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Understanding the origins and variability of the fuel consumption gap: lessons learned from laboratory tests and a real-driving campaign

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Abstract

Background: Divergence in fuel consumption (FC) between the type-approval tests and real-world driving trips, known also as the FC gap, is a well-known issue and Europe is preparing the field for tackling it. The present study focuses on the monitoring of the FC of a single vehicle throughout 1 year with 20 different drivers and almost 14,000 km driven with the aim to analyze and quantify the true intrinsic variability in the FC gap coming from environmental and traffic conditions and driving factors. In addition, the regression model has been developed to evaluate the importance of these different factors on the FC gap's variability.

Results: The 1-year FC gap measured in this study was 29% while driver's averages were in the range from 16 to 106%. The regression model developed had R^2 equal to 90.4 meaning that more than 90% of the FC gap's variance can be explained with this model and factors measured in this study. The results of the model showed that among all factors analyzed the highest contribution in the FC gap's variance is coming from the average vehicle speed (16.6%), followed by the road grade (13.4%), and trip distance (10.1%). Indeed, the highest FC gaps are measured when the average vehicle speeds were below 20 km/h, the average distance-weighted road grades above 1%, and the trip distances below 5 km. In addition, the impact of driver factors is not negligible (25%) and the highest FC gap is measured for the trips where average positive acceleration was higher than 0.7 m/s^2 (indicating aggressive driving) and the electric power demand higher than 800 W.

Conclusions: The future lifetime on-board fuel consumption reporting is a crucial instrument that will allow the monitoring of the evolution of the FC gap and ensuring that it does not increase over time. The analysis presented in this study is a basis for setting up a more detailed and refined prediction model, which could assist the European Commission in closely monitoring the gap and the underlying factors generating it.

Keywords: CO_2 gap, FC gap, WLTP, Real-world CO_2, Real-world fuel consumption, OBFCM

Background

In 2017, important changes took place in the light-duty vehicle certification procedures ("type-approval") in the European Union. In particular, a new driving cycle and test procedure, the worldwide harmonized light-duty vehicle test protocol (WLTP) [1–3] replaced the old and depreciated New European Driving Cycle (NEDC) and the respective test protocol [4]. The NEDC had been criticized for a long time for being non-representative of actual on-road pollutant emissions and fuel consumption [5–10]. Moreover, it was almost impossible to achieve the official NEDC-based fuel consumption in an ex post reproduction of the certification test with deviations reaching in some cases more than 15% [9, 11]. The WLTP

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is significantly more robust, the driving cycle more transient, and it takes into account a series of conditions that were neglected or not standardized over the NEDC. It has been estimated that, compared to NEDC, WLTP would lead to 15–20% higher CO_2 emissions and fuel consumption [12–15]. However, as any other testing procedure, WLTP cannot fully address all possible operating situations, and for practical reasons it includes some margins that over time might become subject to exploitation [6, 12].

Although WLTP results in more realistic emissions of criteria pollutants (nitrogen oxides, carbon monoxide, particulate matter), the problem for what concerns the CO_2 emissions (and fuel consumption) and real-world vehicle energy demands does not stop with the introduction of the new test procedure [16, 17]. Since 2009 when the mandatory CO_2 targets were introduced [18], the gap between laboratory and real-world CO_2 emissions increased to about 40% in 2017, depending on the source [6, 19–22]. There is now more than sufficient evidence to confirm that the FC gap has been growing over the last decade. In addition, the gap is not peculiar to the European market only. Numerous evidences have shown that differences between laboratory and real-world fuel consumption rates exist also in China and USA [23–25].

The need for real fuel consumption and CO_2 emission reduction is highlighted by the fact that CO_2 emissions from road transport increased by 17% between 1990 and 2014 despite the reductions achieved in the officially certified levels of newly registered cars and vans [21], partly due to due to the increase in transport activity. By 2050 the expected increase in passenger kilometers is 40% [26]. Therefore, monitoring the evolution of the gap and ensuring that it does not increase over time is a crucial policy instrument to be set by the European Commission in order to ensure a level playing field for each vehicle manufacturer present on the market, to incentivize the introduction of new fuel-saving technologies, and move to real, low-CO_2 emission vehicles. The recently adopted regulation setting CO_2 emission standards for new cars and vans requires the Commission to undertake such monitoring by collecting fuel consumption information through on-board fuel consumption monitoring devices (OBFCM). These devices will be mandatory in all new cars and vans put in the market over the next years [1, 27].

For what concerns the difference between officially reported and actual fuel consumption, previous studies usually analyzed the European situation based on large sets of real-world fuel consumption data. In most of these cases only one number is attributed per vehicle model, representing the divergence of type-approval and real-world value [20, 23]. This approach works well when the general trends and the average gap of the total fleet need to be analyzed. Even studies that reported variability in fuel consumption of single vehicle models (e.g., 28) do not refer to a single physical vehicle. One needs to be aware that within one vehicle model there still may be differences in the equipment present in the cars. The same model can have automatic or manual transmission, a different body shape (limousine vs. hatchback), tires with different rolling resistance, or even different powertrains. All these parameters have non-negligible impacts on the fuel consumption and variability in the fuel consumption.

This study aims to analyze and quantify the true intrinsic variability in the fuel consumption gap starting from a single-vehicle basis. The fuel consumption of a single vehicle is measured under its certification conditions (NEDC), under the new type-approval procedure (WLTP), in Real Driving Emissions (RDE) test conditions using a portable emissions measurement system (PEMS), and also under real-world driving (RWD) conditions without specific testing boundaries (non-RDE compliant trips). While the focus of previous studies was mostly on vehicle factors (type-approval official FC value, vehicle characteristics, segment, brand, etc.), the focus of this study is on environmental and traffic conditions, and driving factors. These factors, contrary to vehicle factors that are mostly under the control or responsibility of vehicle manufacturers (OEMs), are independent of OEMs and can be translated to any other vehicle. This study contributes to the body of research on real-world FC gap variability by further analyzing the impacts of these factors on FC gap. The last part of the study presents a modeling approach to check if the environmental, traffic, and the driver factors can separately explain the variability of the FC gap. In addition, indications of the relative importance of each variable on the FC gap are presented.

Methodology

This section presents the characteristics of the tested vehicle and the methodology applied to measure CO_2 emissions/FC in the laboratory and on-road using a PEMS and an on-board diagnostic (OBD) logger. In addition, in the last section details about the multi-linear regression model are presented.

Vehicle tested

The vehicle chosen for the analysis was a 2016, Euro 6b, 2.0L C segment diesel vehicle equipped with 9-speed automatic transmission, typical of vehicles sold in the EU market (initial mileage 10,452 km). It was rented for a period of 18 months and instrumented using a OBD logger ad hoc developed to access all the information available at the electronic control unit (ECU), GPS system (to monitor the position of the vehicle over time), and by two current measurement systems to monitor the operation of the battery and of the alternator. The vehicle was compliant with Euro 6b regulation for pollutant emissions. Selection of automatic transmission for this study reduced the potential variability in fuel consumption as the gear-shift behavior of the drivers was more repeatable and not so much influenced by the driving style. The vehicle had three fuel-consumption-relevant driving modes (normal, sport, and 4×4 mode) and the selection of modes was left to drivers for PEMS and real-world driving tests. For laboratory (NEDC and WLTP) tests the modes required by regulations were used. The vehicle also had engine start/stop function that has been used in the laboratory and for most of on-road trips.

Laboratory tests

Before testing on the road the vehicle has been tested at Joint Research Centre (JRC) premises in the Vehicle Emission Laboratory (VELA) on the chassis dynamometer following the NEDC [4] and WLTP [1] test procedure requirements. Vehicle has been tested over the official cold start conditions. Inertia and road load coefficients applied for NEDC testing were calculated using algorithms developed at JRC with the aim to correlate road loads and the main physical characteristics of the vehicles such as inertia and vehicle dimensions [30]. Road load coefficients for WLTP tests have been calculated from NEDC road loads taking into consideration all procedural differences between NEDC and WLTP procedures that have an impact on the road load [12, 29].

PEMS tests

In addition to the NEDC and WLTP laboratory tests, the vehicle has also been tested on the road under RDE testing conditions with a PEMS. Although RDE aims at securing NOx and particle number (PN) emissions in real-driving conditions, also CO_2 emissions are measured during an RDE test to assess trip normality [1]. Therefore, the collected data present a source of information of CO_2 emissions of a vehicle within the RDE boundary conditions. The test route selected fulfilled the criteria defined in the European RDE legislation [30] (trip duration, urban, rural, motorway operation distances and shares, driving dynamics, temperature and altitude boundaries, etc.). The test route and PEMS are described elsewhere [31]. The same test route was driven five times with the same PEMS mounted on-board in different days of November 2016 (3 tests) and April 2017 (2 tests).

Real-world driving (RWD) tests

In order to assess the variability of fuel consumption from normal vehicle use, the vehicle was provided to 20 different drivers on a voluntary basis. Each driver was requested to perform the same driving style as in normal life with their own vehicle. Fuel was not provided in order not to influence the driving style. All drivers were employees of the European Commission JRC for insurance-related reasons. Attention was paid to having as different as possible trip characteristics, trying to cover as much as possible urban, rural, motorway, and mixed driving conditions. However, due to the nature of the JRC location, there was slightly higher prevalence of rural driving conditions. Around 90 parameters were recorded with the OBD logger, and the ones used in this study are: vehicle speed, instantaneous fuel consumption (further referred also as FC), engine speed, slope, ambient temperature, exhaust temperature, percent of soot mass, alternator current, and coolant temperature. Recording frequency was at least 10 Hz for each variable. The testing campaign took place from December 2016 to November 2017.

Accuracy of CAN FC measurements

Due to the fact that the instantaneous FC recorded with the OBD logger (further referred also as OBFCM) in the RWD tests is the manufacturer calculated value (available at the OBD and not directly measured), it is very important to assess the precision and accuracy of that value. In order to do so, the FC measured from laboratory (NEDC and WLTP) and on-road (PEMS tests) is compared with the OBFCM reported during these tests. In laboratory and PEMS tests the FC is calculated by applying the carbon balance (CB) method (Formula 1) for a vehicle with compression ignition engine fuelled with diesel fuel based on the measurements of emissions of carbon dioxide (CO_2), carbon monoxide (CO) and hydrocarbons (THC):

$$\begin{aligned} \mathrm{FC} = \left(\frac{0.1165}{\rho_{\mathrm{fuel}}}\right) \times [(0.858 \times \mathrm{HC}) \\ +(0.429 \times \mathrm{CO}) + (0.273 \times \mathrm{CO_2})], \end{aligned} \tag{1}$$

where ρ_{fuel} is density of the fuel (kg/l); HC are the emissions of HC (g/km); *CO* are the emissions of CO (g/km); and CO_2 are the emissions of CO_2 (g/km). It should be noted that in PEMS tests concentration of HC is not measured and therefore it is not included in the calculation of FC (impact is rather negligible since HC concentration is three orders of magnitude lower compared to the CO_2 concentration).

Multiple regression model

Multiple regression analysis was used in order to quantify the importance of various factors (independent variables) to the FC gap (dependent variable). Although there are many possible definitions of importance, dispersion importance metrics are the most widely accepted and were used in this study, as they answer the main questions posed at the beginning of the study. Dispersion importance refers to the amount of the independent's variance explained by the regression equation that is attributable to each dependent variable.

The metric proposed by Lindeman, Merenda and Gold [32] which satisfies the most important requirements according to Grömping [33], was used for quantifying the dispersion importance. By calculating and decomposing the R-squared coefficient (R^2) it has been determined how much of the variability of the real-world fuel consumption can be explained by each model and each factor. The main goal of this analysis was not to produce a predictive model and present the regression coefficients, hence the factors were not transformed initially, even though some of the relations between the real-world fuel consumption and the factors studied were not linear. To address this issue and see the impact on the results, in the second step the models were reconstructed using the reciprocal values of some factors (average vehicle speed, distance, duration and cruise) for which the linearity has been achieved by these transformations.

Results and discussion

Fuel consumption from laboratory and PEMS tests

Declared Fuel Consumption (FC) (NEDC-based), together with the results from NEDC, WLTP, and PEMS FC testing can be found in Table 1 (phases and combined results). FC measured using the NEDC (type-approval conditions), WLTP (type-approval conditions), and PEMS was approximately 8%, 10%, and 31% higher, respectively, compared to the declared official FC. The 8% higher NEDC FC measured in the JRC laboratory can be explained by one or more uncertainties in the test conditions (NEDC road loads used for the testing, 4% tolerance in declared value, conformity of production margins, etc.). A complete overview of the margins in the NEDC procedure is provided elsewhere [12]. In addition, tests at JRC were performed on 2-axle chassis dynamometer while, even for 4WD vehicles such as the one in the present study, the official NEDC procedure allowed OEMs to use 1-axle chassis dynamometer configuration (~2% impact on FC) by applying the special testing mode (dyno-mode) not available for drivers in real-life conditions. The 8% difference was seen also before [11] and is yet another confirmation for the non-reproducibility of official certification test conditions.

Testing under the WLTP type-approval procedure increased FC by ~10% (6.1 l/100 km) with FC during individual phases ranging from 4.7 l/100 km (high-speed phase) to 8 l/100 km (cold low-speed phase). The average FC from the PEMS tests was 7.2 l/100 km with urban, rural, and motorway phases having 8.1, 5.3, and 7.8 l/100 km, respectively.

Table 1 Fuel consumption declared and measured from the laboratory (WLTP and NEDC) and on-road tests (PEMS)

Test	Fuel consumption (l/100 km) (FC gap[a] (%))				
	Combined	Phase 1[b]	Phase 2[c]	Phase 3[d]	Phase 4[e]
Declared (NEDC)	5.5	6.5	4.9		
NEDC-cold	5.9 (8%)	7.5 (37%)	5.0 (− 8%)		
WLTP-cold	6.1 (10%)	8.0 (45%)	5.7 (4%)	4.7 (− 15%)	6.7 (22%)
PEMS	7.2 (31%)	8.1 (47%)	5.3 (− 3%)	7.8 (42%)	

[a] Difference (%) in FC compared to the official FC on the combined NEDC; [b] Phase 1 FC: in NEDC is urban driving cycle (UDC) FC; in WLTP is low-speed phase FC; in RDE is urban phase FC; [c] Phase 2 FC: in NEDC is extra-urban driving cycle (EUDC) FC; in WLTP is medium-speed phase FC; in RDE is rural phase FC; [d] Phase 3 FC: in WLTP is high-speed phase FC; in RDE is motorway phase FC; [e] Phase 4 FC: in WLTP is extra-high-speed phase FC

Accuracy of OBFCM measurements

OBFCM and carbon balance (CB) FC results (l/100 km) for 5 NEDC, 8 WLTP, and 4 PEMS tests (one PEMS test has been performed without OBFCM) are averaged and compared in Table 2.

The most significant difference between on-board reported and measured FC was observed over the NEDC cycle (3.9 ± 1.8%), with OBFCM reporting higher FC compared to what has been measured in the laboratory. Total FC on PEMS tests calculated from on-board recordings was on average 1.9 ± 0.8% lower than the same parameter calculated using the CO_2 and CO measurements of the PEMS (as noted earlier the PEMS unit used does not measure HCs). There was almost no difference in total WLTP FC calculated per 100 km when comparing results calculated from OBFCM signal and CB regulation method (0.0 ± 0.7%).

Table 2 Percent difference in FC measurements (OBFCM vs. CB) for NEDC, WLTP, and PEMS tests

	OBFCM vs. CB	% Difference	St.dev
Test cycle	NEDC	3.9	1.8
	WLTP	0.0	0.7
	PEMS	− 1.9	0.8

The results suggest promising OBFCM accuracy of vehicles already present on the market, in particular when the WLTP test is used as a reference for comparison. Therefore, it does not seem unrealistic to foresee and require high accuracies for the future OBFCM devices installed in the cars.

Real-world fuel consumption

The previous section analyzed the effect of different official test procedures on FC gap of a single vehicle, while in this section the focus will be on real-world driving (RWD) conditions outside of laboratory and PEMS boundaries.

Overall fuel consumption results

In total, 20 [20] drivers participated in the testing campaign with 458 trips. The majority of routes were taken in Italy and in particular in the area north of Milan. Some trips took place in other countries such as Slovenia, Croatia, Germany, Serbia, Switzerland, and France.

During the data conditioning and analysis, trips were split into different segments if during the trip, the engine switched off for a period longer than 3 min. In addition, the segments that lasted less than 5 min or had a distance lower than 1.3 km are excluded from the analysis. The latest resulted in discarding 2.3% of the entire sample. Finally, the total number of segments created was 473, with a total of 13,990 km driven (237 h of real-world driving). The individual segments lasted from 5 to 196 min and had a driven distance between 1.3 and 284 km. The average speed of the segments ranged from 10 km/h to 130 km/h. The vehicle has been driven throughout the whole year, therefore, the trip-average ambient temperature ranged from − 7.6 °C to 42.2 °C with a global average of 15.8 °C.

The total FC (sum of all liters consumed *100 km/total distance driven (km)) from all 473 segments and all drivers was 7.1 l/100 km which considering the official NEDC declared fuel consumption led to a 28.7% FC gap. This value can be seen as the future lifetime (in this case, after 1 year) FC gap of this particular vehicle. The only difference is that it also represents 20 different driving styles, a situation not very common with private cars for 1 year of use, but representative for rental and company cars. Slightly higher gap (mean = 36%) for cars built in 2014 has been reported previously [22]. Fiat Chrysler Automobiles (FCA) performed a similar study with the same vehicle model (not the same physical vehicle) driven by 25 different drivers over the period of 6 months, and the total FC gap was 26% compared to the WLTP-based official FC [34].

The fuel economy achieved during these 473 segments ("segment averages") was in the range from 2.8 l/100 km to 17.8 l/100 km, and therefore the FC gap was from − 48.5% to 223.4% (Fig. 1). The segment with the best fuel economy was driven downhill with the average slope equal to − 2.4%, average speed of 51 km/h, a low percentage of stop events (6%), and low average positive acceleration (0.35 m/s^2). On the contrary, the segment with the worst fuel consumption was a combination of low average speed (13 km/h), short distance (2 km), a high percentage of stop events (24%) and high electric power demand (1057 W). More considerable variation in the FC gap from the individual segments compared to the lifetime FC gap is normal and has also been observed before. The FCA study showed a variation in the FC gap from individual segments in the range of − 7 to + 194% compared to the WLTP-based official FC [34]. Since the present study used FC from NEDC-based certification, if results are translated to the WLTP, that exhibited a FC increase of 10% as shown in Sect. 3.1, the expected range of FC gap from segments in the present study is going to be from − 38.5 to 213.4%.

The shape of histogram plotted in Fig. 1 is skewed right indicating the higher probability for trips to result in FC gap higher than the median value. The mean value from all individual trips is 47.4% (median = 37.2%). Only 2.7% of segments (13 out of 473) had average FC below the official NEDC FC, while 9.1% (43 out of 473) and 40.6% (192 out of 473) had FC below the average WLTP and PEMS FC, respectively.

Impact of different factors on FC gap and variability

In this section, the parameters that affect FC gap are analyzed (Fig. 2). These factors can be split into 3 groups as described by Fontaras et al. [6]: vehicle-related factors, environmental and traffic related ones, and driving-related factors. Vehicle factors are related to the vehicle characteristics such as vehicle type (power, engine, transmission, tires, etc.) and vehicle road loads (mass, rolling resistance, aerodynamic resistance). In addition, vehicle maintenance and aging is the part of this group.

The impact of vehicle factors on FC gap has been studied in the past. Ntziachristos et al. [28] and Tietge et al. [22] reported that more than 85% of FC variability can be explained by official type-approval value, engine capacity and vehicle mass. Jimenez et al. [19] developed a model that included additional aspects such as: vehicle characteristics (number of doors, seats and gears, transmission, fuel, and body style), vehicle segment, brand, and registration year. The authors also highlighted that the latter two groups (environmental and traffic, and driving factors) comprise the major reason why the gap between real-world and type-approval figures may exist. However, to our knowledge, there are no studies that explained the impact of these factors on the

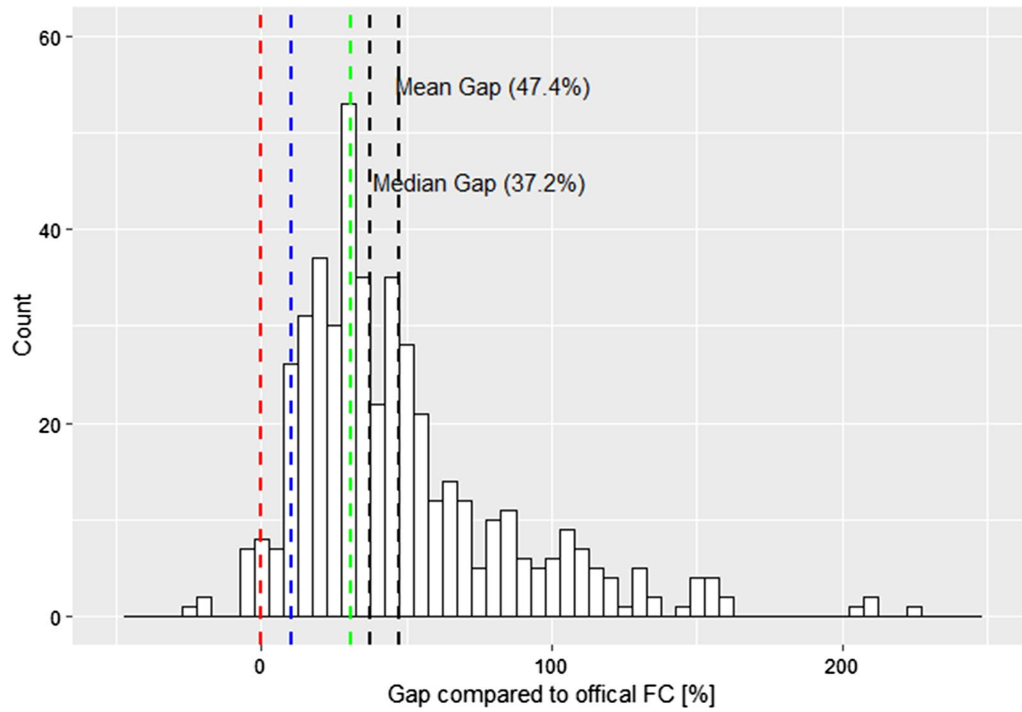

Fig. 1 Histogram of the FC gap from all individual RWD trips (red dashed line represents the official NEDC-based FC gap (0%); blue dashed line represents the average WLTP FC gap; and green dashed line represents the average PEMS FC gap)

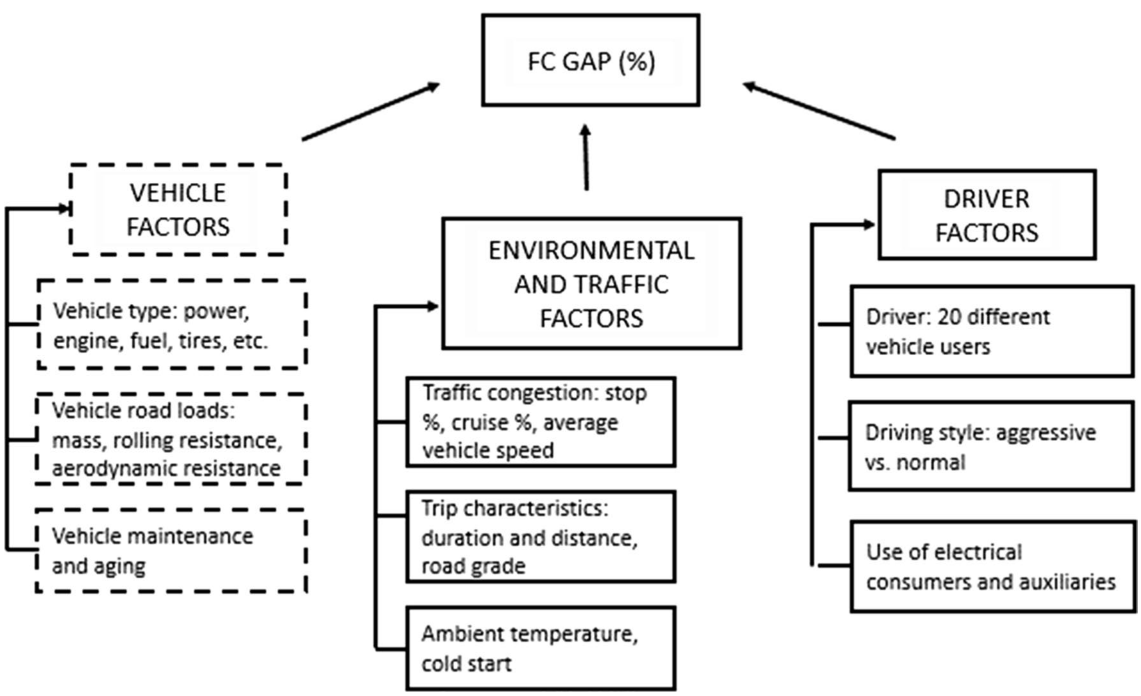

Fig. 2 Factors that impact FC gap. Dashed boxes are the factors not covered by the present study. Full line boxes represent the factors whose impact was analyzed in the study

variability in the FC gap. In the next sections correlations between the factors and FC gap will be presented.

Environmental and traffic conditions are studied through traffic congestion (% stop, % cruise, average speed), trip characteristics (duration and distance, road grade), ambient temperature, and effect of cold start (oil temperature at the beginning of the trip). Driving factors are split into drivers (20 different vehicle users in this study), driving style (normal vs. aggressive), and the use of electrical consumers and auxiliaries.

Impact of environmental and traffic factors *Traffic congestion* Traffic congestion is characterized by low vehicle speeds, low average engine speeds, high percentage of stop and low percentage of cruise duration. Correlations between these factors and FC gap are shown in Fig. 3.

The general trend observed with the average vehicle speed is that increasing the average vehicle speed the average FC gap decreases. The standard deviation of the divergence also decreased. The drop in FC is significant only up to a certain average vehicle speed (60 km/h for this vehicle). After that vehicle speed the average

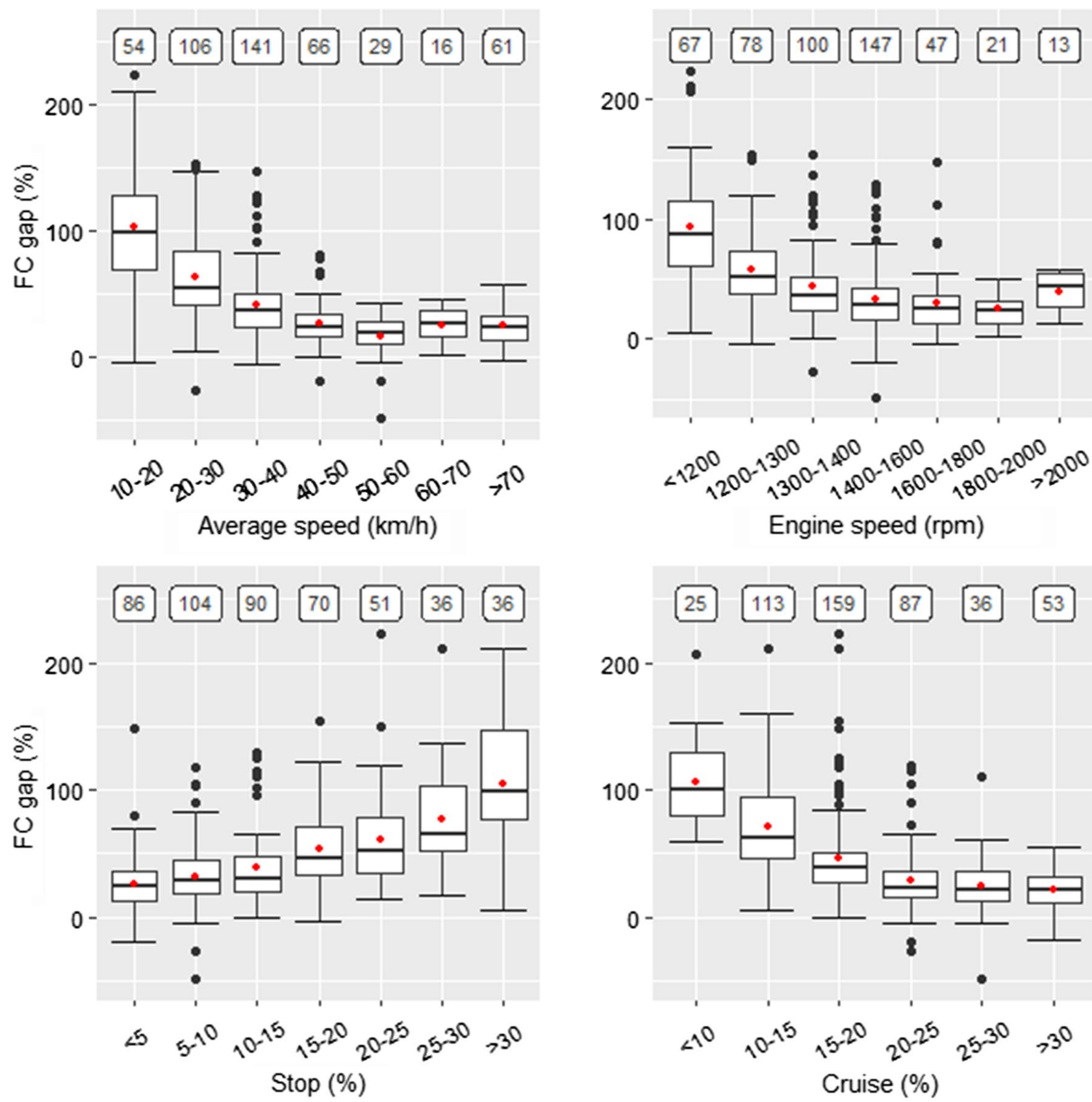

Fig. 3 Relationship between FC gap and parameters related to traffic congestion (the box represents the 1st and 3rd quartile; line is the median FC; red dot is the mean, whiskers represent 1.5*IQR (interquartile range), black dots are values below or higher than 1.5*IQR, and numbers on top of the graphics are the number of segments in each selected bin)

FC increases (not statistically significant). The majority of segments were driven at average vehicle speeds in the range from 20 km/h to 40 km/h (247 segments). Segments with average vehicle speeds between 10 and 20 km/h (54 segments) resulted in the highest average FC gap (103.6 ± 47.1%). The minimum average FC gap (17.1 ± 18.9%) has been calculated for segments with the average vehicle speeds in the range from 50 to 60 km/h (29 segments). Further increase in the average vehicle speed (77 segments with speed > 60 km/h) slightly increased the average FC gap (25 ± 13.2%) but the results are not statistically significant ($p > 0.05$) compared to the previous bin.

For what regards the average engine speed, most of the segments were driven in the range from 1200 to 1600 rpm (~ 69% of segments) with the average gap in FC equal to 57.8 ± 30.6% (1200–1300 rpm),43.7 ± 29.8% (1300–1400 rpm), and 33.3 ± 28.4 (1400–1600 rpm). Operating the vehicle at average engine speeds below 1200 rpm (67 segments) resulted in the average FC gap of 93.2 ± 47.5%. Driving vehicle at average engine speeds above 1600 rpm (81 segments) also does not result in statistically significant results compared to the previous bin and the FC gap was 29.7%, 24.7%, and 39.6% (bins 1600–1800 rpm, 1800–2000 rpm, and > 2000 rpm, respectively). Most of the segments driven below 1200 rpm are associated with average vehicle speeds below 20 km/h (45 out of 67 trips) indicating traffic congestion. In addition, long idling periods (average engine speeds usually below 1000 rpm) where travelled distance is equal to 0, but not the FC, increase the overall trip FC that is at the end expressed as sum of all liters consumed * 100 km/total distance driven (km).

In order to confirm traffic congestion, stop and cruise (vehicle speed ≥ 5 km/h and acceleration from -0.1 m/s^2 to $+0.1$ m/s^2) percentage of each segment is also calculated. Results from this study confirmed that having frequent stops has negative impact on the average FC gap. Increasing the percentage of stop from < 5% (86 segments) to > 30% (36 segments) resulted in the average FC gap increase from 26.0 ± 22.6% to 104.8 ± 48.0%, respectively. Having trips with more cruise events will help in achieving the lower FC gap. When cruise increased from < 10% (25 segments) to > 30% (53 segments) the average FC gap dropped from 105.5 ± 36.3% to 21.3 ± 16.7%.

Trip characteristics Trip characteristics are studied throughout trip duration, distance, and road grade. An increase of trip time and distance resulted in lower average FC gap (Fig. 4) and lower standard deviation of the gap's divergence. Segments with the highest average FC gap had duration lower than 10 min (79.8 ± 41.7%) and distance shorter than 5 km (85.8 ± 44.3%). On the contrary, the segments with the lowest average FC gap lasted more than 60 min (24.8 ± 15.3%) and were driven more than 30 km (25.5 ± 14.2%). Bins with trip duration between 20 and 60 min and trip distance longer than 10 km are not statistically different ($p > 0.05$) in terms of FC gap. Seen from a technical perspective this observation could be linked to the vehicle warm-up effect, the influence of which is much more pronounced at shorter trips (in terms of both time and distance) and will be also discussed later.

Another important parameter that impacts FC gap and characterizes one trip is the road grade (slope). Road grades calculated for each segment and shown in Fig. 4 represent distance-weighted road grades (%). Most of the trips performed in this study were in the range of mild road grades with values between ± 0.5% (62%). The lowest average FC gap (36.9 ± 34.0%) is calculated for segments with road grades lower than − 1%. On the contrary, increase in the distance-weighted road grade to > 1% resulted in the highest average FC gap equal to 93.0 ± 35.3%. In addition, results from these two bins are statistically different ($p < 0.01$). Therefore, the average impact of road grade on FC gap can be about 56% if one compares segments with road grades lower than − 1% with segments with road grades above + 1%. Other studies found also significant and comparable impact of road grade on the FC, ~ 80% for road grade change from 0 to 5% [35] and ~ 170% for road grade increase from − 4 to 5% [36].

Ambient temperature and cold start The trips performed in this study were in an average temperature range from − 7.6 °C to + 42.2 °C. From the statistical analysis a linear correlation between ambient temperature and FC gap has not been found as expected. However, one can see from Fig. 4 that the highest mean FC gap and the highest variability in FC gap is measured for segments where ambient temperature was below 0 °C and above 30 °C (use of heating and A/C systems, respectively). While the ambient temperature can influence all kinds of external resistances on the vehicle [6], the big impact of ambient temperature is also linked with the excess cold start FC. Cold start occurs when the vehicle starts operating and lasts until all vehicle components reach their nominal operating temperature for the first time (warm-up phase) and therefore becomes less important for longer trips. For that reason, the key parameters that need to be analyzed in order to see the impact of cold start on FC gap are the starting engine oil temperature and the trip duration.

The effect of cold start is analyzed for both short and long trips as depicted in Fig. 4. The first three bins include cold start segments and the next three bins hot start segments (temperature of oil > 0 °C). All

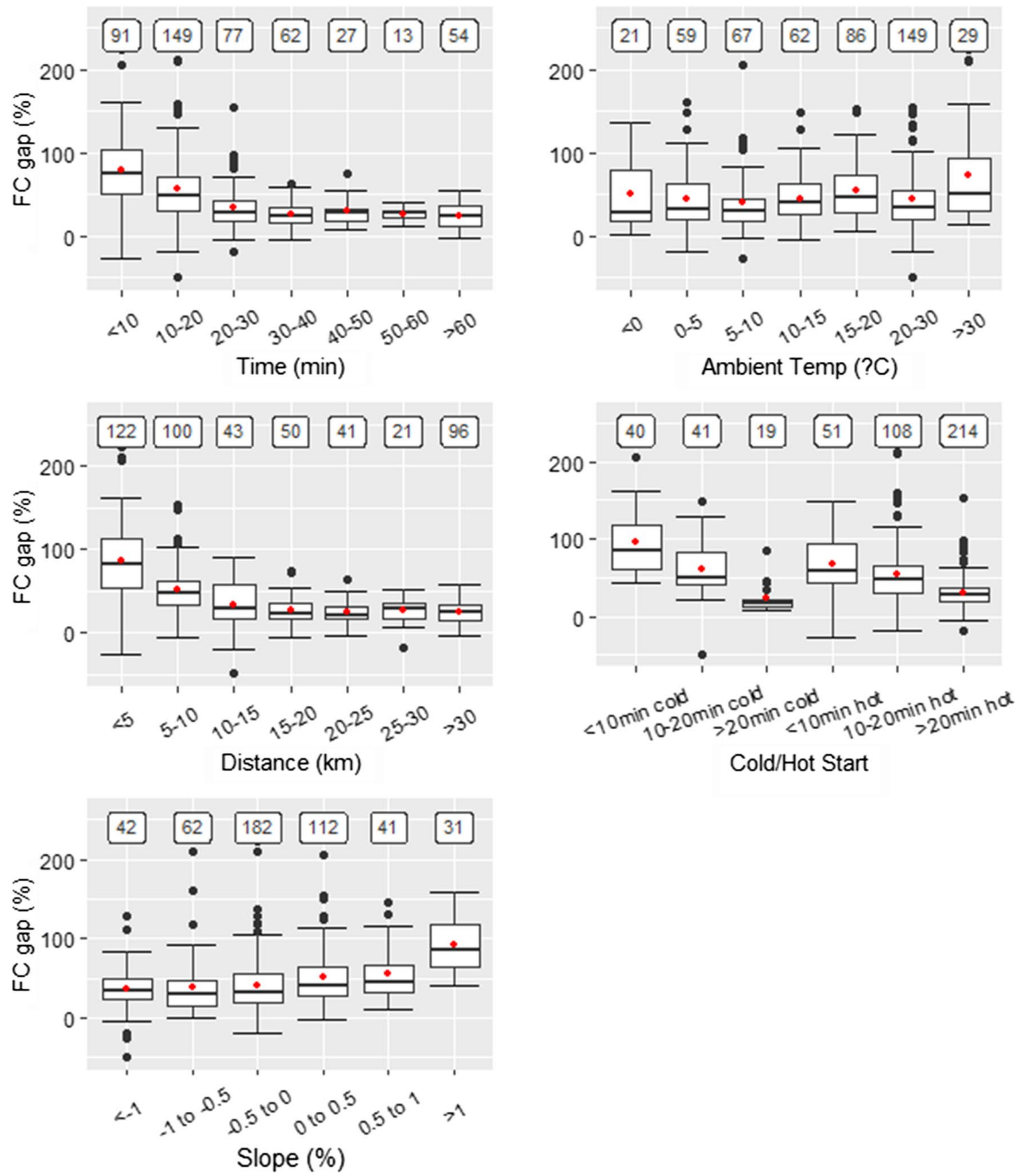

Fig. 4 Relationship between FC gap and parameters related to trip characteristics (trip duration, distance, and road grade), ambient temperature and cold/hot start (the box represents the 1st and 3rd quartile; line is the median FC; red dot is the mean, whickers represent 1.5*IQR (interquartile range), black dots are values below or higher than 1.5*IQR, and numbers on top of the graphics are the number of segments in each selected bin)

segments are separated by trip duration (< 10 min, 10–20 min, > 20 min). Having engine hot during the shortest trips (< 10 min) resulted in ~ 30% lower average FC gap (96.5% for cold start compared to 66.7% for hot start). Such impact was expected and previous study confirmed that first 300 s of cold start can have 25–55% higher CO_2 emissions compared to the last 300 s of the trip [37]. As trip distance and duration increased (10 min < t < 20 min), the impact of cold start becomes only 6% and the results are not statistically different ($p > 0.05$). The lowest average FC gap is found for cold start segments that lasted more than 20 min (22.7%). Hot start segments with the same duration had surprisingly higher average FC gap (29.5%) and the results were statistically different. These results confirm that drivers that in their daily routines perform mostly longer trips (hot or cold start) will save on average ~ 70% of fuel compared to the drivers that drive mostly short trips with cold engine at the start.

Impact of driver factors

Driver Vehicle drivers have a crucial impact on the FC and the FC gap. The impact is linked to the way the vehicle is driven (average speed, accelerations), route selection, use of electrical consumers (A/C, entertainment equipment), etc. Therefore, one should note that, although listed here as a separate factor, "driver" is a complex group of different factors that impact almost every parameter mentioned in this study. Summary analysis of the average FC/FC gap grouped by 20 drivers is shown in Table 3.

The shortest total distance driven by a single driver was 44.6 km and the longest 2576.5 km. Although it is evident that some drivers had very low contribution in the total mileage share, this does not correlate with the number of segments that they performed. One driver can drive 9 segments with only 44.6 km (Driver #6), while the other with the same number of segments will get more than 300 km (Driver#12), etc. Driving needs and the routes taken on a daily basis are different and therefore each of the segments has its value in assessing the variability of FC gap.

The average vehicle speed of drivers was between 22.2 km/h and 88.3 km/h indicating that some drivers used the vehicle only for low-speed urban routes, while some others drove mostly motorway trips. The average FC grouped by different drivers was in the range from 6.4 l/100 km (Driver 14; 16.1% FC gap) to 11.3 l/100 km (Driver 6; 105.9% FC gap). FCA's study mentioned before reported driver FC gap averages from 0 to 132% compared to the WLTP-based TA FC [35].

The divergence in FC gap that is coming from each driver is better depicted in Fig. 5. It is also clearly visible from the figure that the official NEDC-based FC of this vehicle (and in almost all cases measured in the lab WLTP FC as well) is below the FC gap of 1st quartile calculated for each driver. The interquartile range (IQR) as a measure of statistical dispersion in FC gap was in the range from 4.3% (Driver #1) to 62.5% (Driver #20). The standard deviation that is another dispersion measure was from 5.0% (Driver #1) to 72.8% (Driver #4). The results suggest that in the future lifetime FC monitoring scheme, when one have data coming from exactly the same vehicle model and version, but different drivers, it

Table 3 Summary of average conditions and fuel consumption results grouped by drivers

Drivers	Number of segments	Total time (h)	Total distance (km)	Average speed (km/h)	Average positive acceleration (m/s^2)	Average temperature (°C)	Average fuel consumption (l/100 km)	Average fuel consumption gap (%)
1	3	2.9	165.6	56.5	0.41	20.3	6.5	17.8
2	27	7.0	235.0	33.4	0.58	18.5	8.0	45.6
3	12	9.4	669.2	70.9	0.43	14.2	7.3	32.2
4	5	4.3	299.9	70.4	0.53	6.0	7.5	35.7
5	22	14.5	1281.1	88.3	0.37	26.7	7.4	34.2
6	9	2.0	44.6	22.2	0.53	31.0	11.3	105.9
7	9	4.0	118.7	29.9	0.56	17.9	8.4	52.7
8	42	20.8	1033.1	49.8	0.46	11.2	7.3	33.4
9	16	19.5	1186.4	60.7	0.40	26.7	6.7	21.1
10	25	7.8	309.2	39.8	0.47	27.9	7.0	27.3
11	31	11.7	429.2	36.6	0.49	13.6	6.9	25.9
12	9	6.6	304.4	45.8	0.52	6.7	7.1	29.5
13	24	5.8	171.6	29.5	0.46	25.8	7.9	43.3
14	49	33.9	2576.5	76.1	0.34	1.3	6.4	16.1
15	86	36.7	1958.2	53.3	0.53	20.2	7.3	32.0
16	13	13.9	1047.3	75.6	0.34	22.2	6.8	23.8
17	19	6.6	282.8	42.8	0.53	5.4	7.0	26.4
18	26	5.8	168.9	29.4	0.50	18.4	7.8	41.8
19	10	5.9	300.7	51.2	0.44	13.4	6.3	15.1
20	36	18.1	1407.8	77.8	0.64	4.2	7.7	39.6

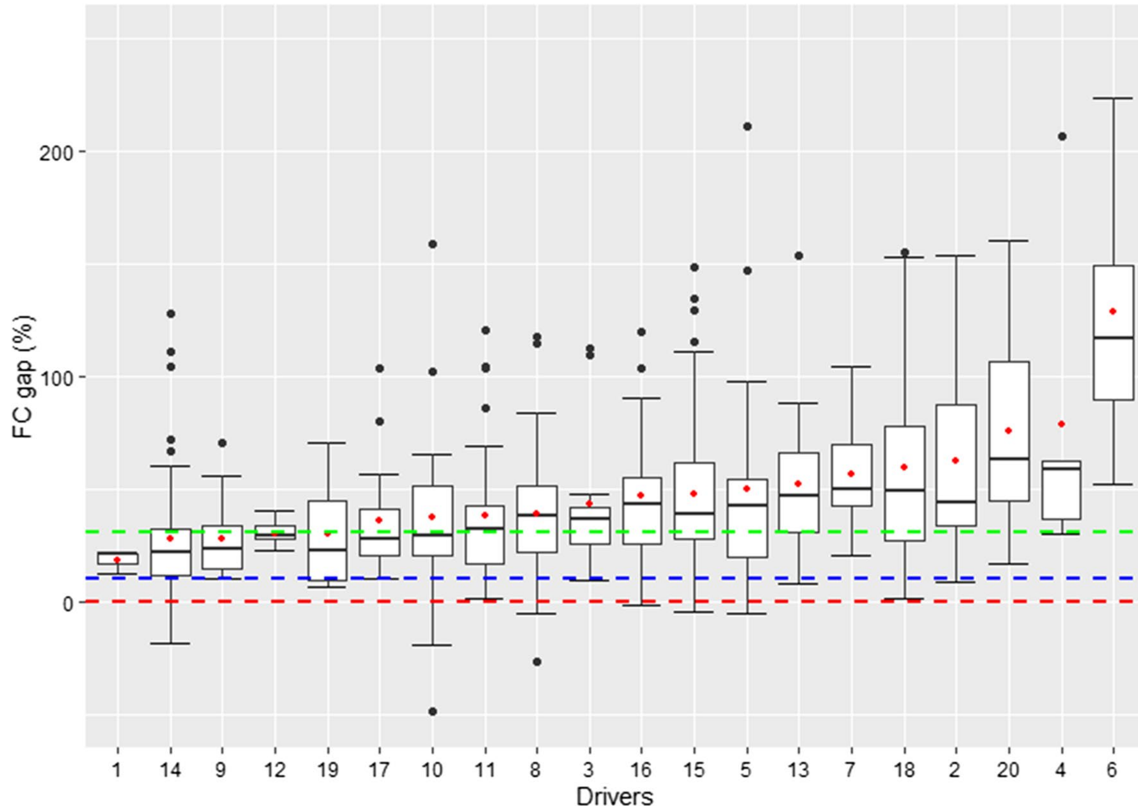

Fig. 5 Variation in FC gap grouped by drivers and sorted by mean values (from lowest to highest value). The box represents the 1st and 3rd quartile; line is the median; red dot is the mean; whiskers represent 1.5*IQR; and dots values below or higher than 1.5*IQR (red dashed line represents the official NEDC-based FC gap (0%); blue dashed line represents the WLTP FC gap; and green dashed line represents the PEMS FC gap)

is reasonable to expect significant variability in drivers lifetime averages that will be impacted not only by different driving styles (aggressive vs. normal driving) but also by different driving needs (duration of majority of the routes, driving in the traffic congested cities, rural areas, or motorways, use of A/C when living in areas with hot temperatures, etc.).

Aggressive driving The driver's behavior is studied through the average positive acceleration (a_{pos}). It is reminded that the vehicle had an automatic transmission hence it was not possible to assess the impact of gearshifting at driver level on FC/FC gap. Most of the segments (62.6%) were driven with a_{pos} in the range from 0.4 to 0.6 m/s^2 and resulted in the average FC gap from 41.0 to 53.4%. These middle two bins (Fig. 6) represent segments with normal driving. First two bins (a_{pos} below 0.3 m/s^2 and 0.3–0.4 m/s^2) are created to depict very soft driving, and the average FC gap from these 2 bins was 20.5% and 28.7%, respectively. The last two bins (a_{pos} between 0.6–0.7 m/s^2 and > 0.7 m/s^2) are linked to the dynamic and aggressive driving, respectively, and the average FC gap from these 2 bins was 81.1 and 96.7%, respectively. When comparing the average results from the first and the last bin, one can see that the aggressive driving resulted in ~ 76% higher average FC cap compared to the soft driving. Impact of aggressive driving compared to the normal driving is ~ 50% (comparison of the average FC gap from the last bin and the average of two middle bins). Previous studies that used similar a_{pos} definitions found also up to 50% increase in FC related to aggressive driving [35, 38, 39].

Use of electrical consumers and auxiliaries This category is composed of components and devices such as A/C, lights, pumps, ventilator, monitor, and sound systems [6] that are not allowed over the official vehicle certification tests. All these devices impose higher mechanical or electrical loads, increased alternator operation, and consequently additional FC. The total power requirements of the European vehicle certification test are estimated to be 350 W, while over the real-world driving are estimated to be 750 W [40, 41]. During the RWD tests in this study the alternator current is monitored and the total power calculated. The minimum electric power demand measured over the trips was 318 W and

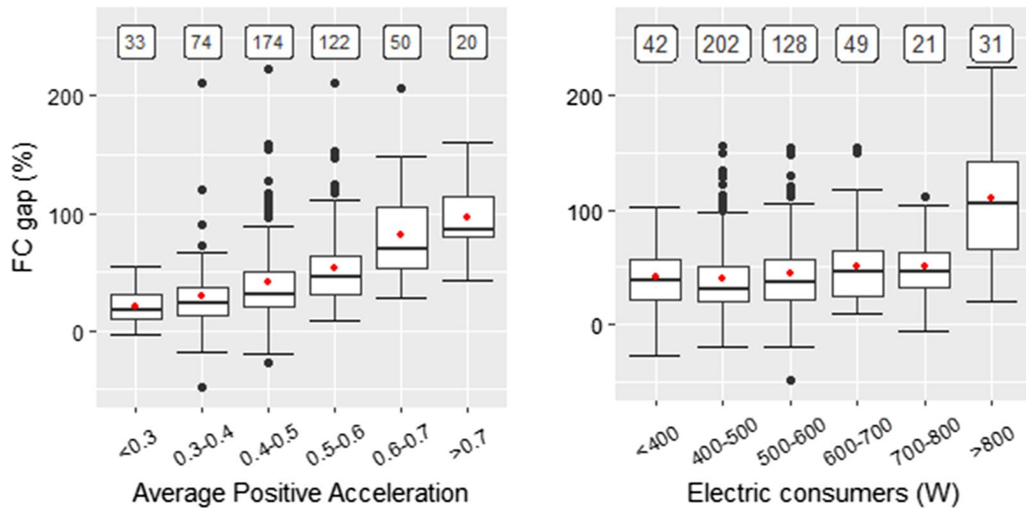

Fig. 6 Relationship between FC gap and parameters related to a_{pos} as a proxy of driving style and power consumption (the box represents the 1st and 3rd quartile; line is the median FC; red dot is the mean, whiskers represent 1.5*IQR (interquartile range), black dots are values below or higher than 1.5*IQR, and numbers on top of the graphics are the number of segments in each selected bin)

the maximum 1125 W (average = 526 W). The majority of the segments were driven with the electric power demand in the range from 400 to 600 W (69.8% of total segments).

All bins shown in Fig. 6 exhibit an increase in average FC as a result of increasing electric loads. However, the power below 800 W did not result in statistically significant differences (the average FC gap was in the range from 39.7 to 51.2%). Only the bin with the power higher than 800 W had statistically significant difference in average FC gap (109.6 ± 55.0%). Previous study based on simulations showed a 20 and 30% increase in CO_2 emissions for a diesel vehicle when electrical loads increased by 1000 W over the WLTP and NEDC cycle, respectively [42]. High increases in FC observed for electric demands over 800 W can only partially be analyzed with the alternator current data recorded.

Regression model results

Multi-linear regression models were developed in order to check if the parameters associated with the environmental and traffic, and driver factors can separately explain the variation of the FC gap. The following three models were developed:

1. 1. Driver factor:

$$FC\text{gap} = \beta_0 + \sum_{j=1}^{19} \beta_j \text{Driver} + \beta_{20}\text{Apos} + \beta_{22}\text{Power}; \tag{2}$$

2. Environmental and traffic factors:

$$\begin{aligned} FC\text{gap} =& \beta_0 + \beta_1\text{Duration} + \beta_2\text{Distance} + \beta_3\text{Slope} \\ &+ \beta_4\text{AmbientTemp} + \beta_5\text{EngineTemp} \\ &+ \beta_6\text{Stop} + \beta_7\text{Cruise} + \beta_8\text{VehicleSpeed} \\ &+ \beta_9\text{EngineSpeed}; \end{aligned} \tag{3}$$

3. All factors together:

Table 4 Results of the multi-linear regression models that quantify contribution of: (1) driver factors; (2) environmental and traffic factors; and (3) all factors together on FC gap variance

Factors	Importance (relative importance (%))		
	Model 1	Model 2	Model 3
Driver	16.1 (33.7)	–	8.3 (9.2)
Average positive acceleration	19.6 (41.0)	–	5.0 (5.5)
Power consumption	12.1 (25.3)	–	8.6 (9.5)
1/duration	–	5.5 (6.7)	4.8 (5.3)
1/distance	–	10.0 (12.2)	9.1 (10.1)
Road grade	–	13.1 (15.9)	12.1 (13.4)
Ambient temperature	–	0.9 (1.1)	0.4 (0.4)
Engine temperature	–	5.9 (7.2)	3.6 (4.0)
Stop	–	8.6 (10.5)	7.9 (8.7)
1/cruise	–	11.9 (14.5)	8.8 (9.7)
1/vehicle speed	–	17.8 (21.6)	15.0 (16.6)
Engine speed	–	8.5 (10.3)	6.8 (7.5)
Total R^2	47.8 (100)	82.2 (100)	90.4 (100)

$$FC\text{gap} = \beta_0 + \sum_{j=1}^{19} \beta_j\text{Driver} + \beta_{20}\text{Apos} + \beta_{22}\text{Power} + \beta_{23}\text{Duration} + \beta_{24}\text{Distance} + \beta_{25}\text{Slope} + \beta_{26}\text{AmbientTemp} + \beta_{27}\text{EngineTemp} + \beta_{28}\text{Stop} + \beta_{29}\text{Cruise} + \beta_{30}\text{VehicleSpeed} + \beta_{31}\text{EngineSpeed}. \tag{4}$$

Table 4 summarizes the results of all three models and shows the importance of each parameter on the FC gap's variability. As already mentioned in the methodology first model runs were performed without any transformations of the parameters. In the second step, the models were reconstructed using the reciprocal of the average vehicle speed, distance, duration and cruise in order to satisfy the criteria of linearity. The results of that second step are shown in Table 4 (driver factors are the same since transformations didn't affect any of them). The R^2 value of the first model (driver factors) is equal to 47.8 meaning that almost half of the FC gap's variance can be explained with this model. The second model (environmental and traffic factors) explains 82.2% of the FC gap's variance ($R^2 = 66.4$ without transformations). When all factors are combined in the third model their impact on the FC gap's variance is 90.4% ($R^2 = 80.7$ without transformations).

Figure 7 illustrates the relative importance (% contribution) of each individual factor to the total FC gap's variability that in this case equals to 100%. As shown in Table 4 and Fig. 7, and for what regards the driver's factors, the average positive acceleration (a_{pos}) and drivers are identified as the highest contributors of the FC gap's variability (impact 41.0% and 33.7%, respectively).

Among the environmental and traffic factors, the average vehicle speed and the road grade explain most of the FC gap's variability (21.6 and 15.9%, respectively). In the third model where all factors are considered together the ones contributing most to the FC gap were again the average vehicle speed and road grade (16.6 and 13.4%, respectively), followed by the distance and cruise (10.1 and 9.7%, respectively). It should be noted that in the third model the most important environmental and traffic factors remained the same (average vehicle speed and road grade) which is not the true for the most important driver factors and in particular for the a_{pos} with contribution of only 5.5% on the FC gap's variability. The reason for lower individual contribution of a_{pos} than expected is the high correlation of a_{pos} with some other factors introduced from the second model (such as the cruise) and hence its contribution is divided and added to the other factors. The same is true also for the average speed, distance, and duration that were highly inter-correlated and that could result in their lower individual contributions.

In summary, results show that the driver factors identified and measured in this study can impact FC gap as high as 25%. Traffic congestion (stop, cruise, average vehicle speed, engine speed) has the highest contribution equal to 42.5%, while factors associated with trip characteristics (duration, distance, and road grade) have contribution equal to almost 29%. The lowest impact on the FC gap's variability is calculated for the ambient temperature and the cold start (4.4% total). It should be noted that FC gap in this study is calculated based on the declared

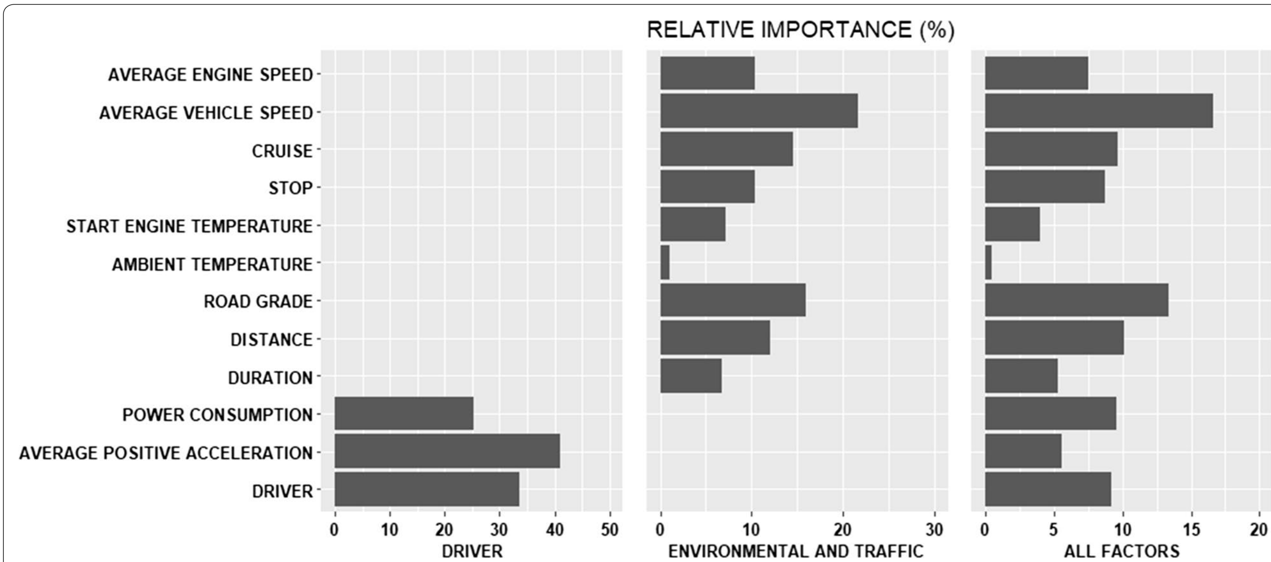

Fig. 7 The relative importance (% contribution) of individual factors to the total FC gap's variability

NEDC value. Changing the regulatory cycle to WLTP will change the type-approval value. However, since all trips are performed with the same vehicle, this would imply the same change to the type approval FC for all the trips. In the other words, the methodology is not impacted and no matter what the type-approval value is, the results and the analysis performed in this study would be the same.

Conclusions

The issue of the FC gap is widely known and legislation has been put in place in the EU for monitoring this gap over the years to come with the aim of avoiding its further growth. The present study focused on monitoring of FC of a single vehicle throughout 1 year with 20 different persons driving the vehicle.

The study confirmed the divergence in FC between the type-approval tests (NEDC and WLTP) and real-world driving trips. In addition, almost 60% of the real-world driving trips had an average FC higher than the average one measured with PEMS on an RDE compliant trip.

The present study showed three ways of presenting the FC gap in order to allow its interpretation. The first one would be the FC gap measured over a longer period of time, which in the present study for this vehicle after 1 year of use was 28.7%. The second way of presenting the FC gap would be as the driver averages. As seen from the present study, if the same vehicle is driven by 20 different drivers the FC gaps might range from 16.1 to 105.9%. The third way of presenting the FC gap is through the daily (individual) trips. The present study showed that individual trips can result in the range of FC gap from −48.5 to 223.4%. Obviously, this has the highest variability, but a significant amount of variability is reduced when data are collected over longer time periods (as confirmed in the first approach).

When analyzing the impact of different traffic parameters on the FC gap, the highest FC gap is measured when the average vehicle speed was below 20 km/h, the average engine speed below 1200 rpm, the percent of vehicle stops higher than 30% and the percentage of cruise lower than 10%. For what regards the trip characteristics, the highest FC gap can be expected for short cold start trips (< 10 min and < 5 km), with average distance-weighted road grade above 1%. The regression model focused on the environmental and traffic factors explained more than 80% of the FC gap variability with the average vehicle speed and the road grade as the main contributors (21.6 and 15.9%, respectively).

When driver factors are analyzed, the highest FC gap is measured for the segments where average positive acceleration was higher than 0.7 m/s^2 and the electric power demand higher than 800 W. The regression model concentrated on the driving factors explained almost 50% of the FC gap variability with the average positive acceleration and drivers as the main contributors (41.0 and 33.7%, respectively). When all parameters are considered together the R^2 of the linear regression model increased to 90.4. In this case the FC gap variability showed the greatest susceptibility to the average vehicle speed, road grade, and distance (16.6%, 13.4%, and 10.1%, respectively). These results indirectly imply that higher lifetime FC gap can be expected from the vehicles driven in congested areas with lower speeds, low distance trips, and/or areas with convoluted topography.

In addition, the impact of driver factors is not negligible (25%). Once the real-world FC monitoring mechanism is established further options for FC reduction should go in the direction of promoting the eco-driving, public awareness of the factors affecting the FC gap such as the ones outlined in this study and understanding how to improve them, and different forms of incentives for drivers (economic, fiscal, insurance, etc.). The analysis presented in this paper may provide a basis for setting up a more detailed and refined prediction model for monitoring the fuel consumption gap and the underlying factors generating it. It is expected that factors such as drivers, environmental conditions, and traffic can be monitored in the future, as well as the main technical characteristics of the vehicles. Hence explaining possible changes of the FC gap on a fleet-wide basis is conceivable while a statistical approach for screening out cases where any increases in the gap can be attributed to the certification process, rather than real world driving itself, appears to be plausible.

Abbreviations

FC: Fuel consumption; NEDC: New European Driving Cycle; WLTP: World-wide harmonized light-duty vehicle test protocol; PEMS: Portable emissions measurement system; RDE: Real-driving emissions; RWD: Real-world driving; OBFCM: On-board fuel consumption monitoring; OEM: Original equipment manufacturer; OBD: On-board diagnostic; ECU: Electronic control unit; JRC: Joint Research Centre; VELA: Vehicle emission laboratory; PN: Particle number; THC: Total hydrocarbons; FCA: Fiat Chrysler Automobiles; UDC: Urban driving cycle; EUDC: Extra-urban driving cycle; IQR: Interquartile range.

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Authors' contributions

The study was designed by JP and BC. JP drafted the original manuscript with major support by GF. KA and DK helped in post-processing of OBD logger data. MK developed multi regression model. MC followed laboratory (NEDC and WLTP) and PEMS tests. GF, MK, VV, and MC reviewed original manuscript and contributed specific aspects. All authors read and approved the final manuscript.

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Ethics approval and consent to participate
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Competing interests
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