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Characterisation of real-world CO_2 variability and implications for future policy instruments

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Characterisation of real-world CO_2 variability and implications for future policy instruments

There is increasing evidence suggesting that real-world fuel consumption and CO_2 emissions improvements in the last decade have been much lower than the officially reported ones. Scientific studies show that the offset between officially reported values and real-world vehicle CO_2 emissions in Europe has constantly increased over the last years. The difference between officially reported and actual CO_2 emissions of vehicles has three main implications: a) it undermines the collective effort to reduce greenhouse gas emissions in Europe, b) it creates an unfair playing field for different competitors, and c) it affects the credibility of vehicle manufacturers.

As a fundamental step to deal with this issue the European Commission has replaced the old and outdated NEDC test procedure used so far in the emission type-approval of vehicles by the Worldwide harmonized Light vehicles Test Procedure (WLTP). Being a lab-based test-procedure, the WLTP, by its nature, can only cover part of the CO_2 gap. Some stakeholders have suggested that the remaining gap could be tackled by additional measures based on real-world measurements.

The objective of the present report is to analyse possible ways to deal with the remaining CO_2/fuel consumption gap. In particular, fleet-wide monitoring of real-world fuel consumption and model-based tools able to provide customized information to road users are the measures suggested. In addition, the paper presents experimental evidence on the variability of the CO_2/fuel consumption of vehicles, putting into question the idea that a single central estimate of these quantities may be sufficient.

Contents

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Executive summary

As part of its policy for reducing the greenhouse gas emissions from transport and improving its energy efficiency, Europe has set a target for the average CO_2 emissions of new passenger cars at 95 gCO_2/km, applying from 2021 on. Over the past years, improvements in fuel efficiency have been claimed, on the basis of emission tests, which are part of the type approval of the vehicles. Nevertheless there is increasing evidence that fuel consumption improvements are only partly visible in real-world operating conditions, since they originate, at least in part, from test-oriented vehicle optimizations and test-related practices. As a result, the offset between officially reported values and real-world vehicle CO_2 emissions has increased year by year, and is estimated to be around 40% for 2015/2016.

There are three main reasons why a high and increasing difference between officially reported and actual CO_2 emissions of vehicles constitutes a problem: a) it undermines the collective effort to reduce greenhouse gas emissions in Europe, b) it creates an unfair playing field for different competitors, and c) it affects the credibility and the competitiveness of the European automotive industry. Different stakeholders have been suggesting approaches for dealing with the gap both to provide consumers with more reliable information and to ensure that progresses to meet fuel-economy/CO_2 emission standards are also visible in real life. Among different options, the following ones are frequently mentioned: i) the development of an RDE test for CO_2 and fuel consumption, ii) the development of a fleet-monitoring system based on a fuel consumption meter introduced in all new vehicles, iii) the use of statistical and/or model-based approaches to correct the type-approval figures in order to be closer to the real-life conditions [1]. However, a fundamental question remains unanswered: does a single real-life fuel consumption figure make sense, and helps to better address the issue, or alternative approaches (distributions, ranges, customized figures, ad-hoc calculators etc.) need to be developed?

In this light, the present study aims at characterizing the uncertainty (variability) in the vehicle fuel consumption. This should help to develop an appropriate and effective approach to deal with the gap between type-approval and real-world vehicle fuel consumption, in the context of the CO_2 target setting and compliance monitoring as well as for informing consumers on the CO_2 emissions and fuel consumption (car labelling).

Two types of data sources are used in the analysis, namely (i) data collected during a period of ~6 months from the same vehicle driven by different drivers and in different conditions, and (ii) data collected from different vehicles tested by a few drivers on a limited number of routes. Combining these two sets of data allowed pooling together a wider coverage of testing conditions (first data set) with a wider coverage of vehicle technologies (second data set).

As shown in Figure E.1, the variability of the vehicle fuel consumption over different operating conditions is high (ranging from 5 to 13 l/100km in 95% of the cases), both for the same driver and for different drivers. The average fuel consumption measured for all trips is 8 l/100km and the median fuel consumption is 7.4 l/100km. As the type-approval value for the vehicle is 5.5l/100km ("TA NEDC FC"), the mean and median value imply a gap of 45%, and 35%, respectively, which is overall in line with the evidence reported in the existing literature.

These findings put into question the meaningfulness of solutions, which try to characterize the fuel consumption of a vehicle by using a single central value measured ex-ante, over the RDE or any other test protocol developed for the purpose.

From the perspective of monitoring the real-world fuel efficiency improvements under a regulatory target, one may wonder how to ensure that a single figure corresponds to the average of the fuel consumption experienced by all drivers using the same vehicle. Similarly, from the perspective of providing reliable information to the users, one may also question the value of a median figure when the variability for different drivers over different trips can be so high.

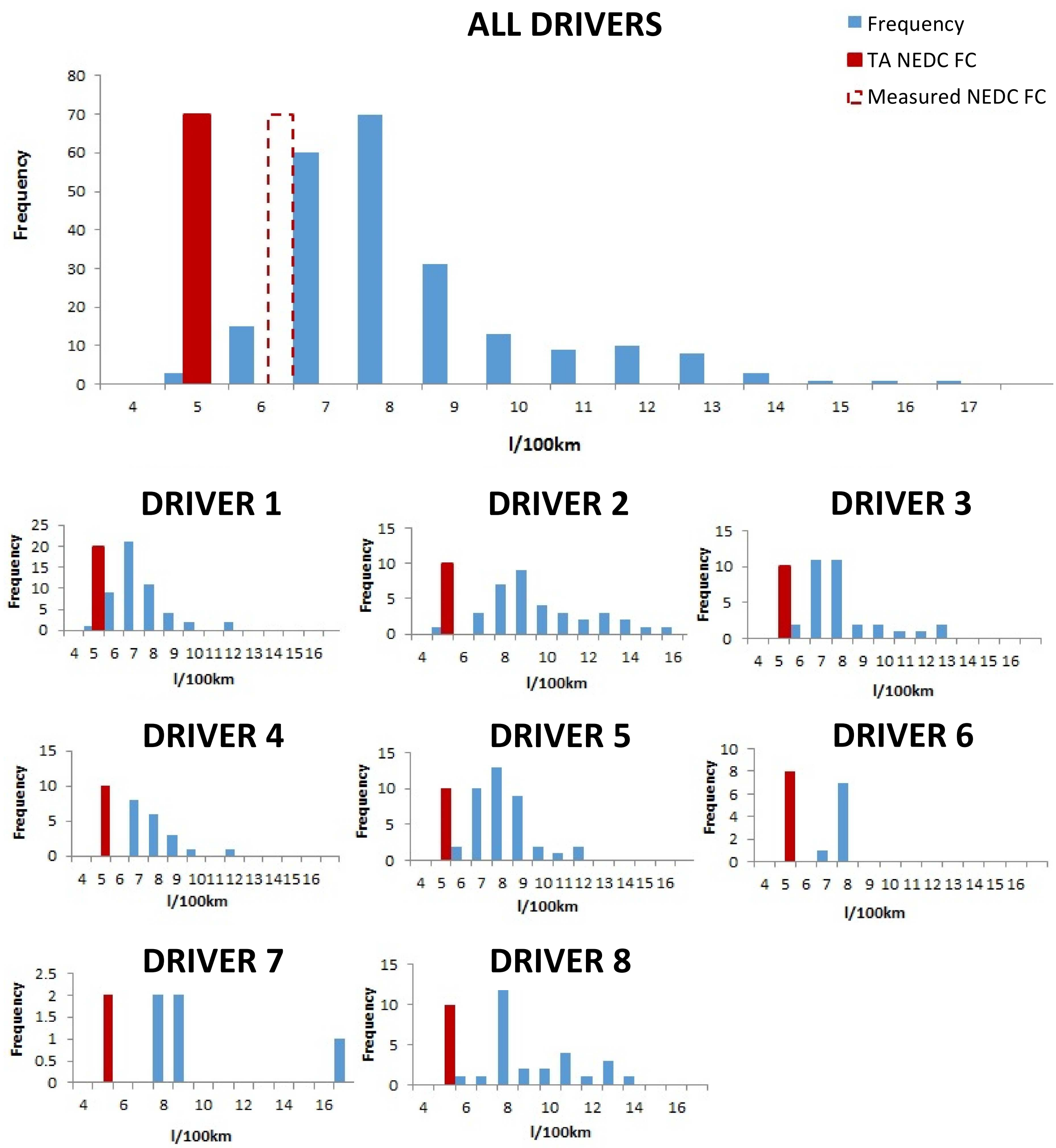

Figure E.1 Distribution of FC for each driver and for all drivers together. The charts also report the Type-Approval fuel consumption value (TA NEDC FC) and the fuel consumption measured at the Vehicle Emission Laboratory (VELA) of the JRC (Measured NEDC FC)

Figure E. 1 also shows the fuel consumption measured in the Vehicle Emission LAboratory (VELA) of the Joint Research Centre for the same vehicle over the NEDC test procedure ("Measured NEDC FC"). As already reported in the literature (please refer to Table 1 in the report), the NEDC TA value is systematically lower than the results of measurements carried out in an independent lab. Introducing a more robust test procedure, such as WLTP, will therefore significantly increase the representativeness of the lab-based test. Since, as of September 1st 2017, the WLTP has replaced the NEDC as test procedure to be used in the emission type-approval of light-duty vehicles, it is expected that the vehicles that will be introduced in the market in the near future will show a more realistic single value of fuel consumption and CO_2 emissions.

The results of the present study suggest however that there is further potential to enhance the existing type-approval system by coupling it with additional instruments, such as a fleet-wide fuel consumption monitoring system (to monitor the evolution of the gap between real-world and type-approval figures) and/or tools able to provide users with customized fuel consumption information derived on the basis of driver-specific conditions of vehicle use.

1 Introduction

In 2009, the European Union (EU) set a target for the fleet-wide average CO_2 emissions of new passenger cars at 95 gCO_2/km, which applies from the year 2021 on. For vans, such a target was defined in 2011 and confirmed in 2014 (147 g/km from 2020 on). Both targets are set by reference to the NEDC test cycle. The Commission is now preparing a review of the legislation with a view of setting new CO_2 targets for light duty vehicles for the next decade.

There is however increasing evidence (Table 1) suggesting that real world fuel consumption and CO_2 improvements in the last decade have been much lower than those measured during type approval. Scientific studies have found that the offset between officially reported values and real-world vehicle CO_2 emissions increases year by year. For 2015, this gap was estimated at about 36%. Results from Real Driving Emissions (RDE) tests for CO_2 emissions show differences in the same order (30±12%) [11]. Furthermore, several investigations have shown that the reported CO_2 values could not be reproduced under the official laboratory test conditions and that offsets in CO_2 emissions of about 10-15% exist on average [13].

Table 1: Evolution of the average gap between real-world and type approval CO_2 emissions of passenger cars in Europe as reported by different authors in the period 2011-2016

Authors	**Year**	**Geographical area**	**Real world – Certification value CO_2 gap**
Weiss et al. [2]	2011	EU	21%
Mellios et al. [3]	2011	EU	25%
Fontaras and Dilara [4]	2012	EU	22.5%
Ligterink et al. [5]	2013	Netherlands	30%
Mock et al. [6]	2014	EU	38%
Ligterink et al. [7]	2014	Netherlands	44%
Reynaert and Sallee [8]	2014	US	41%
Tietge et al. [9]	2015	EU	40%
Zacharof et al. [10]	2015	EU	36%
Fontaras et al. [11]	2016	EU	40%
Duarte et al. [12]	2016	EU	24%

There are three main reasons why a high difference between officially reported and actual CO_2 emissions of vehicles, which is increasing over time, constitutes a problem: a) it undermines the effectiveness of the CO_2 Regulations for cars and vans in reducing greenhouse gas emissions in Europe, b) it distorts competition between vehicle manufacturers, c) it undermines innovation by hampering the development of new vehicle efficiency technology.

Certain initiatives have been already taken in order to limit the increasing divergence between the officially declared and actual CO_2 emissions of light duty vehicles. The recent introduction of the new Worldwide harmonized Light vehicles Test Procedure (WLTP) [14] will bring type approval results closer to reality. Through the correlation and target translation legislation ([15], [16]) the CO_2 target value will be linked to the WLTP by 2017, and this is an important step towards the definition of new, WLTP-based, CO_2 targets for the post 2021 period [17]. In addition, the introduction of the RDE test procedure in the European Type-Approval legislation [17], although designed for measuring pollutant emissions, can potentially offer an additional valuable source of data regarding the performance of vehicles in terms of CO_2 emissions and fuel consumption under more realistic operating conditions. The usefulness of this data however depends on their availability, the representativeness of the "standard-operating" conditions defined by the RDE procedure considering the variable real-life vehicle operations and robustness of the test itself.

Many studies have tried to provide a thorough explanation of the elements affecting the fuel consumption variability of vehicles in real-driving conditions (a recent comprehensive overview has been provided in [11]). However only a few attempts to experimentally determine the possible fuel consumption variability due to a combination of e.g. temperature/weather, driver, traffic, landscape, road conditions etc. do exist in the literature and usually only focus on a limited number of factors. The present study therefore aims at filling this gap. In particular, it will present the results of the empirical evidence collected by the European Commission's Joint Research Centre (JRC), with the aim of characterising the uncertainty (variability) in the vehicle fuel consumption. This will help to understand whether an approach based on the determination of a single figure representing the real-world performance of a vehicle (determined through an ad hoc real-world test or through corrections to the lab-based type-approval value) could be acceptable from a conceptual point of view or not. The report is organized as follows. In the next section the methodology used for this analysis is briefly presented, followed by a presentation of the main results achieved. A discussion section then follows to outline the main implications of the results achieved. A final section then summarizes the main conclusions of the study.

2 Methodology

The characterization of the uncertainty/variability in the fuel consumption of light duty vehicles is performed by using two different data sets:

- **Data set n. 1**. Data collected during a period of 6 months from a vehicle driven by different drivers over trips with different origin and destination and under different environmental conditions;
- **Data set n. 2**. Data collected from the RDE tests carried out at the JRC during the last years using different vehicles and driven by a few specific drivers over a limited number of routes;

The two data sources have different characteristics. In the first experimental campaign, everything is known concerning the vehicle usage, the trips, and the drivers. Therefore an in-depth characterization of the fuel consumption variability both in terms of quantification of the uncertainty and understanding the main factors leading to it is possible. However, the analysis refers to a single vehicle only and therefore the results are certainly biased by its technology configuration and particular characteristics. The second campaign includes different vehicles. Many pieces of information on the vehicles and the routes are known. The number of tests per each vehicle is limited (around 10 trips per vehicle) and they concern a limited number of drivers and routes. Some characterization of the uncertainty is possible, but the reasons leading to it are not necessarily captured.

In spite of their intrinsic limitations, the use of the two sets of data in the same study allow to validate one with the other and to extend the results achieved to dimensions that would not be possible if the two studies were taken in isolation.

The two data-sets required a different approach in order to quantify the fuel consumption variability. In the first case, indeed, since only one vehicle is considered, the specific fuel consumption (in l/100km) can be directly used in the analysis. In the second case, instead, since different vehicles are involved a direct comparison of the fuel consumption is not possible. However, since the focus of the study is not the absolute fuel consumption but rather its variability, all the values of fuel consumption have been normalized with respect to the average fuel consumption measured for that vehicle throughout the different RDE test. In addition, since each RDE test requires driving the vehicle in three different conditions (urban, rural, and motorway), per each RDE test all three values of fuel consumption plus their combination were considered in order to enrich the information content of the entire sample.

The analysis is carried out by plotting the histograms of the fuel consumption distributions derived from the two samples and by computing the main statistics from the two distributions.

3 Results

As briefly mentioned in the previous section, the present study tries to draw inference about the uncertainty in the vehicles' fuel consumption from two different sets of experimental data. A brief description of the data used and results achieved is reported in the next sections.

3.1 Data set n.1

In this activity a vehicle was hired for a period of 12 months. The vehicle was instrumented by an On Board Diagnostics (OBD) II logger ad-hoc developed to access all the information available at the electronic control unit (ECU) of the specific vehicle. In addition the device was complemented by a 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. In this way, it was possible to achieve a complete characterization of the vehicle operations.

The vehicle chosen for the analysis is a 2.0L C segment diesel vehicle equipped with automatic transmission (see Table 2 for details). The vehicle is compliant with Euro 6 regulation for pollutant emissions. Automatic transmission reduces the potential variability in fuel consumption as the gear-shift behaviour of the drivers is more repeatable and is not so much influenced by the individual driving style. The vehicle has three fuel-consumption relevant driving modes (normal, sport, and 4x4 mode) and the selection of modes was left to drivers. It also has engine start/stop function that has been used for the most of trips.

Table 2: Specification of the vehicle and details related to tests in laboratory and on the road

Vehicle Class	***M1***
Model Year	***2016***
Engine capacity/power	***1956 cm^3/103 kW***
Transmission	***Automatic (9-speed)***
Emission standard	***Euro6b***
After-treatment system	***DOC, EGR (low and high pressure), LNT, DPF***
RL coefficients NEDC (JRC calculated)	***Inertia: 1590 kg; F0: 101; F1: 0.351; F2: 0.034***
Number of drivers	***8***
Number of trips	***217***
Total mileage driven (km)	***6716***

Before testing on the road the vehicle has been tested at JRC premises in the VELA laboratory on chassis dynamometer following the New European Driving Cycle (NEDC) test procedures. Inertia and road load coefficients applied for NEDC testing can be found in Table 1. Road load coefficients were calculated using algorithms developed at JRC able to correlate road loads with the main physical characteristics of the vehicles. The NEDC tests were done in three repetitions. The average Fuel Consumption (FC) results of these tests (phases and combined) together with declared (Type Approval) results can be found in Table 2. As it can be seen from the table, the combined test results were higher (6.2 l/100 km) than declared value (5.5 l/100km). Accordingly, the phase (Urban Driving Cycle - UDC and Extra Urban Driving Cycle - EUDC) test results were also higher than the corresponding type-approval values. The approximately 13% difference (declared vs. measured) can be explained by the 4% Declared Value (DV) and by the several uncertainties in the test conditions (exact road loads, test temperature, state of charge of the battery, conformity of production margins, etc.) allowed by the NEDC procedure (for a complete overview, please refer to [19]). In addition, tests in JRC were performed on 2-axle chassis dynamometer while, even for the 4WD vehicles, the NEDC procedure allowed the Original Equipment Manufacturers (OEMs) to use 1-axle chassis dynamometer for testing after applying the special procedure that temporarily disables the second axle to engage during the test. According to our experience this NEDC flexibility could account for additional couple percent in fuel consumption/CO_2 savings. Such a deviation is however in line with previous experience by the authors [20].

Table 3: Comparison of phase and combined FC (l/100 km) NEDC type-approval and test result values

TEST	PHASE 1 - UDC	PHASE 2 - EUDC	COMBINED
Type-Approval NEDC	6.5	4.9	**5.5**
Measured NEDC	7.7	5.4	**6.2**

In addition to the laboratory NEDC tests, this vehicle has also been tested on the road for RDE performance. Fuel consumption measured during RDE tests are shown in Table 4. In the table it is reported also information on whether the RDE test was a valid test or not. For valid test it is meant a test fulfilling the criteria contained in the European RDE legislation [17] concerning urban, rural, motorway distance shares, driving dynamics, etc. Concerning the differentiation between urban, rural and motorway conditions, urban operation is characterized by vehicle speeds up to 60 km/h, rural operation by vehicle speeds between 60 and 90 km/h, and motorway operation by vehicle speeds higher than 90 km/h.

Table 4: FC (l/100 km) of PEMS trips (complete trip and phase results)

PEMS Test ID	Valid	Complete	Urban	Rural	Motorway
1	No	7.0	8.1	5.6	6.8
2	No	7.4	8.2	5.3	8.4
3	Yes	7.1	7.9	5.4	7.8
4	Yes	7.3	8.7	5.7	7.2
5	No	7.3	8.1	5.3	8.2
6	No	7.9	9.2	6.0	8.1
7	No	7.9	9.0	5.9	8.3
8	Yes	7.1	8.3	5.4	7.2
9	Yes	7.0	8.2	5.7	7.0
10	Yes	7.1	8.0	5.3	7.6
Average of compliant tests	--	**7.1±1.5%**	**8.2±3.8%**	**5.5±3.4%**	**7.4±4.5%**
Average of non-compliant tests	--	**7.5±5.2%**	**8.5±6.3%**	**5.6±5.8%**	**8.0±8.3%**
AVERAGE OF ALL PEMS TESTS	--	**7.3±4.6%**	**8.4±5.3%**	**5.6±4.7%**	**7.7±7.6%**

Table 4 reports the specific fuel consumption (l/100km) for each RDE test and the statistical mean value on all trips, on all the compliant trips and on all the non-compliant trips. Also the statistical coefficient of variation per each of the three sets of data is reported next to the average value (the coefficient of variation is the ratio of the standard deviation to the mean of a distribution).

From the results it is possible to draw the following considerations:

- as expected, the fuel consumption from all RDE trips is always higher than the corresponding NEDC values. However,
  - considering the average of all RDE trips and the type approval value for the vehicle, the gap is approximately 33%;
  - considering the average of all RDE trips and the measured NEDC value, the gap is approximately 18%;
  - considering the average of all RDE valid trips and the type approval value, the gap is approximately 29%; and
  - considering the average of all RDE valid trips and the measured NEDC value, the gap is approximately 15%.

  Even though the results only refer to a single vehicle, considering the figures reported in Table 1 regarding the average gap measured or calculated in different studies, it can be argued that CO_2 emissions and fuel consumption measured during valid RDE trips would not be able to entirely cover the existing gap. Since, according to some studies (see e.g. [21]), the introduction of the WLTP will already increase the average type-approval fuel consumption by approximately 20%, the added value brought by the result of an RDE test seems rather limited.
- The fuel consumption derived from valid RDE trips is systematically lower and less variable than the fuel consumption derived from non-valid trips and from real-world operation. The constraints introduced by the legislation aim to limit the variability in order to have a more robust and repeatable RDE test procedure for regulating criteria pollutant emissions. More controlled test conditions increase the repeatability of such a procedure and hence reduce the spread of CO_2; at this point it is recognized that the tests carried out in the present study were performed over a limited number of routes and conditions. The fuel consumption from an RDE trip is therefore likely to represent a rather conservative estimation of the vehicle fuel consumption. This is confirmed by the results reported in Figure 1 on the distribution of the fuel consumption from different drivers.

In order to assess the variability of fuel consumption from normal vehicle use, the vehicle was provided to different drivers on a voluntary basis. Each driver was requested to drive as they would have done with their own vehicle. Fuel was not provided in order not to influence the driving style. Driving activities for the first couple of trips of data acquisition were discarder and not taken into account in the analysis to allow at least a basic familiarization with the vehicle. Some drivers drove the vehicle for a period of couple days (minimum was 3 days) and some others for a period of couple weeks (maximum was 2 weeks). Drivers were requested to take note of the following elements at the end of each driving activity: weather conditions, traffic conditions, number of passengers, specific additional loads added to the vehicle (luggage, etc.), and general way of functioning of the vehicle as well as any unexpected situation faced during the trip. All drivers were employees of the European Commission JRC for insurance-related reasons. In travel related surveys/experiments, income and education levels are usually taken into consideration as sample stratification dimensions. In this light the sample of people driving the vehicle might have a polarization with respect to these two dimensions. This is not considered as a strong limitation as this induces a slightly reduced uncertainty in the measured fuel consumption that, given the objective of the paper, can be considered as a safety margin. Attention was paid to have as different as possible trip characteristics, trying to cover as much as possible urban, rural, motorway, and mixed driving conditions. However, due to the configuration of the area, there is slightly higher prevalence of rural driving conditions. At the same time, due to the morphology of the area, influence of slope and road geometry is expected to contribute to an increase in the uncertainty in the fuel consumption.

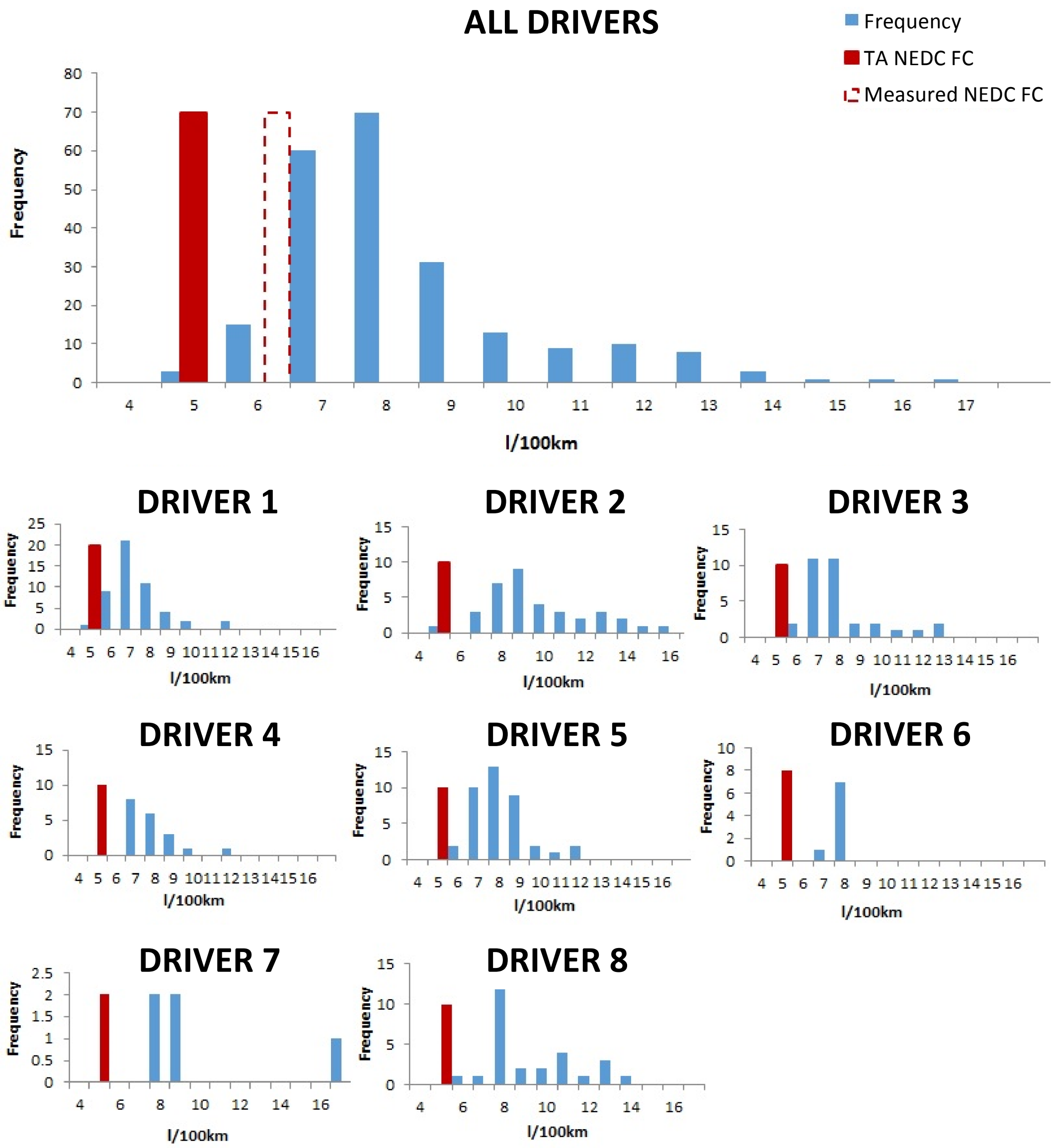

Figure 1: Distribution of FC for each driver and for all drivers together. The charts also report the Type-Approval fuel consumption value (TA NEDC FC) and the fuel consumption measured at the Vehicle Emission Laboratory (VELA) of the JRC (Measured NEDC FC)

Tests evaluated in this report include trips from 8 different drivers and were recorded during the period from December 2016 to April 2017. The number of trips recorded during this period is equal to 197 and in total 6716 km were driven. All trips that contain pauses longer than 5 minutes were split in different trips. The minimum duration of a trip was set to 5 minutes. In total 217 trips were created and evaluated for distribution of FC. A number of OBD signals (between 80 and 90) were registered during the trips. However, for the purpose of this report the relevant signals are vehicle speed (km/h) and fuel consumption (l/h) from which the average FC (l/100km) of each trip is calculated. Histograms that show the distribution of FC for each driver and for all trips can be found in Figure 1 together with labels for type-approval and measured NEDC test results reported for an easy comparison purpose.

Descriptive statistics related to Figure 1 can be found in Table 5. The mean FC for each driver was calculated as the total fuel consumption divided by the total distance travelled (by each driver or by all drivers together) and resulted in the range from 6.9 l/100km (Driver 1) to 9.8 l/100km (Driver 7) and that is significantly (25 to 78%) higher than the combined type approval value of 5.5 l/100 km. Minimum FC of a registered segment was 4.5 l/100km and maximum 16.9 l/100km. In fact, only few trips (5 out of 217) had average FC lower than the type-approval fuel consumption of 5.5 l/100km. The mean FC of all trips was 8.0 l/100km (standard deviation = 2.1 l/100km), 45% higher than declared combined NEDC FC and higher than the average FC for complete RDE trips (7.3 l/100km for all trips and 7.1 l/100km for valid RDE trips). The coefficient of variation for the entire distribution of fuel consumption is 26.2% which is significantly higher than what reported for the RDE trips (as expected due to a much higher variability of the trip characteristics and number of drivers).

Table 5: Inputs of the Vehicle Simulation Tool

Statistical Test	*ALL TRIPS*	*DRIVER 1*	*DRIVER 2*	*DRIVER 3*	*DRIVER 4*	*DRIVER 5*	*DRIVER 6*	*DRIVER 7*	*DRIVER 8*
Mean*	**8.0**	**6.9**	**9.5**	**7.7**	**7.5**	**7.7**	**7.2**	**9.8**	**8.9**
Median*	7.4	6.7	9.0	7.3	7.0	7.5	7.1	8.7	7.9
St. Dev.*	2.1	1.4	2.5	1.7	1.3	1.5	0.3	4.0	2.1
CV***	26.3%	20.3%	26.3%	22.1%	17.3%	19.5%	4.2%	40.8%	23.6%
Skewness*	1.5	1.5	0.6	1.5	1.8	1.1	0.4	2.0	0.8
Range*	12.4	7.1	11.1	6.9	5.1	6.8	1.0	9.7	8.0
Min.*	4.5	4.5	4.6	5.6	6.1	5.2	6.8	7.1	6.0
Max.*	16.9	11.6	15.6	12.5	11.2	12.0	7.7	16.9	13.9
Count**	217	50	36	32	19	39	8	5	28

*All values expressed in l/100km; **Represent number of trips per each driver; *** Coefficient of variation

The median of the fuel consumption distribution is systematically higher than the mean, showing the distribution is right-skewed (the tail of fuel consumption values higher than the average one is longer than the tail of lower fuel consumption values), and therefore that the right part of the distribution covers a higher spectrum of fuel consumption values than the left part.

3.2 Data set n.2

As briefly mentioned in the methodology section, the second dataset is composed by the fuel consumption experienced by 37 vehicles undergoing a total of 274 RDE tests in the period 2014-2016. On the basis of the characteristics of the trip each of them is divided, according to the RDE test procedure, in urban, rural and motorway conditions. The analysis is here based on CO_2 and not on fuel consumption because fuel consumption is not measured but calculated during standard RDE tests. However, given the approximately constant relationship between CO_2 and fuel consumption, using one or the other should not have effects in the analysis of the variability. The combination of the CO_2 from the difference phases is the combined CO_2. Performing this differentiation, from the 274 RDE tests, 547 different values of fuel consumption/CO_2 emissions were derived to assess the uncertainty in the fuel consumption values. As already mentioned, since the 547 measures of consumption refer to 37 different vehicles (differing in technology configuration, size, emission legislation etc.) the statistics could not be directly drawn on the absolute CO_2 emissions and a normalization of the CO_2 was necessary. To clarify how this was carried out, the following table (Table 6) reports the elaborations carried out on the data from the first vehicle tested.

Table 6: Elaboration of the results of the RDE tests of vehicle n. 1

Vehicle n. 1	Unit	RDE Trip				
		1	2	3	4	5
CO2 Urban	g/km	217.32	199.35	176.84	169.18	195.60
CO2 Rural	g/km	126.54	143.83	137.96	179.48	87.27
CO2 Motorway	g/km	165.22	176.21	168.83	FALSE	FALSE
CO2 Combined	g/km	173.49	175.49	164.27	169.49	190.28
Norm CO2 Urban 1	--	1.13	1.04	0.92	0.88	1.02
Norm CO2 Rural 1	--	0.94	1.07	1.02	1.33	0.65
Norm CO2 Motor 1	--	0.97	1.04	0.99	FALSE	FALSE
Norm CO2 Combined 1	--	0.99	1.01	0.94	0.97	1.09
Norm CO2 Urban 2	--	1.30	1.19	1.06	1.01	1.17
Norm CO2 Rural 2	--	0.76	0.86	0.82	1.07	0.52
Norm CO2 Motor 2	--	0.99	1.05	1.01	FALSE	FALSE
Norm CO2 Combined 2	--	1.04	1.05	0.98	1.01	1.14

From the table it is possible to observe that the vehicle underwent 5 RDE tests. In two cases the tests did not include motorway driving. For this reason 18 CO_2 observations were derived. Two types of normalization were applied. In the first normalization (Norm 1) each CO_2 value is normalized by the average CO_2 emissions of the vehicle under the same driving conditions. As an example, values reported in the fifth row of the table (Norm CO_2 Urban 1) have been obtained by dividing the CO_2 emissions reported in the first row (CO2 Urban) by the average of the CO_2 emissions in the same row.

The second normalization (Norm 2) is instead carried out with respect to the average of all the CO_2 values from the same vehicle. Similarly to the previous example, values reported in ninth row of the table (Norm CO_2 Urban 2) have been obtained by dividing the CO_2 emissions reported in the first row of the table (CO_2 Urban) by the average of the 18 different values of CO_2 emissions. As it is possible to observe, the second normalization approach, as expected, shows higher variability in the normalized CO_2 emissions.

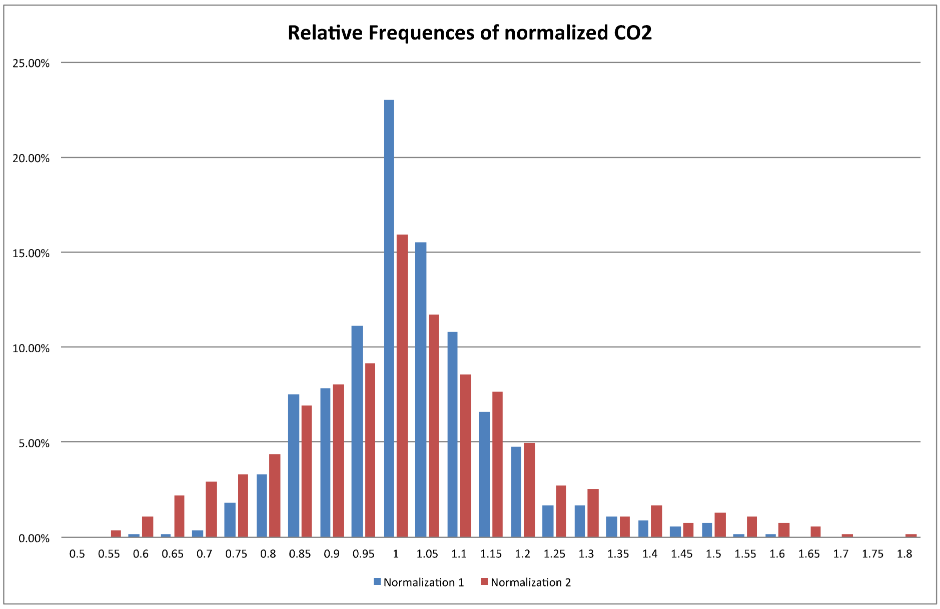

Figure 2: Empirical distribution of normalized fuel consumption derived from the pool of vehicles subject to RDE tests in the period 2014-2016

From a conceptual point of view, though, the second approach is the most correct one as in real life the average CO_2 emissions for a vehicle derive from all the trips that a certain vehicle has performed (which can involve totally different driving conditions).

Iterating the procedure over all the trips of all the vehicles tested, the distribution of the normalized CO_2 emissions can be empirically drawn. The resulting histogram is reported in Figure 2, while main statistics concerning the two distributions are reported in table 7.

Table 7: Main statistics of the empirical distribution of normalized fuel consumption

	Normalization 1	Normalization 2
Average	*1.000*	*1.000*
Standard Deviation	*0.140*	*0.203*
Min	*0.598*	*0.521*
Max	*1.569*	*1.793*
10° percentile	*0.830*	*0.752*
90° percentile	*1.174*	*1.252*

Both the Table 7 and the Figure 2 show that the distribution of fuel consumption follows a fairly normal distribution. Given the way the normalization is carried out, both distributions are centred in 1. As expected the first normalization has a slightly smaller uncertainty and a peak of probability around 1. In both cases, the size of the fuel consumption uncertainty is significant. From the standard deviation it is possible to derive that around 95% of the observations are expected in a range of 40% of the average value in both directions. Considering that the RDE tests were carried out by a limited number of drivers and were only including a limited number of routes in the same area, it can be expected that the actual uncertainty in the fuel consumption of a single vehicle can be even higher. This is indeed confirmed by the results obtained from the data set n.1 where the overall standard deviation is 26% of the average value (suggesting that 95% of the observations are expected in a range of ~50% of the average value). During a single RDE test, any value in these distributions can be achieved and therefore the representativeness of this value as real-world fuel consumption is questionable.

4 Discussion

Given the uncertainty in the fuel consumption of a vehicle (due to the several factors having an effect on this variable), using the value measured during an RDE test (according to the current protocol or a protocol specifically designed for the CO_2) as a representative a-priori measure of the fuel consumption of a vehicle on the road seems at least questionable (whatever the purpose of determining this value is). Data presented in this report (Table 4) show that the same vehicle driven for RDE purposes on a limited number of routes in the same area and with similar environmental conditions only accounts for a limited variability and therefore the representativeness of the derived fuel consumption and CO_2 emissions would be bounded by the route selected for the test. In addition, as reported in the discussions of the results for the RDE tests carried out on the vehicle used to derive the data set n. 1, we can expect that the value obtained from a valid RDE test will be a conservative estimation of the average fuel consumption of a vehicle. Considering that vehicle manufacturers could even have the possibility to select to their own advantage specific locations, environmental conditions and driving circumstances from the many uncertainties intrinsic of an RDE test, again the representativeness of the results of a valid RDE test could be further challenged. With RDE type approval measurements becoming increasingly available with the passing of time, the degree of representativeness of the fuel consumption determined under this procedure will need to be assessed and any risk of bias further investigated. The RDE test may at the same time offer the possibility to collect sufficient parameters to model a vehicle accurately. A corresponding vehicle simulator could then be used to calculate its fuel consumption in any driving situation or test conditions.

The significant variability of the fuel consumption among different drivers (in the range 4.5-16.9 l/100km for the vehicle that has been tested in the present study) shows that even in the case that a more "central" estimation is achieved by means of a CO_2-RDE test, the benefits for users will be limited. Furthermore, alternative approaches are available, which, from a technical point of view, are simpler to be used.

Today's vehicles are all equipped with sensors and control units able to accurately estimate the instantaneous fuel consumption. Most of them have or will soon have connectivity features, which allow information on average fuel consumption over a certain period of time to be collected and monitored. Since post-2020 CO_2 targets will be based on WLTP, the real-world monitoring could be used to verify that any remaining gap between real-life and type-approval emissions does not significantly change over time.

The gap for an OEM in the year *t* could be defined in the following way:

$$GAP(t) = \frac{\dfrac{\sum_{i=1}^{N} FC_i(t-1) \cdot D_i(t-1)}{\sum_{i=1}^{N} D_i\,(t-1)}}{\dfrac{1}{N}\sum_{i=1}^{N} FC_i^{TA}} \qquad (1)$$

where $FC_i(t-1)$ is the specific fuel consumption of vehicle *i* in real life in the year *t-1*, D_i(t-1) is the distance travelled by the vehicle *i* in the year *t-1*, FC_i^{TA} is the specific fuel consumption of vehicle *i* at TA, *N* is the number of vehicles registered by the OEM in the year *t-1*. On the basis of the evolution of the gap over different years the CO_2 target for an OEM could be adapted. This mechanism would ensure that the reduction of CO_2 emissions under type-approval conditions corresponds to a proportional time-invariant reduction in real life. In addition, a mechanism of this type would encourage the introduction of technologies having an effect in real life and including those whose effect is not or only partially visible during the vehicle type-approval.

Unfortunately a real-world CO_2 monitoring system cannot be used for providing more reliable a-priori fuel consumption information to users. Moreover, characterizing the fuel consumption of a vehicle through a single number may be insufficient for consumer information given the stochastic nature of this parameter (exemplified by the results collected in the present study). A possible alternative approach might be considered in which a user is provided instead with a simple modelling tool to calculate the fuel consumption of its vehicle in different conditions. By providing indications on the driving preferences (e.g. the usual route, the number of passengers and additional loads, the usage of the on-board devices and instruments, the type of tires installed, etc.) a significant part of the uncertainty in the fuel consumption can be reduced to a sufficiently low level. The Green Driving tool developed by the JRC [22] is a first attempt in this direction. In the case that a link is established between the vehicle type-approval, the vehicle commercialization, registration and a tool like Green Driving, technical information on the vehicle and the results of the type-approval test could be used to characterize the vehicle efficiency in a way that could be sufficient to calculate a real world fuel consumption in a sufficiently reliable way. In the case of the Green Driving tool this was possible using the correlation tool CO_2MPAS to calculate CO_2 and fuel consumption under many possible conditions (a visualization of the tool is reported in Figure 3 for illustrative purposes).

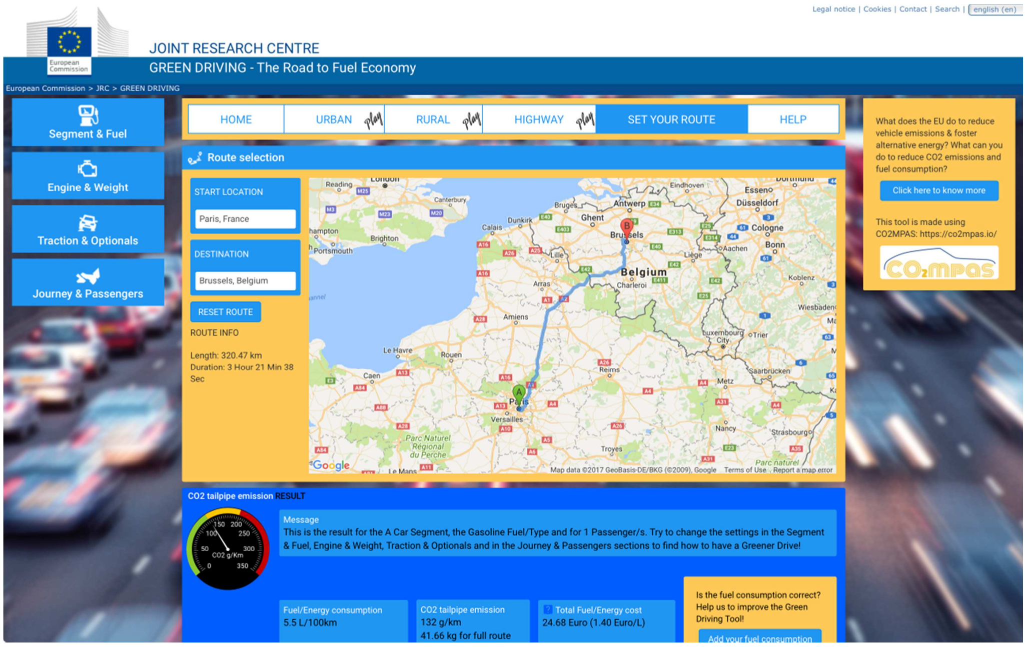

Figure 3: The Green Driving tool developed by the JRC

Finally, in the case that, during an RDE test, sufficient information on the vehicle operations is gathered (e.g. instantaneous power at the wheels, instantaneous consumption, etc.) the information collected during the test could be used as input to a simulation model to calculate and forecast vehicle CO_2 and fuel consumption either under standardized conditions (representative type approval test) or under individual real-world conditions as previously mentioned [18].

5 Conclusions

No matter how sophisticated and elaborate a test procedure is, inherently it cannot capture the multitude of factors affecting CO_2 emissions of cars in reality. WLTP is an important tool towards creating a level playing field for assessing the compliance of vehicles against regulatory limits and for comparing the fuel consumption of individual vehicles. However, at the end of the day, real savings in CO_2 emissions come during the real-world operation of cars. For fully covering this, new concepts need to be considered in addition to the traditional certification and monitoring schemes present in the European legislation. As an example, new vehicle communication technologies offer a relatively simple and cost effective opportunity to access the average fuel consumption of vehicles in real life without putting additional burden and costs in the vehicle certification process and at the same time offering a direct connection to the actual improvements of vehicle efficiency. This type of opportunities cannot be disregarded.

In addition, drivers should be given more information for making purchase decisions that match their actual needs and everyday use of their vehicle, and should be empowered to provide visible feedback when such information reveals false or misleading. Vehicle labelling can be improved in order to offer such aspects with more detailed information. CO_2 monitoring in real world should be considered either by means of two-way voluntary interaction with the drivers or by establishing anonymized, fuel consumption data collection instruments (e.g. on board fuel consumption data registration).

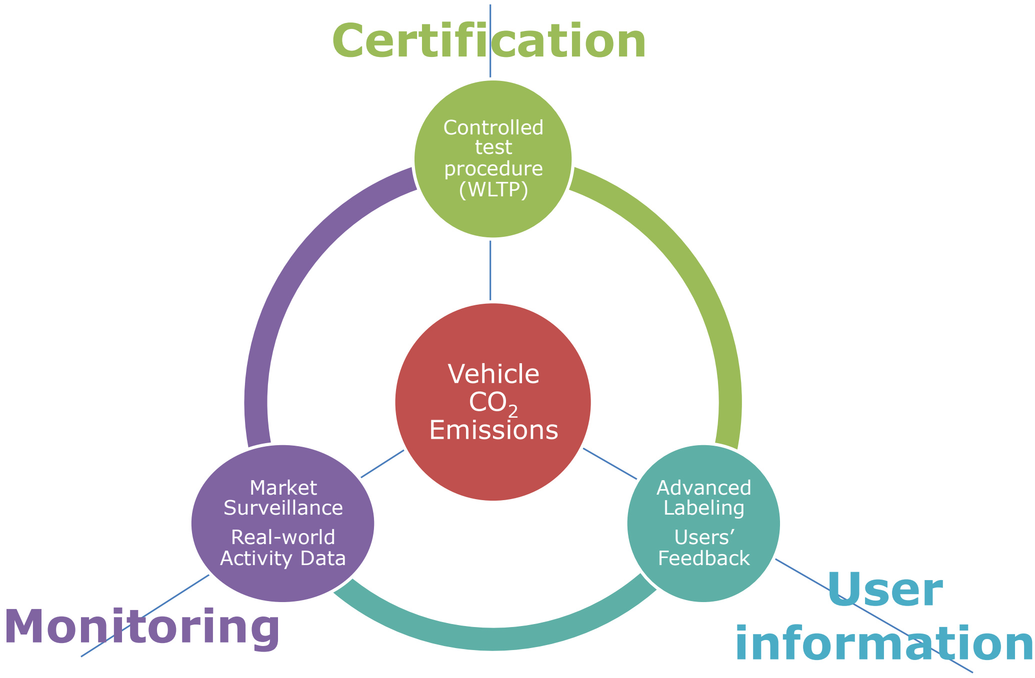

Figure 4: Schematic representation of the main elements that could form the future integrated approach for fuel consumption and CO_2 emissions certification and labelling.

Finally in a world of applications and communication, the development of modelling tools and driver "communities", which will provide valuable feedback on the performance of vehicles and possibilities to reduce CO_2 emissions through efficient everyday practices, cannot be overlooked. In this sense new policies should aim at an integrated framework covering all three aspects, official certification, real world and lab based emissions, monitoring and driver information-communication measures (as schematically reported in Figure 4). Some primordial tool towards the direction of providing a relevant platform to the users and for establishing two-way communications between vehicle drivers and emission monitoring system has been embedded in the Joint Research Centre's Green-Driving tool [22].

This three pillar concept based on Certification, Monitoring and User information can constitute a working bridge between reality and the lab, combining the benefits of all worlds and reducing the risks of future market or policy failures. It can provide a solid basis for sensible policy making in the decades to follow enabling an accurate quantification of the CO_2 reductions achieved and revealing the great efforts put by the industry for increasing the energy efficiency of vehicles.

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List of abbreviations and definitions

EU	*European Union*
EC	*European Commission*
NEDC	*New European Driving Cycle*
WLTP	*Worldwide Light duty vehicle Test Procedure*
2WD	*2 Wheel Drive*
4WD	*4 Wheel Drive*
F_0, F_1, F_2	*Road Load Coefficients (N, N/(km/h), N/(km/h)^2)*
FC	*Fuel Consumption (l/100km)*
OEM	Original Equipment Manufacturer
TA	Type-Approval

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