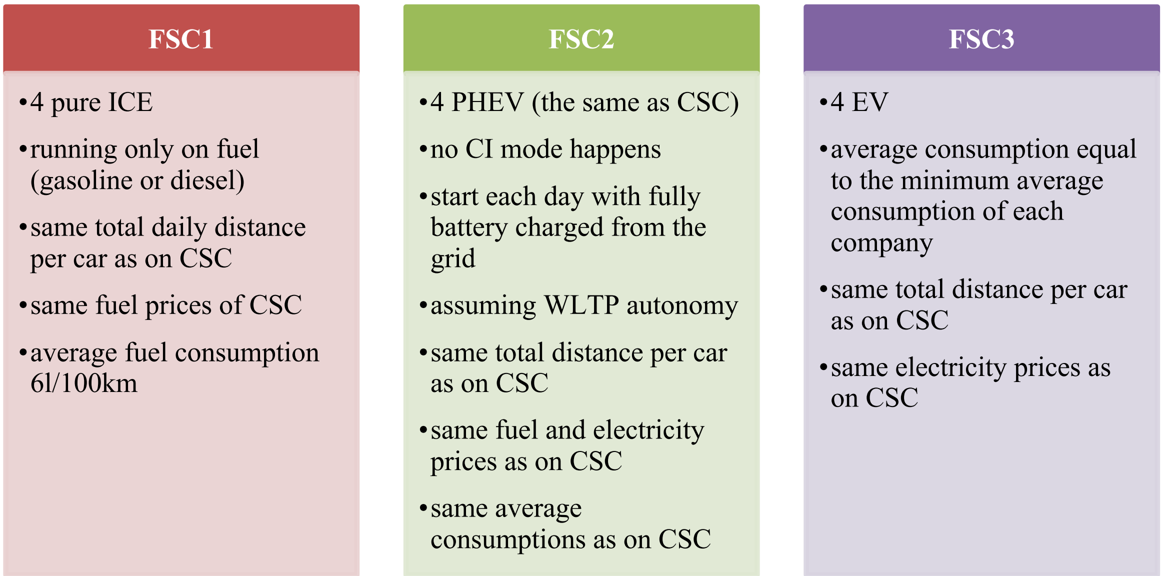

Figure 7: Explanation of FSC limitations

$$Total\ fuel\ cost\ [€] = \sum_{i\ in\ (diesel, gasoline)} fueltype_i\ consumed\ [l] \times fueltype_i\ price\ [€/l] \qquad (6)$$

$$Total\ electricity\ cost\ [€] = electricity\ charged\ grid\ [kWh] \times\ electricity\ price\ [€/kWh] \qquad (7)$$

$$Total\ costs\ CSC\ [€] = Total\ fuel\ cost\ CSC\ [€] +\ Total\ electricity\ cost\ CSC\ [€] \qquad (8)$$

$$Total\ costs\ FSC_i\ [€] =\ Total\ fuel\ cost_i + Total\ electricity\ cost_i\ , where\ i\ is\ the\ scenario \qquad (9)$$

$$Financial\ savings_i\ [€] =\ Total\ costs\ CSC - Total\ costs\ FSC_i\ , where\ i\ is\ the\ scenario \qquad (10)$$

Table 7 column *Total electric distance (ED) from fuel (FF) (km)* represents the total electric distance running with electricity generated by the ICE and it can be computed via equation (11),

$$Total\ ED\ FF\ [km] = \sum_{i=1}^{n} \frac{total\ elect.from\ fuel_i\ [kWh]}{average\ elect.consumption_i\ [kWh/km]}\ , where\ i\ is\ the\ vehicle \qquad (11)$$

In order to compute the *Total costs (€)* on both FSC1 and FSC2 we require 1) average fuel consumption (AFC) per vehicle and average energy consumption (AEC) per vehicle. The AEC and AFC on Table 7 for FSC1 and FSC2 represent the average of the company, but to calculate the *Total costs (€)* we use average per vehicle in order to be more precise (these values are not on the table). These average values are the same as CSC to compare with the same vehicles operation. Regarding FSC3, AEC is the minimum value per company as shown on Table 5.

An interesting result is obtained regarding A - FSC1 if we compare it with A - CSC. It shows that company A is not using their PHEVs economically because it is actually cheaper to run on gasoline than keeping the current behavior.

Table 7: CSC versus future scenarios (FSC1 – ICE running the same daily distance; FSC2 – PHEV running the same daily distance and start the day with fully charged battery from the grid; and FSC3 – EV running the same daily distance)

Scenario	AEC (kWh /km)	AFC (l/100 km)	Total electricity cost (€)	Total fuel cost (€)	**Total costs (€)**	Total electric distance (km)	Total electric distance FF (km)	Total ICE distance (km)	Total distance (km)
A-CSC	0.26	8.46	314.7	4,168	**4,483**	12,485.8	5,496.7	21,127.2	33,613
A-FSC1	0	6	0	3,733	**3,733**	0	0	33,613	33,613
A-FSC2	0.26	8.46	1,049.5	1,899.2	**2,949**	21,547.5	0	12,065.5	33,613
A-FSC3	0.21	0	1,263.5	0	**1,264**	33,613	0	0	33,613
B-CSC	0.31	6.78	616.3	6,988.2	**7,605**	29,010.9	13,755.9	42,617.1	71,628
B-FSC1	0	6	0	7,955	**7,955**	0	0	71,628	71,628
B-FSC2	0.31	6.78	1,862.8	3,440.2	**5,303**	42,802	0	28,826	71,628
B-FSC3	0.25	0	2,381.6	0	**2,382**	71,628	0	0	71,628

About FSC2, with a single and simple improvement on charging behaviour, e.g. keeping the battery fully charged each day that the vehicles moves, this could improve their electric driving share: on company A – FSC2 it would be increased to 64% (compared to 37% of CSC) and on company B – FSC2 to 60% (compared to 40% of CSC). For FSC3, comparing the same distance by running with an EV, there is a clear difference, as no fuel is consumed. The costs reduction would be 72% and 69% for company A and B respectively.

4 Conclusion

Two different companies' fleets covering four different vehicle models and a total of eight PHEV were analysed with data from the same year within different time periods. Our analysis focused on comparing the PHEVs usage and possible improvement scenarios; the study did not focus on possible New European Driving Cycle (NEDC) versus WLTP analysis nor comparison of company/business versus personal usage. All vehicles were assigned to employees with middle management responsibilities typically using the vehicles for both business and private purposes.

The overall total electric distance was less than 40% of the total distance. Even if companies have local EV charging facilities their charging behavior is still not efficient; their employees only charge once every 3 days although their average daily distance is similar to 60 km, so the charging frequency is not enough to cover the daily needs.

Companies should create incentives to keep the vehicles fully charged at the beginning of every business day, as our FSC2 suggests, otherwise fuel consumption and CO_2 emissions will be similar to (or higher than) the equivalent ICE vehicles. FSC2 simulation shows, for these specific companies, that they still could improve their electric driving share to at least 60% just by keeping vehicles fully charged at the begining of the business day. Financial savings between CSC and FSC2 allow a cost reduction of 34% and 30%, on company A and B respectively (regarding fuel expenses).

When a business electrifies their fleet and choses to adopt PHEVs they typically have defined a number of goals, either financial or environmental (or both). This study emphasizes the need to have data-driven decision-making together with adequate behaviour-changing approaches. Even if sometimes the major goal may not be financial at all, there may be a wrong perception of environmental friendliness, where they may be emitting from 3 to 7 times more than the advertised values and even more than a pure ICE vehicle.

As a conclusion, our findings and suggestions about typical PHEV business fleets suggests that:

- EV drivers do not plug them in on a daily basis as they should
- CO_2 emissions are 3 to 7 times more than WLTP
- Charge increasing mode should be avoided
- EDS could increase to 60%
- Financial savings per kWh charged from the grid could increase from 70% to 76% of the fuel cost

Acknowledgments

The authors would like to acknowledge the collaboration of the companies (not named) involved in the study, allowing the data to be collected and analyzed, and which have benefitted from its results.

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