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LABORATORY AND ON-ROAD CHARACTERIZATION OF EXHAUST EMISSIONS FROM PLUG-IN HYBRID VEHICLES AT MULTIPLE BATTERY STATES OF CHARGE CONDITIONS

Summary. This paper discusses emissions from plug-in hybrid vehicles under various driving scenarios and reports experimental data obtained under laboratory and real-world conditions. Two European plug-in hybrid passenger cars were tested using the two test types in use in the EU (chassis dynamometer and on-road), with some modifications. The best-case and near-worst-case battery states of charge were used for testing. Behavior in terms of CO_2 emissions, regulated emissions, and unregulated emissions was characterized and analyzed. Differences were generally much greater for on-road testing, especially for urban driving, during which the potential for purely electrical propulsion of the vehicle is greatest. The long distances covered by current EU legislative test procedures limit the impacts of some effects. Regardless of the traction battery's state of charge, regulated emissions were well below the applicable EU limits under all driving conditions—for example, combined emissions of reactive nitrogen compounds (nitrogen oxides, ammonia, and nitrous oxide) were consistently < 10 mg/km when tested under laboratory conditions. The two vehicles tested showed that the state of the battery had a large impact on the proportion of electrical propulsion and the resulting CO_2 emissions, but differences in regulated pollutants decrease with increasing distance and are generally relatively limited for longer journeys, which include non-urban driving.

1. INTRODUCTION

The number of in-use passenger cars has expanded massively in recent decades. In the European Union (EU), the number of passenger cars per 1,000 inhabitants is around 560 [1]. Despite recent gains made by battery electric vehicles in the EU in terms of new vehicle market share, sales of new vehicles remain dominated by those featuring internal combustion engines (ICEs) [2]. The EU's in-use passenger car fleet is strongly dominated by vehicles propelled exclusively or primarily by ICEs [3]. Growing concern about anthropogenic emissions of greenhouse gases (GHGs), most notably CO_2, has led to a range of restrictions, non-binding targets, and financial incentives being imposed on certain sectors of the economy.

In the road transport sector, fuel and energy consumption are not subject to absolute limits, but the vast majority of passenger cars sold globally are subject to some form of energy efficiency legislation. In the EU, this takes the form of fleet average CO_2 limits, which apply to exhaust emissions only and

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are the target of weight-normalized limits with strong financial incentives to discourage exceedances [4]. Since the limit applying to a given vehicle manufacturer (or group of manufacturers) is a sales-weighed fleet average limit, many manufacturers have chosen to sell vehicles with a range of powertrain types, ranging from conventional ICEs to pure electric (i.e. BEV).

Between these two extremes, plug-in hybrid electric vehicles (PHEVs) aim to combine the benefits of electrified propulsion with the range and overall performance of vehicles with an ICE. So-called "upstream" environmental impacts (including CO_2 emissions) associated with manufacturing (including battery production) and the production of electricity used to charge traction batteries are not included in official emissions figures. This fact is an important consideration and a further contributory factor for manufacturers' focus on PHEVs as a compliance strategy. In turn, this partially explains the increasing numbers of PHEVs found on European roads, as reflected in statistics for sales of new vehicles by powertrain type [5], although it is to be noted that as of 2020, the EU in-use fleet featured a share of PHEVs of around 0.6% [3]. When their traction batteries are fully charged, PHEVs are normally able to travel some considerable distance before their combustion engine starts for the first time; short-length (and even medium-length) trips may be completed without any ICE operation at all, in which case the trip has zero exhaust emissions (and zero fuel consumption).

The conditions imposed by the EU legislative test procedure for quantification of CO_2 emissions [6] are relatively favorable for PHEVs in terms of the impact they have on the distance normally covered before the ICE starts for the first time. The key factors behind this are the ambient temperature (23 °C), the generally moderate rate of acceleration, the road load simulation requirements (which simulate a smooth, completely flat road), and the stipulation that no electrical cabin accessories be used. Due to the aforementioned factors, most modern PHEVs sold in the EU can run the entire legislative test cycle (a distance of 23.3 km) without using the ICE. Such powertrain operation is known as "charge depleting" since the traction battery is depleted—that is, its state of charge (SOC) gradually reduces—as the route is driven and the total driving distance accumulates. In recognition of this fact, the EU type approval procedure requires that further test repetitions are performed until a defined criterion is met. The aforementioned criterion is that the proportion of cycle energy demand met electrically is < 0.04 (i.e., less than 4% of the driving energy demand has been met using the electrical energy stored in the vehicle's traction battery or batteries). The particular test (repetition of the test cycle) during which the ICE starts for the first time is not necessarily the one during which this criterion will be reached. The cycle in which the 4% criterion is met is called the "transition" cycle. Following this cycle, one further cycle is required, which is termed the "charge-sustaining cycle". As the name implies, during this cycle, the traction battery's SOC is at a low (but non-zero) level, which necessitates the extensive use of the ICE. Under such conditions, PHEVs' exhaust emissions of CO_2 are normally at levels comparable to those of similar vehicles featuring non-plug-in hybrid powertrains [7].

As discussed above, the EU legislative method for quantifying CO_2 emissions places heavy emphasis on electrified propulsion—for example, if the 4% criterion is met during the third repetition of the test cycle and the fourth iteration is the final one, then a considerable distance will have been covered in purely electrical mode, leading to low final distance-specific CO_2 emissions. Significantly, for the legislative laboratory test, the vehicle is only tested in the best-case condition in terms of traction battery SOC. As shown and commented upon in a range of recent studies [8-10], the real-world charging behavior of PHEVs is often imperfect for several reasons. Firstly, the frequency of charging events may be significantly lower than assumed. Secondly, not every charging event lasts long enough for the SOC to reach its maximum level of 100%. While there are individual and regional variations, there is substantial quantitative evidence that a relatively high proportion of trips made in PHEVs commence with SOC values, which are significantly less than 100% [8-10]. These tendencies have obvious implications for the real-world performance of PHEVs in terms of their fuel consumption, exhaust emissions, and overall environmental impact during their lifetimes. Aside from environmental impact, the long-term cost of PHEV ownership is partially controlled by the proportion of driving that occurs in electrical propulsion mode (as well as by the relative prices of electricity and fuel).

A further consideration is real-world vehicle usage (i.e. driving) profiles [11]. First and foremost, this relates to the characteristics of the speed trace, particularly the mean speed and the frequency and duration of intensive acceleration events. Moreover, real-world road load, increased vehicle payload, variable terrain (especially uphill slopes), lower ambient temperatures, and usage of electrical cabin accessories such as heating and air conditioning can reduce the electrical propulsion range. These effects will cause earlier, more frequent, and generally more extensive ICE usage during normal driving. Real-world fuel consumption can be monitored on scales ranging from individual vehicles to entire fleets in multiple ways, including via the internet-facilitated sharing of driver-reported fuel consumption, as well as harvesting of data from company fuel cards and even making use of data collected by vehicles' onboard computers. For BEV, the equivalent data on electricity consumption can also be collected and analyzed. PHEVs represent an intermediate case (i.e., both types of data should be gathered and analyzed in such contexts).

In this study, two market-available PHEV vehicles were tested. One test vehicle was tested under Worldwide Harmonized Light Vehicle Test Procedure (WLTP), and both test vehicles were tested under real-world, on-road conditions using the Real Driving Emissions (RDE) procedure.

2. MATERIALS AND METHODS

2.1. General details on the test vehicles and their configuration

Both test vehicles were popular models from the 2020 model year, were in sound mechanical condition, and had mileages within the range of 5,000 to 15,000 km. Both featured plug-in hybrid powertrains with spark ignition combustion engines of approximate displacement 1.5-2.0 dm^3. Vehicle 1 (Euro 6d-temp) featured a three-way catalyst for control of gaseous exhaust emissions. Its engine featured indirect fuel injection and, thus, was not subject to particulate emissions limits and did not feature a gasoline particulate filter (GPF). Vehicle 2 (Euro 6d-temp) was also equipped with a three-way catalyst to control gaseous exhaust emissions. Its engine featured direct injection and, thus, was subject to particulate emissions limits under EU law and factory-fitted with a GPF. The manufacturer-declared pure electric range of both vehicles was within the range of 60-65 km (equivalent all-electric range). The same market-available European gasoline fuel was used for all testing (all test vehicles and both test types). This fuel contained ethanol at a nominal level of 5% by volume. The test vehicles' fuel levels were within the range of 50-80% for all RDE testing and WLTP testing. The test vehicles were in sound mechanical condition, and their onboard computers showed no on-board diagnostic (OBD) errors before, during, or after any testing. The total mass of the PEMS, its batteries, and all accessories was around 120 kg. No further payload was added, and no passengers other than the driver were present in the vehicle during testing. The tire pressure for each vehicle was set in accordance with the manufacturers' recommendations – for RDE testing with the PEMS installed, the mass of the PEMS and its location within the vehicle were taken into consideration when setting the tire pressure. Daytime running lights were used for both laboratory and on-road testing. All cabin accessories were turned off for laboratory testing, while during RDE testing, cabin accessories were used according to the driver's judgment of what constituted normal usage. The ventilation system was used constantly at low power, but air conditioning and other electrical cabin accessories were not used at any point.

2.2. Methodology employed for laboratory WLTP testing

During laboratory testing, which was performed on one vehicle (Vehicle 1), a modified version of the EU legislative test procedure (WLTP) was used to characterize emissions behavior. For this purpose, the base WLTP procedure was used in an unmodified form. However, the data treatment steps were modified, as emissions are presented "as measured" from each repetition of the cycle. The first test sequence itself consisted of performing four WLTC cycles consecutively with a 10-12 minute pause between cycles for practical reasons; a break of up to 30 minutes is permitted by the legislation

[6]). The first time this procedure was performed, it commenced with the test vehicle's traction battery fully charged (SOC = 100%). By the end of this procedure, the traction battery SOC had stabilized at a low (but non-zero) level. The vehicle was then left standing with its powertrain off ("soaked") overnight. Four repetitions of the WLTC test cycle were then performed again, this time commencing with the vehicle's battery in its "as found" state (i.e., low SOC). The key steps of the procedure followed for laboratory testing (of one vehicle) are summarized below:

1. Chassis dynamometer road load setting procedure to obtain the setting used to simulate real-world driving resistance (so-called "coastdown").
2. Initial vehicle preconditioning on the chassis dynamometer: constant speed driving at high speed to trigger extensive ICE operation (15 km at 140 km/h).
3. Preconditioning driving as required by WLTP procedure (1 WLTC cycle) at 23 °C.
4. 16-hour waiting period ("soak") at 23 °C with the powertrain switched off and continuous charging of the traction battery (ensuring that SOC = 100%).
5. Emissions test sequence: Four WLTC cycles performed at 23 °C, measured using the legislative method, using sample bags (SOC = 100% start condition).
6. Preconditioning driving (one further WLTC cycle) at 23 °C.
7. 16-hour soak at 23 °C with the powertrain off and without battery charging (i.e., maintaining the SOC = low condition).
8. Emissions test sequence: Four WLTC cycles performed at 23 °C, measured with bags (SOC = low start condition).

The aforementioned laboratory tests were conducted in an advanced climate-controlled exhaust emissions laboratory that meets all the demands of current EU exhaust emissions legislation [12-14] and has equipment for characterizing and quantifying exhaust emissions beyond the level required by EU legislation [14]. Gaseous emissions applicable to the ICE type present in the hybrid powertrain were measured according to the WLTP procedure. Particulate emissions are not regulated in the EU for spark ignition engines without direct injection. However, in this study, the legislative methods were employed to measure particle mass and number for spark ignition engines (those with direct injection). As is required by the Euro 6 standard, solid particles as small as 23 nm in diameter were measured. In addition to the legislative measurements, exhaust emissions of the harmful but unregulated compounds NH_3 and N_2O were measured. Such emissions are not subject to a legislative measurement procedure but were measured using a dedicated automotive analyzer, measuring raw emissions in line with good engineering practice. Specifically, these compounds were measured from raw exhaust gas, with the exhaust flow calculated based on the so-called tracer method (obtained from the calculation of CO_2 dilution). Since NO_x, NH_3, and N_2O are all reactive nitrogen compounds (RNCs), a simple summation operation was performed to determine total RNC emissions (on a gravimetric basis).

2.3. Methodology employed for on-road RDE testing

On-road RDE testing was conducted on both vehicles (Vehicle 1 and Vehicle 2). The legislative EU RDE procedure [5] was followed but with the important exception that results were not normalized for the CO_2 emission level. The PEMS (AVL M.O.V.E.) equipment used for RDE testing, and all its analyzers, components, associated accessories, etc., and computer software satisfied the latest legislative requirements applicable at the time of writing. As required by RDE legislation, the PEMS installation was verified, and all analyzers were checked and calibrated before and after the RDE test. The exhaust gas flow meter diameter was chosen based on the exhaust flow determined from preliminary testing. In line with RDE legislation and standard practice for PEMS testing of light-duty vehicles in the EU, the emissions analyzed during on-road tests were CO, NO_x, PN (diameter > 23 nm), and CO_2. Both vehicles were subjected to RDE tests under low-SOC and high-SOC conditions. The lower SOC starting condition ("SOC = low") was achieved by performing a preconditioning drive over the same route used for testing, of length 95 km and including motorway operation at speeds > 100 km/h, leading to extensive use of the ICE. The first RDE test conducted from this starting condition served as the preconditioning cycle for the second test under the same condition. (The non-motorway distance from the end of the motorway section back to the starting point was < 2 km, for which the ICE was running approximately 50% of the time. It was judged that the impact of this "return to base" section of the route on the SOC was minimal). For the high-SOC condition, the same procedure was followed but with the crucial difference that an external charger of the type recommended by the vehicle manufacturer was used to charge the traction battery to 100% during the soak period. (This charging commenced as soon as the soak commenced. Following confirmation that SOC = 100% had been reached, the charger was disconnected 80-90 minutes before the RDE test started.) In all cases, the entire soak period lasted 22 hours (±30 minutes).

The key steps of the procedure followed for on-road RDE testing of both the test vehicles are outlined below:

1. Preconditioning: driving the entire RDE route with the PEMS and all associated equipment onboard (no emissions measurement).
2. Overnight soak at ambient temperature without traction battery charging (i.e., SOC = low).
3. RDE test 1 (SOC = low).
4. Overnight soak at ambient temperature without traction battery charging (i.e., SOC = low).
5. RDE test 2 (SOC = low).
6. Overnight soak at ambient temperature with traction battery charging (i.e., SOC = 100%).
7. RDE test 1 (SOC = 100%).
8. Overnight soak at ambient temperature with traction battery charging (i.e., SOC = 100%).
9. RDE test 2 (SOC = 100%).

The route used for RDE testing was specially designed to meet all of the demands for RDE test routes in force at the time of writing [5] (see [12, 15] for discussions of the general RDE route design process). The mean altitude of the route was relatively low (< 250 m), and the cumulative altitude gain was well within the RDE limit since most of the route consisted of relatively flat or gently undulating terrain. The altitude difference between the route's start and finish points was < 10 m. The total distance covered by the route (as measured by GPS and validated by the body computer speed signal) was 95 km, with little variation between tests (< 0.5%). In accordance with RDE requirements, the route started with urban driving, followed by rural driving, then motorway driving. The distance shares (distance-based proportions) of the three parts (urban, rural, and motorway) were in the ranges stipulated in RDE legislation. For urban operation, the permitted range is 0.29-0.44, the mean of which is 0.365, which is very close to the test route's actual value of 0.35. For rural and motorway operation, the permitted ranges are 0.23-0.43, giving a mean value of 0.33, which is very close to the test route's actual values of 0.31 and 0.34 (respectively). The dynamic parameters RPA and V_{apos95} from the tests were within the mandated limits (10-20% from the permissible limit values) and relatively constant from test to test (within approximately 10%).

2.4. Data processing

For laboratory testing, the standard technique used for chassis dynamometer testing of light-duty vehicles was employed. This methodology and all its steps and calculations are described in the relevant sections of EU legislation [5]. Briefly, it can be stated that the exhaust produced by the vehicle is collected and diluted with ambient air. Following corrections for the rate of dilution and the contribution of species such as CO_2 from ambient air, the quantity of a species emitted is calculated. This quantity is divided by the distance driven for the period under consideration (e.g., one repetition of the test procedure), giving a distance-specific emissions factor.

For RDE testing, the methodology via which species in the exhaust gas are measured and their concentrations converted to distance-specified emissions factors is described in detail in the EU legislation [5]. Briefly, it can be stated that the approach is as follows:

1. During the test, the exhaust gas flow rate, concentrations of species of interest in the exhaust gas, and instantaneous vehicle speed are measured continuously at high resolution.
2. Following the test, mass flows of species of interest are calculated based on the recorded data (exhaust gas mass flow rate and concentrations of species).

3. Mass flows per unit of time may be analyzed. Furthermore, the sum of the mass flow for a given period (e.g., the entire test or a portion of it) may be divided by the total distance driven during that period, yielding distance-specific exhaust emissions factors.

The aforementioned emission factors can be directly compared (e.g., from vehicle to vehicle, for different SOC levels for the same vehicle, or to emissions limits of manufacturer-declared values).

3. RESULTS

3.1. Laboratory results (WLTP chassis dynamometer procedure) obtained from a single test vehicle

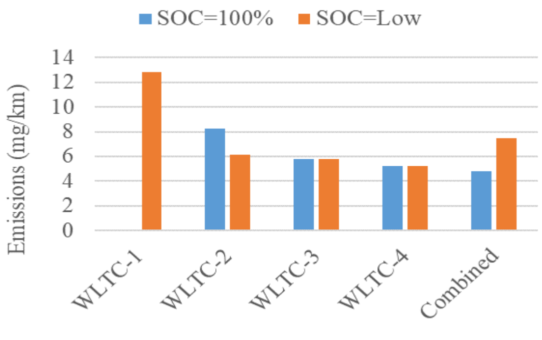
The drive quality parameters stipulated in the WLTP were fulfilled in all tests, and all analyzer checks and verifications were passed. For cycles for which the ICE did not start at any point, any non-zero values resulting from measurement in-accuracies were set to zero. Fig. 1 presents distance-specific emissions results obtained from Vehicle 1, the two test conditions examined (SOC = 100%; SOC = low) for each of the four WLTC cycles performed, as well as the combined result from all four repetitions. The combined result is weighted by distance only (i.e., each cycle has exactly the same weighting).

3.2. On-road results (RDE procedure) obtained from both test vehicles

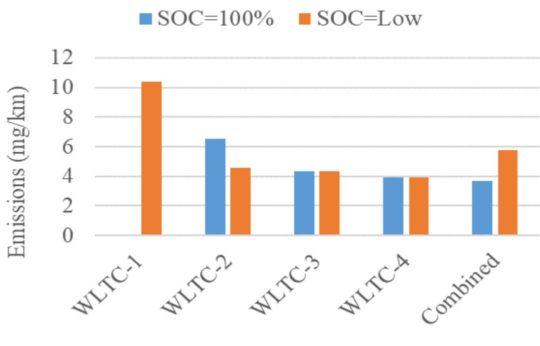
All planned RDE tests were successfully executed, with all validation checks relating to emissions analysis and driving parameters being found to be within legislative RDE limits [6]. Thus, the validation conditions for the RDE tests were considered fulfilled/passed. The results are shown graphically below. Fig. 2 presents distance-specific emissions results obtained from the test vehicles under the two test conditions examined (SOC = 100%; SOC = low), as well as the EV share values. As previously mentioned, each vehicle-SOC combination was tested twice, and the graphs show mean values from the tests (n = 2). Note that the range of compounds quantified by PEMS during RDE testing is narrower than during laboratory testing (as NH_3, N_2O, and PM are not quantified by standard PEMS used for testing light-duty vehicles in the EU). According to Figs. 2i and 2j, the EV share is ~50%, which is lower than the declared electric range of the two PHEVs.

3.3. Comparison of the impact of traction battery SOC on emission behavior (WLTP and RDE)

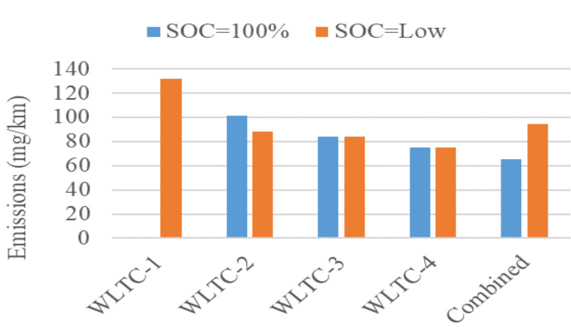
The dimensionless ratio of the results obtained for a given portion of the test procedures may be used to analyze the impact of the traction battery SOC on emissions. Fig. 3 shows the results, which were obtained by dividing the result obtained for the SOC = low condition by the results obtained for the SOC = 100% condition (i.e., a value of 2 signifies that emissions were twice as high at the low-SOC starting condition). No comparison was possible for WLTC-1 since the ICE did not operate during that cycle for the SOC = 100% start condition.



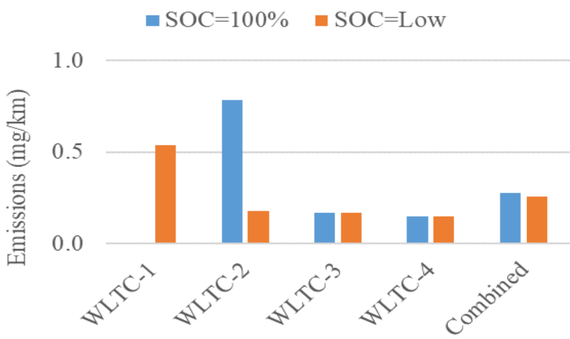
(a) THC emissions obtained under laboratory conditions



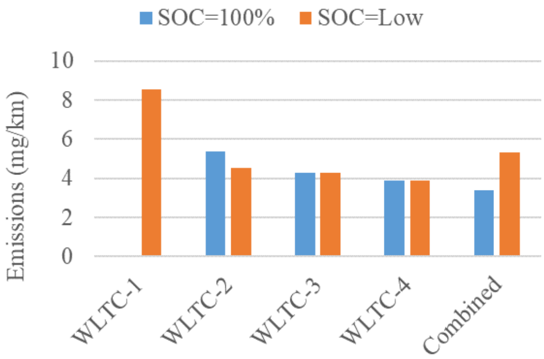
(b) NMHC emissions obtained under laboratory conditions



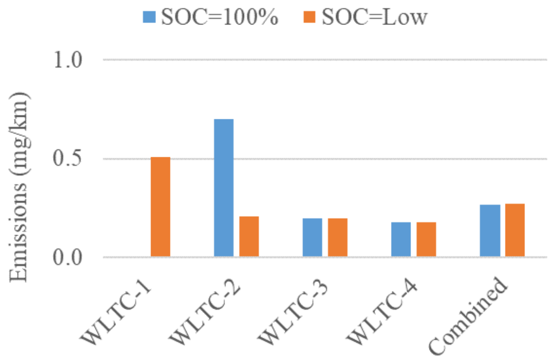
(c) CO emissions obtained under laboratory conditions



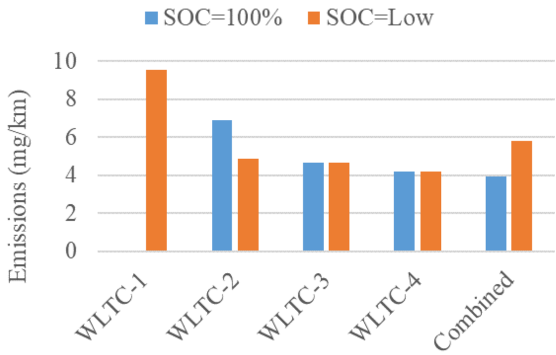
(d) NO_x emissions obtained under laboratory conditions



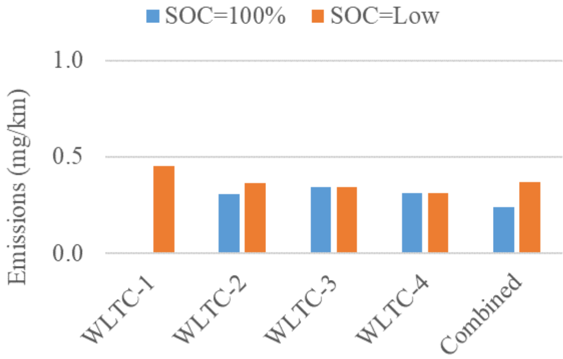
(e) NH_3 emissions obtained under laboratory conditions



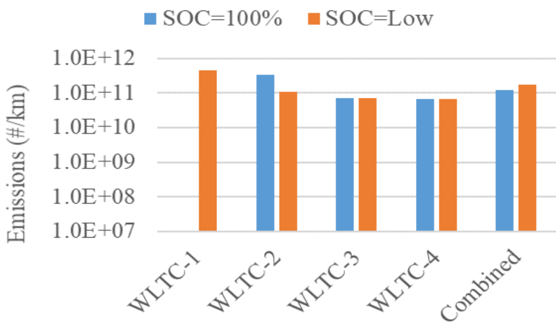
(f) N_2O emissions obtained under laboratory conditions



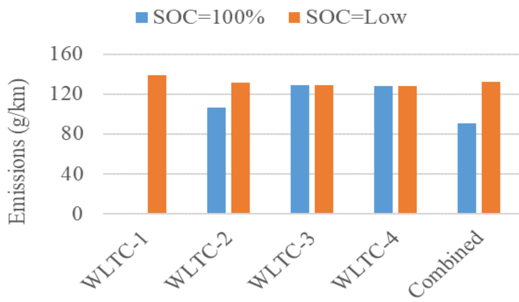
(g) RNC emissions obtained under laboratory conditions



(h) PM emissions obtained under laboratory conditions

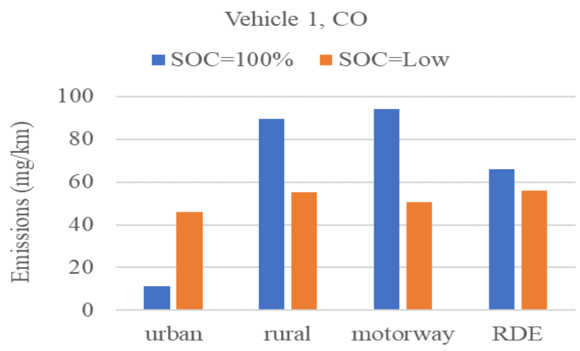


(i) PN emissions obtained under laboratory conditions

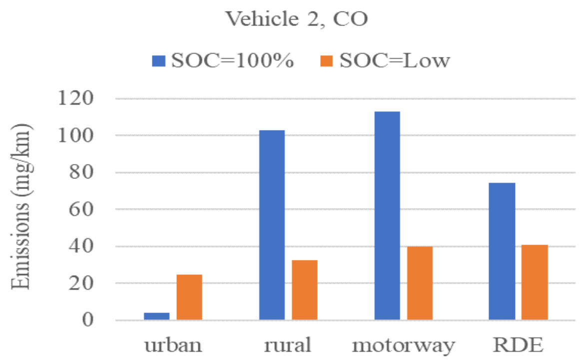


(j) CO_2 emissions obtained under laboratory conditions

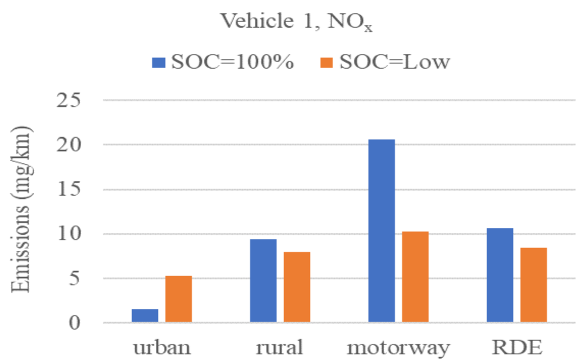
Fig. 1. Distance-specific exhaust emissions from all WLTC cycles performed on the test vehicle tested under laboratory conditions



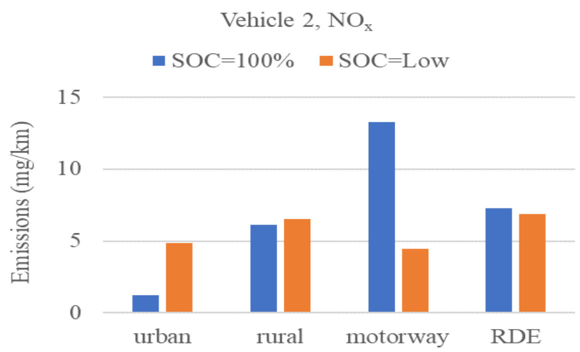
(a) CO emissions obtained under on-road conditions



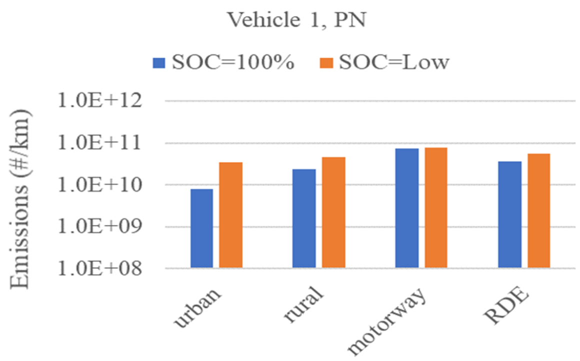
(b) CO emissions obtained under on-road conditions



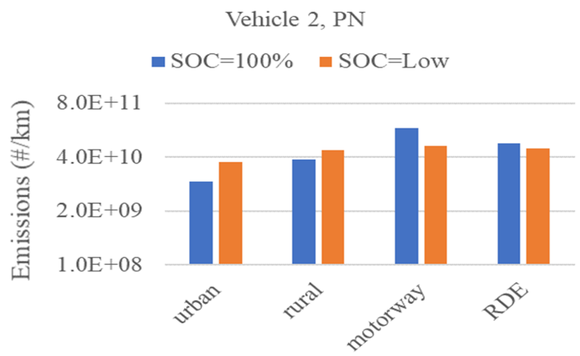
(c) NO_x emissions obtained under on-road conditions



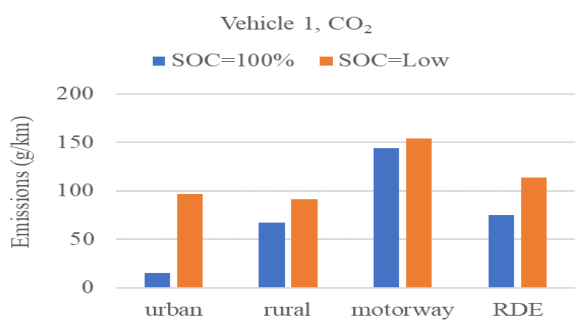
(d) NO_x emissions obtained under on-road conditions



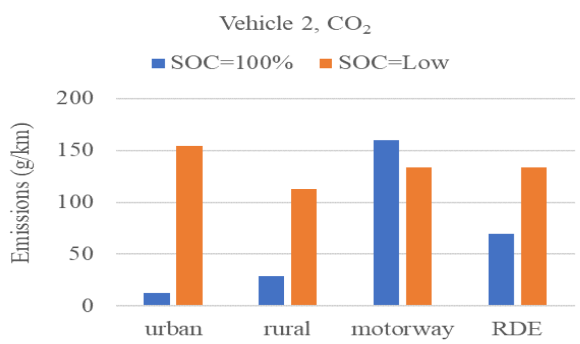
(e) PN emissions obtained under on-road conditions



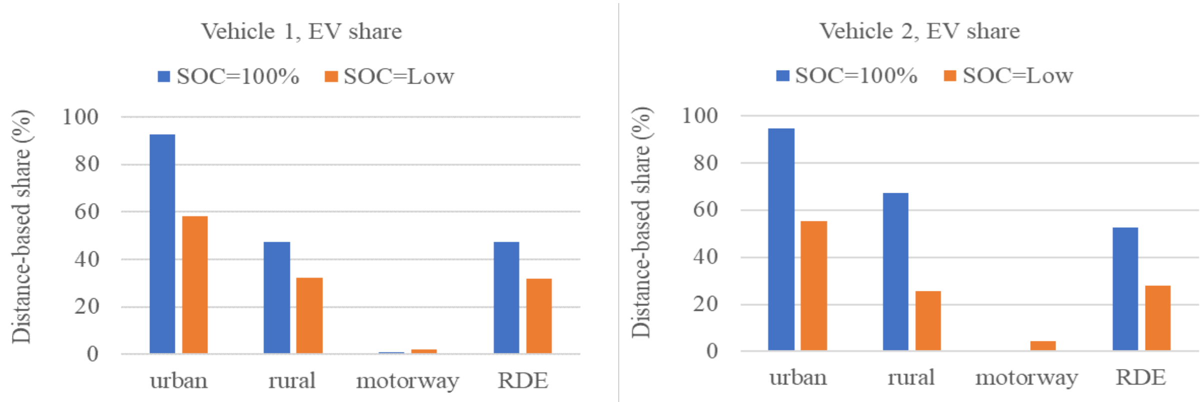
(f) PN emissions obtained under on-road conditions



(g) CO_2 emissions obtained under on-road conditions

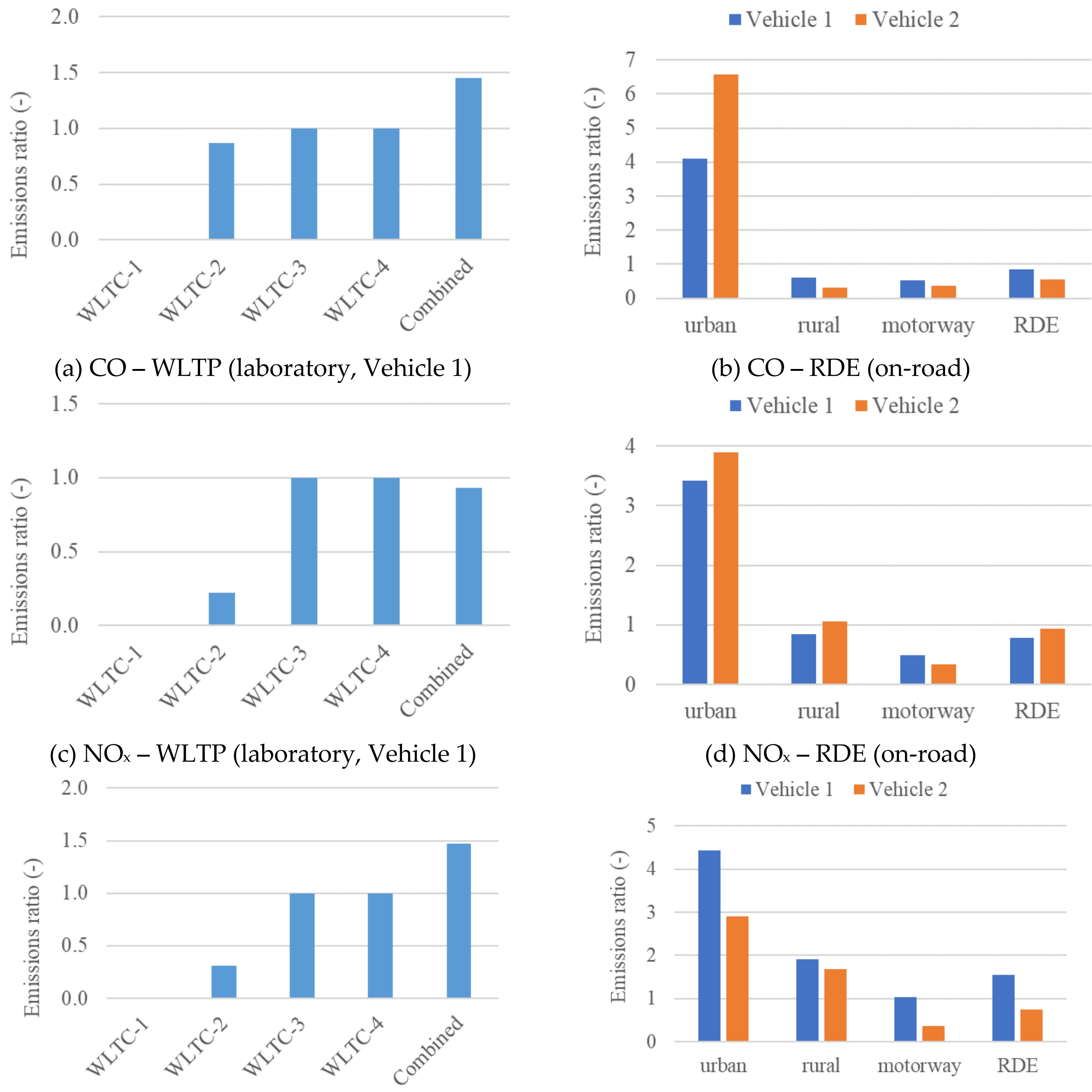


(h) CO_2 emissions obtained under on-road conditions



(i) EV share (j) EV share

Fig. 2. Distance-specific exhaust emissions and EV shares from the RDE tests (rural/urban/motorway/entire test) performed on the two test vehicles



(a) CO – WLTP (laboratory, Vehicle 1) (b) CO – RDE (on-road)

(c) NO_x – WLTP (laboratory, Vehicle 1) (d) NO_x – RDE (on-road)

(e) PN – WLTP (laboratory, Vehicle 1) (f) PN – RDE (on-road)

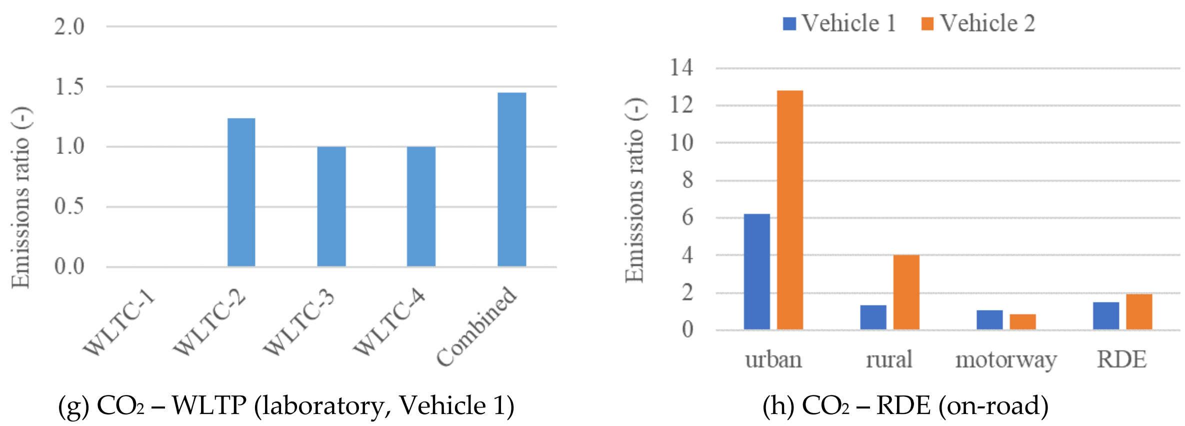


Fig. 3. Comparison of the ratio of exhaust emissions for the two SOC conditions for Vehicle 1 under laboratory conditions (WLTP) and both vehicles under on-road conditions (RDE)

4. DISCUSSION

4.1. Analysis of results from a single vehicle tested under laboratory conditions (WLTP)

Fig. 1 indicates that regulated gaseous exhaust emissions were low; even the highest measured results from individual cycles were well below the applicable EU limits (shown in the Supplementary Material). Such behavior is typical for modern PHEVs [16, 20]. In virtually all cases, the combined result was higher for the low-SOC starting condition. This was expected since the ICE must run much more extensively at low SOC. NO_x and N_2O emissions did not follow this trend but were at a very low level (for NO_x, the highest result measured under laboratory conditions was approximately 1% of the Euro 6 limit). However, for individual tests, the same tendency was not always observed. Sometimes, there were no significant differences in emissions for the two SOC levels tested, or the tendency was inverted. This is due to the great impact of the timing of when the engine starts and the complex warmup behavior of the powertrain. The PN result was relatively high and rather close to the EU limit, but the limit does not apply to vehicles of this type. Thus, the lack of a dedicated filter in the test vehicle explains this result. The CO_2 result for the high-SOC test was substantially lower than at low SOC, although differences are only evident for the first two repetitions of the cycle. The CO_2 emissions at SOC = 100% significantly exceeded the manufacturer-declared value. This mainly results from the methodology adopted here, which is on a strictly "as-measured" basis rather than following the type approval requirements in full.

The results confirm that for Vehicle 1, the starting SOC has an impact not only on CO_2 but also on other exhaust emissions (regulated and unregulated; e.g., NH_3, N_2O). However, even the worst-case results for pollutants are well below current EU limits and low compared to similar vehicles with non-hybrid powertrains. For CO_2, the high-SOC starting condition gave CO_2 benefits (reductions) only during the first two cycles (i.e., a total distance of approximately 47 km). Thereafter (i.e., for WLTC-3 and WLTC-4), the starting SOC had no impact on CO_2/fuel consumption. The aforementioned distance of 47 km is lower than the electric range declared by the manufacturer. This difference may be partially attributable to the test vehicle having suffered some battery degradation.

4.2. Analysis of results from both vehicles tested under on-road conditions (RDE)

Overall CO emissions were low (approximately 10% of the Euro 6 limit) and showed similar trends for both vehicles. Emissions in the urban part were much lower at the higher SOC condition for both vehicles, which is directly attributable to the EV share for the urban part. For the rural and motorway parts, the effect was inverted, and the high-SOC start condition was associated with significantly higher emissions of CO. For the rural part of the high-SOC condition, this may have resulted from incomplete warmup attributable to intermittent operation during the previous (urban phase). For the motorway part, the ICE was always warmed up by the time that part commences (regardless of starting SOC), and thus, thermal effects are unlikely to be the main cause of the observed emissions increase. In addition to the overall EV/ICE propulsion share, the number of ICE start events can exert a noticeable influence on CO emissions since engine restart events can be an important source of CO emissions. Dynamic motorway driving in response to variable traffic conditions is a more likely explanation for the observed tendencies. The number of repeat tests (2) and the high variability of RDE testing should be recalled in this context. Further testing at intermediate traction battery SOC levels would reveal the behavior between starting SOC and the CO emissions from the RDE rural and urban parts.

Unlike CO emissions, NO_x emissions are subject to legal limits during RDE testing, but the emissions levels of both vehicles in both SOC conditions were always < 4% of the applicable limit. Low starting SOC caused higher NO_x emissions for the urban part (although the absolute difference was small). There was very little difference for the rural section, and lower emissions were noted for the motorway part, although it is unclear if this difference is statistically significant. Particulate emissions by number (PN) are regulated for vehicles with SI ICE with direct injection (i.e., Vehicle 2 but not Vehicle 1). Both vehicles met the limit of $6 \cdot 10^{11}$ 1/km by some margin – the highest measured result was precisely one-third of the limit. The PN results show relatively variable trends for the two vehicles. However, for both vehicles, the low-SOC start condition caused higher emissions for both the urban and rural parts. This is directly related to the proportion of ICE operation and the quantity of fuel consumed. Different behavior for the motorway part affects the result for the entire test.

CO_2 emissions showed similar trends for both vehicles but with much greater numerical differences between the two start conditions in the case of Vehicle 2. Similarly, the EV share values reflected this. The EV shares for the motorway part are subject to low repeatability, and the observed differences are unlikely to be significant. Dynamic motorway driving at speeds > 100 km/h includes situations in which the driver abruptly reduces the pressure on the accelerator pedal (or releases it entirely), which causes the ICE to turn off and purely electrical propulsion to be used for a few seconds. At 120 km/h, 100 meters are covered every three seconds, and thus, the frequency and duration of such situations in response to variable traffic conditions can affect the distance-based EV share to a significant degree. It is expected that smoother motorway driving would show very low EV shares for both vehicles in both SOC conditions. As for the test route used, the motorway part commences following 63 km of driving (urban and rural parts), which depletes the SOC from its initial starting value and causes thermal stabilization of the ICE. Note that 63 km is very close to both test vehicles' official purely electric range values (for a starting SOC of 100%).

4.3. Further analysis of results from both vehicles tested under laboratory (WLTP) and on-road conditions (RDE)

As is apparent from Fig. 3, it can be stated that, overall, the observed behavior (the ratios of the results) was different for the two procedures. Results obtained using the WLTP procedure show lower differences between the two SOC conditions, while the RDE results show more sensitivity to the starting SOC, particularly in the case of the RDE urban part. Even though the WLTP and legislative RDE test route employed in this study covered virtually identical total distances (within 2%), the WLTC has the important characteristic that each 23-km cycle begins with urban operation and includes much non-urban driving and a final high-speed section (up to 131 km/h). The RDE route, on the other hand, begins with some 35 km of urban driving, which, by definition, consists of speeds < 60 km/h; speeds > 60 km/h are encountered only after this (rural and then motorway parts). Thus, the RDE of the urban part gives extensive opportunities for EV propulsion, even in the low-SOC condition. At SOC = 100%, the first WLTC is always completed without starting the ICE, but the urban part of the RDE route cannot be completed without starting the ICE (EV shares are always < 95% for the two vehicles tested). Combined emissions (from all four WLTCs and the entire RDE route, respectively) show reasonably good agreement in the cases of NO_x, PN, and CO_2 but not for CO, for which the aforementioned effect causes the mean ratio of both test vehicles to take a value of roughly 5:1.

The variability inherent in RDE testing represents a significant source of uncertainty, and it is recommendable to perform further repeat tests to obtain a clear picture of emissions behavior. As mentioned previously, it would also be worth performing further tests (both WLTP and RDE) under intermediate SOC starting conditions in order to characterize the full range of behaviors from all possible SOC levels occurring during the real-world usage of PHEVs.

Recent studies of note [10, 17] have chiefly focused on the increased CO_2 emissions that result from the starting SOC of PHEVs of < 100%. Another study [18] noted very low regulated emissions of PHEVs regardless of the starting SOC. Other recent studies [19, 20] have noted variability in PHEVs' pollutant exhaust emissions but have also underlined the generally low magnitude of these emissions. A further factor noted is that the section of the test where the ICE starts for the first time or where the first few start events occur is normally the section that dominates the pollutant emissions profile. Such behavior has been confirmed in this study. Nevertheless, for the test vehicles examined, under the same conditions, regulated emissions were often comparable to and sometimes slightly lower than when the SOC was 100%. For the test vehicles examined in this study, charge-sustaining operation was characterized by very low emissions of regulated pollutants and even certain unregulated pollutants (e.g., NH_3 and PN). In this respect, charge-sustaining operation makes the vehicle function similarly to a non-plug-in hybrid in terms of pollutant emissions. Here, it should be recalled that the weight of the traction battery adds to the inertia and resistive forces of the vehicle, thereby increasing energy demand. The levels of regulated emissions reported in this study were in many cases at least an order of magnitude below the applicable limits. Such behavior is broadly comparable to that of similar vehicles with hybrid powertrains of non-plug-in type reported elsewhere (see [21] and references therein). In this study, under closely controlled laboratory conditions, emissions of RNCs and particulates for the combined test procedure covering 93 km showed barely any impact of the starting battery condition. It should be noted that shorter test routes might reveal larger differences and a stronger correlation (refer to Fig. 1).

It was observed that the link between emissions of regulated and unregulated pollutants and the quantity of fuel consumed is generally very weak. However, the effect is scale-dependent: for the first WLTC cycle, the high-SOC condition leads to no exhaust emissions whatsoever. Notwithstanding this point, emissions measured in the laboratory were significantly below legal limits during all cycles, including in the worst-case scenario from the point of view of pollutant emissions (the cycles where the ICE started for the first time). Correspondingly, for the RDE urban part, elevated emissions were observed, although they remained well below legal limits.

Certain limitations associated with the real-world representativeness of the RDE results, such as the long distance covered before high speeds, were encountered and can be overcome by deviating somewhat from the legislative prescriptions. Indeed, the range of real-world trip lengths and daily mileages conducted by ordinary drivers provides insight into the real-world performance of PHEVs in terms of EV share and fuel consumption. However, test routes shorter than the manufacturer-declared electric range are likely to have a very high EV share if the starting SOC is high. Thus, such routes would likely show very limited sensitivity to the starting SOC. As such, there may be important differences between laboratory conditions and real-world usage scenarios, including the speed trace (aggressiveness of the driving style), which should be further investigated.

5. CONCLUSIONS

This study employed somewhat modified versions of the two procedures currently used to demonstrate compliance with exhaust emissions requirements in the EU. Two PHEVs were tested, one of which was subjected to laboratory (WLTP) testing. Both vehicles were subjected to on-road (RDE) testing. Here, it is important to recall that the regulated emissions measured during RDE testing were not normalized for the CO_2 measured using the equation given in the legislation. As such, the results more accurately reflect the actual flow of pollutants into the environment rather than being normalized for primarily legal reasons. It can be assumed that the test conditions examined represent so-called best-case and worst-case conditions (i.e., fully charged and with the battery discharged to its lowest level). The emissions results confirmed significantly increased CO_2 and PN emissions for the low-SOC start condition (for Vehicle 1, always; for Vehicle 2, only for the urban and rural parts), resulting from the increased fuel flow resulting from much greater reliance on the ICE for propulsion. Other emissions, however, showed variable responses and were not always higher for the low-SOC condition, a fact relating primarily to cold start effects and test-to-test variability during RDE testing. These observations suggest that if PHEVs are not used as intended (i.e., if they are not charged to 100% regularly), the main emissions penalty is determined in terms of CO_2 emissions (and fuel consumption), while the impact on non-CO_2 pollutant exhaust emissions is generally relatively small (although not always for PN). Particularly for extended driving under urban traffic conditions, CO_2 was 6-12 times higher than the manufacturer-declared value. Discrepancies of this magnitude must be borne in mind in analyses, policy decisions, and projections of the real-world impact of the expanding PHEV market share. However, tendencies observed in this study may not apply to all PHEVs and all driving behaviors. Using other procedures simulating other driving conditions, especially more aggressive driving cycles, might reveal more noticeable responses of pollutant emissions to the starting SOC condition and perhaps an even higher response in CO_2 emissions. While the results of RDE testing are rarely used for direct analysis of CO_2 emissions, this study has shown such an approach to be a useful tool. In terms of further work, it would be beneficial to identify the portions of RDE tests where emissions and fuel/energy consumption were substantially higher than under laboratory conditions and attempt to explain the observed differences. Various models available in the literature might be employed for determining fuel/energy consumption and analyzing the share of electrical propulsion in such a context.

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