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2017-01-2391

A Comparison of Tailpipe Gaseous Emissions for RDE and WLTC using SI Passenger Cars

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Abstract

The drive characteristics and gaseous emissions of legislated Real Driving Emissions (RDE) test data from 8 different spark ignition vehicles were compared to data from corresponding Worldwide harmonized Light vehicles Test Cycle (WLTC) tests. The effect of the official RDE exclusion of cold start and idling on the RDE test, and the effect of the use of the moving averaging window (MAW) analysis technique, were simultaneously investigated. Specific attention was paid to differences in drive characteristics of the three different driving modes and the effect this had on the distance-based CO_2, CO and NO_x emission factors for each. The average velocity of the RDE tests was marginally greater than the WLTC tests, while the average acceleration was smaller. The CO_2 emission appeared on average 4% lower under the RDE tests compared to the WLTC tests, while the CO was 60% lower. The NO_x values were 34% lower under the RDE testing, and appeared to be linked to the average acceleration. No link was seen for the maximum acceleration or deceleration, indicating that this is not a good indicator for test cycle emissions. The exclusion of cold start and idling decreased all RDE emissions. RPA (Relative Positive Acceleration) had little correlation with CO_2, CO and NO_x distance-based emissions, and was shown to be uncorrelated with any mass-rate emissions. The range of RPA values seen was much greater for RDE tests than WLTC tests, with individual RDE tests having variable values for each drive mode. The application of the MAW technique had minimal effect on the CO_2 distance-based emission, but it appeared to decrease CO and NO_x emissions by 12% and 21% on average respectively. The MAW also decreased the variation in emissions across different modes.

Introduction

There are three main legislated steps to the method to control regulated pollutant emissions [1]. A type approval test ensures that any new vehicle designs adhere to the aforementioned emission standards. Conformity of production then requires that all cars be manufactured to those same standards. Finally, in-service conformity and durability requirements ensure that the vehicle maintains similar emissions factors after being sold [2]. Since the 1990's a set of European Emission Standards for light duty and heavy duty gasoline, diesel, LPG and CNG vehicles have been launched for European Union (EU) type approval testing. From Euro 3 up until Euro 6, Europe employed the New European Driving Cycle (NEDC) for the certification of cars [3]. However the NEDC test has some downfalls, which have been widely discussed in the literature [4–6]. The main arguments are that the NEDC test procedures are outdated for current vehicle technologies and unrepresentative of real-world driving, as well as too lax, allowing car manufacturers to 'play the system' to their advantage and give emissions values that can never be achieved in the real world [7,8].

In response to these concerns, the World Forum for the Harmonization of Vehicle Regulations (WP.29) of the United Nations Economic Commission for Europe (UNECE) launched a program to develop a new Worldwide harmonized Light vehicles Test Cycle (WLTC) and procedure (WLTP) [8]. They aimed to develop a cycle that represented average worldwide driving characteristics, and to have it tested using a world-harmonized type approval testing procedure. The WLTC is not a single cycle, but a set of different cycles to be used on different vehicles with different characteristics. WLTC cycle class 3 is used by the majority of European cars [8].

The WLTC has been formulated for the currently enforced Euro 6 legislation, and differs from the NEDC in various ways, including more aggressive driving styles and a greater range of engine operating points [9]. Although the WLTC test more accurately replicates the type of driving behaviors seen in real world driving than the NEDC, it still carries the same disadvantages of any standard laboratory test cycle. One disadvantage is that these laboratory test cycles cannot adequately cover the wide range of ambient and driving conditions seen in real world vehicle use [1]. This means that while vehicles may comply with emission limits in laboratory tests, they could have substantially higher emissions on the road under conditions outside those tested [10]. These standard cycles are also very predictable, allowing car manufacturers the possibility of 'cheating' the tests, most notably in the VW scandal of 2016 [11].

It has therefore been deemed necessary for a complimentary test procedure to be formulated alongside the WLTC to address the above issues, called a real driving emissions (RDE) test. This will limit the trend of overly narrow optimization of emissions control technologies that is currently such a problem for climate and air quality, as well as encouraging the adoption of novel emission abatement technologies [1].

The individual results from an RDE test are not reproducible, and this lack of repeatability creates uncertainties that have to be accounted for when designing emissions limits [12]. For example, driver behavior is problematic. While driver behavior is pre-determined with random cycle testing, this is not the case for Portable Emissions Measurement System (PEMS) on-road testing. Similarly, weather conditions, particularly temperature, are not defined. It was therefore necessary to define appropriate boundary conditions to limit the ability of the manufacturer to manipulate results [1], which will be discussed in the next section.

Many papers have previously explored the regulated emissions from real world driving compared to type approval testing. However, most have been limited to comparisons between the old NEDC test and non-legislated on-road driving emissions. Merkisz et al. [13] compared road tests for a 2006 year gasoline vehicle with NEDC tests. Each road test consisted of the same route, 76 km long, with emissions of carbon monoxide (CO), nitrous oxide (NO_x) and carbon dioxide (CO_2) measured in real-time using a Semtech DS analyzer. They found that the road tests gave lower values of NO_x and CO compared to the NEDC test, while they gave higher values of CO_2. This same trend was seen under pure urban driving conditions while for pure extra-urban driving the CO values under real driving were increased past the NEDC values, and NO_x increased but remained marginally below the NEDC values. The trend for increasing on-road CO_2 emission was also witnessed by Weiss et al. [14], which studied the on-road emissions of 12 light duty gasoline and diesel vehicles of Euro 3-5 emission limits, and compared them to the NEDC results. This paper found that NO_x emissions were also higher for on-road testing than NEDC tests, in contrast to Merkisz et al. [13]. The CO_2 exceeded the 130 g/km emission limits, while NO_x remained below its Euro limit. For CO this paper saw varying test results, but with a trend toward increasing emission under real-world conditions than the NEDC, so again contrasting with Merkisz et al. [13]. May et al. [15] used a Semtech-D PEMS analyzer to measure the emissions of a gasoline vehicle over pre-selected routes, and these were then compared to NEDC and WLTC tests performed for that same vehicle. Their results showed increasing emissions of CO_2, CO and NO_x compared to both NEDC and WLTP tests, with the WLTP results being higher than the NEDC results for all tests. Both CO_2 and CO emissions were still within their legislated limits, while NO_x was on average 23% above the limit. These results are generally in agreement with those of Weiss et al. [14]. Merkisz et al. [16] conducted an extensive study, testing 150 different Euro4 and Euro 5 cars on RDE tests and comparing results to corresponding NEDC and WLTC tests. A Semtech DS analyzer was the PEMS used for this study, and the protocol being considered for EU RDE legislation at the time was employed. The protocol used does however vary from that in legislation today, having different speed delineations between modes and the inclusion of cold start and idling. This paper found that CO and NO_x emission on RDE tests were both around 80% of their legislated limits, while WLTC gave values equal to just 31% and 60% of those respective limits. The NEDC test gave far lower NO_x emissions than the WLTC in this study, while the CO gave approximately equal values. No work into CO_2 was conducted.

Merkisz et al. [13] performed an analysis into the engine operating parameters during their road tests, and related the dynamic behavior to the emission of pollutants. They found that the highest emissions of CO per unit time were for accelerations from -0.6m/s^2 to 1.4 m/s^2 for vehicle speeds from 2 to 24m/s. They found the CO emission clearly increases for higher levels of acceleration. For NO_x, speeds of 4 - 12 m/s with -0.6 - 1.8 m/s^2 acceleration, and 10 - 26 m/s with -0.2 - 1 m/s^2 acceleration produced the highest emission peaks. On comparison of the distance-specific emissions during individual test portions to equivalent NEDC portions, this study again concluded that acceleration and cruise velocity for these sections are the most influential factors on toxic CO and NO_x emissions. Few other papers have gone into detail regarding the engine operating conditions during testing and their correlation with emissions. Similarly, few other studies have investigated how the drive properties affect the production of gaseous pollutants.

In order to elucidate the link between the emission of CO_2, CO and NO_x over the RDE compared to the WLTP cycles, further study is clearly required. In particular, work relating the dynamic behavior required of the newest version of the RDE test procedure to the WLTP procedure would be useful to see how the changes in driving styles affect the pollutant emissions. It is the aim of this paper to compare the driving styles used in the latest RDE testing to those legislated in the WLTC, and investigate how this appears to affect the relative pollutant emissions.

EU RDE Legislation

An RDE element using PEMS, as discussed above, is now being brought into EU legislation [17]. This consists of portions of different driving styles, performed where possible in the order presented below:

1. 34% urban operation, characterized by vehicle speeds up to 60 km/h
2. 33% rural operation, characterized by vehicle speeds between 60 and 90 km/h
3. 33% motorway operation, characterized by vehicle speeds over 90 km/h

There are also environmental conditions that must be adhered to in order for the test to be valid:

1. The test must be performed under ambient conditions of 0°C ≤ T ≤ 30°C or ‘extended conditions’ of -7°C ≤ T ≤ 0°C or 30°C ≤ T ≤ 35°C.
2. The test must be performed at a moderate altitude of less than or equal to 700 meters above sea level, or an ‘extended altitude’ of 700 m ≤ altitude ≤ 1300 m.

The emissions values from a RDE test can be calculated using the Moving Averaging Window (MAW) method outlined in the current EU legislation [18]. The second-by-second emission rates in g/s are averaged over moving averaging windows, the duration of which is determined by a reference quantity of CO_2. The principle is that the mass emissions are not calculated for the complete data set, but for sub-sets of the complete data set, the length of these sub-sets being determined so as to match the CO_2 emissions over the WLTC. The window then moves forward in the same increments as the measurement interval once this reference quantity has been reached. The value of average CO_2 emissions for each window are recorded and compared to the vehicle CO_2 emissions versus average speed measured at type approval on the WLTC test, called the “vehicle CO_2 characteristic curve”. The windows are also categorized into the three speed classes (urban, rural and motorway) defined above. The test is ‘complete’ when it is comprised of at least 15% urban, rural and motorway windows, out of the total number of windows. The test is ‘normal’ when at least 50% of the windows are within the primary tolerance (normally ±25%) of the characteristic curve values. The windows are weighted according to their similarity to the reference CO_2 curve, and then total emissions from the test, per km or per kWh, along with the average concentrations, are calculated from the normal windows.

The following data points are excluded from the calculation of the CO_2 mass:

1. Cold start (when engine coolant temperature has not yet reached 70 °C)
2. Durations with vehicle speeds under 1 km/h (idle)

3. Durations where the vehicle engine is switched off

Methodology

Testing Vehicles and Ambient Conditions

A range of gasoline powered spark ignition passenger vehicles were selected, and used to perform WLTC and RDE testing cycles in compliance with the latest EU emissions legislation. The vehicles were all light duty vehicles of class M1, and were sufficiently varied so as to contain a mixture of port fuel injection (PFI) and direct injection (DI) fuel delivery systems, and a mixture of naturally aspirated (NA) and turbocharged (T) engines. All vehicles are Euro 5 emission compliance, with the exception of a hybrid electric vehicle, of Euro 2 emission compliance. All vehicles used the same three way catalyst (TWC) emission reduction technique. Table A1 in the appendix summarizes some key characteristics of these vehicles. The ambient conditions under which the RDE and WLTC tests were performed and the drive properties of the tests are given in table A2 in the appendix.

RDE Equipment and Testing Procedure

The RDE tests were performed using PEMS devices. Six of the tests were performed using the Horiba OBS-ONE-GS PEMS equipment, while two of the tests were performed using the AVL M.O.V.E Gas PEMS iS equipment. Both systems measure the gaseous emissions of CO, CO_2, NO and NO_2, the latter two of which can be used to calculate NO_x. Exhaust flow rates were also measured by these two systems, to allow calculation of tailpipe mass emissions. These PEMS devices allow gases regulated in current legislation, in combination with a range of vehicle operating parameters, to be measured in real time at a 10Hz frequency. The instruments used are given in table 1.

Table 1. Instruments used by the Horiba and AVL PEMS devices.

Property	Horiba OBS-ONE-GS	AVL M.O.V.E Gas
NO	Chemiluminescence (CLD)	Non-dispersive Ultraviolet (NDUV)
NO_2		
CO	Non-dispersive Infrared (NDIR)	Non-dispersive Infrared (NDIR)
CO_2		
O2	-	Electrochemical
Exhaust flow rate	Pitot flow meter	Pitot flow meter

For each test, the particular equipment was placed into the rear of the vehicle, with the tailpipe attachment and heated sample probe connected to the tailpipe as per the corresponding manufacturer manual (figure 1). A global positioning system (GPS) antenna and an ambient temperature and humidity sensor were placed on the roof of the vehicle, while an on-board diagnostics (OBD) interface unit was connected to the OBD port. These sensors were all connected to the main gas sensor unit via universal serial bus (USB) cables. The equipment was connected to batteries placed inside the car, so that power was provided by a source external to the engine. The equipment was then warmed up and calibrated according to the manufacturer's instructions before testing commenced.

Each test was performed according to the RDE test procedure guidelines set out in Commission Regulation (EU) 2016/427 [18]. The tests were performed in two different Chinese cities; Beijing and Xiamen. All tests began with an urban driving mode section, followed by a rural driving mode section and then a motorway driving mode section. These were apportioned to give percentage ratios of approximately 34%, 33% and 33%, respectively.

Each vehicle test was commenced from a cold start, so in accordance with the legislated RDE test procedure the following exclusions were made to a set of the data: the warm-up period and any idling periods where the speed was less than 1km/h were cut. In this paper, the term "RDE exclusions" will refer to the exclusion of cold start and idling periods of velocity less than 1km/h. The data with such exclusions is called "MAW unapplied, with RDE exclusions". A set of such data then had the MAW method applied to it, and is called the "MAW applied, with RDE exclusions". For comparison, characteristics of the tests are also presented both without the exclusions required by the RDE legislation and without application of the MAW method. These are termed "raw RDE".

Figure 1. Examples of a) the Horiba OBS ONE and b) the AVL M.O.V.E PEMS devices in vehicles prior to RDE testing.

WLTC Equipment and Testing Procedure

The WLTC tests were conducted according to the standard test procedure for WLTC testing (WLTP) as outlined in EU legislation [19]. Cold start tests were performed for each car following the legislated soak period. The WLTC cycle is split into four speed phase sections: low, medium, high and extra high. However, the results in this paper are presented as three different speed phases, with the medium and high speed phases combined into one phase. This increases the parity with the RDE results. The WLTC data presented in this paper for each vehicle has been attained from the WLTC report for that particular vehicle.

Data Analysis

The raw data for each RDE test consisted of a raw, pre-aligned data file giving a range of operational parameters and pollutant emission concentrations at 10 Hz frequency. These were averaged to give a 1 Hz frequency. Using the exhaust flow rate, the pollutant emission concentrations were converted into mass emission rates. The velocity distributions were then studied to discern which sections belonged to the urban, rural and motorway driving modes. Figure 2 gives an example velocity-time plot in green, with the mode divisions indicated by red lines.

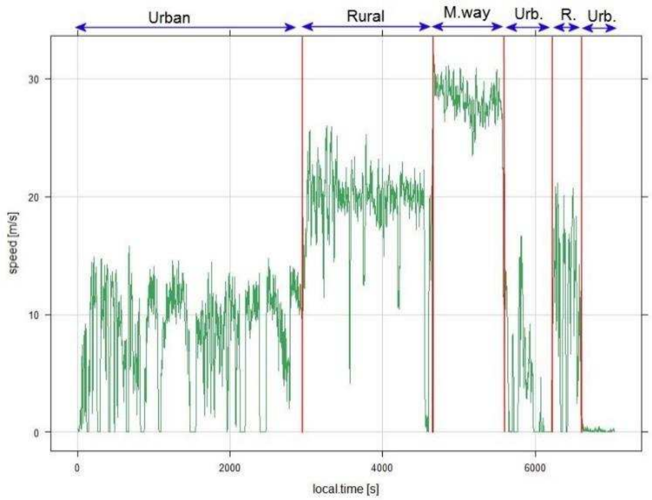

Figure 2. Example of the visual inspection and selection process to determine drive mode divisions. The modes are separated by red lines, being classified into urban, rural, motorway, urban, rural and urban sections chronologically.

In accordance with the official EU RDE legislation, the cold start and idle data points were removed from a copy of the data to comprise the "MAW unapplied with RDE exclusions" dataset. As instructed in the legislation, cold start was delineated by the period of time before the engine coolant temperature first reached 70 °C, and idling was counted as any time with velocity less than 1 km/h. The originals, with cold start and zero velocity included, comprise the 'raw RDE' dataset. Quality Assurance on the data was performed and any outliers were removed. The same processing was then performed on both datasets for each vehicle, as described below.

Average distance-based mass emission factors for the different modes of each dataset were calculated by summing the total mass emissions for each section and dividing by the distance covered during that section. Similarly, the average drive properties for each test were calculated by averaging the particular property for each drive mode, and then the total value for the whole cycle was an average of the values for the three individual drive modes, taken proportional to the distance covered in each mode.

Some of the properties were not in the raw data file, but were instead calculated from other information. The stop time was calculated as a sum of all the times when the velocity within the Raw RDE dataset was less than 1km/h, while the number of stops was calculated as the number of discontinuities in the official RDE data. Both of these values were then divided by the distance covered to give distance-based values.

The relative positive acceleration (RPA) was calculated using the same method as outlined in May et al. [15], taken from methods used to characterize vehicle trips in the development of the WLTC. The calculation is described by equation 1, where a_i is the acceleration at time step i if a_i is greater than 0 m/s^2, v_i is the vehicle speed at time step i (m/s), Δt is the time increment and s is the total trip distance (m).

$$RPA = \frac{\sum_{i=1}^{n} a_i v_i \Delta t}{s} \quad (1)$$

An analysis was conducted into the effect of the use of the moving averaging window (MAW) method on the emission of pollutant gases. In this case the MAW technique was applied to the "MAW unapplied with RDE exclusions" dataset manually (without the use of the automated PEMS RDE software) to attain mass emissions for each drive mode individually. The resulting total values were compared to the RDE report output total values by PEMS to confirm the manual technique was accurately applied for each RDE test. The emissions factors of the "MAW applied with RDE exclusions" datasets were then compared back to those of the "MAW unapplied with RDE exclusions" datasets. The divisions between urban, rural and motorway drive modes are different for the MAW applied data than the "raw RDE" and "MAW unapplied with RDE exclusions" results, due to the different methods used to select these drive modes.

The WLTP data consisted of the output report, which gave average mass emission values (g) and rates in g/s and g/km for each drive section. For the characterisation of the drive cycle, the legislated velocity distribution with time was used, as given in the Annex to EC 715/2007 [20]. The drive characteristics were calculated as described above, with the exception of the stop number, for which the value given in Tutuianu et al. [7] was used. There are four parts of the WLTC cycle, so for the purposes of comparison with the RDE cycle, the second and third parts were combined into one for data analysis. These three sections were then assigned the same names as the RDE cycle (urban, rural and motorway) for the data presentation.

Results and Discussion

Test Cycle Driving Characteristics Comparisons

As discussed in the methodology, the RDE testing took place in 2 different locations, and at different times. As a result, each test varies from the others to various extents. Figure 3 gives an overview of the speed characteristics of the different RDE tests 1-8, and of the WLTC test, for comparison. One can see that the velocity patterns across different RDE tests vary, but all are most dissimilar to the WLTC test, which is far shorter.

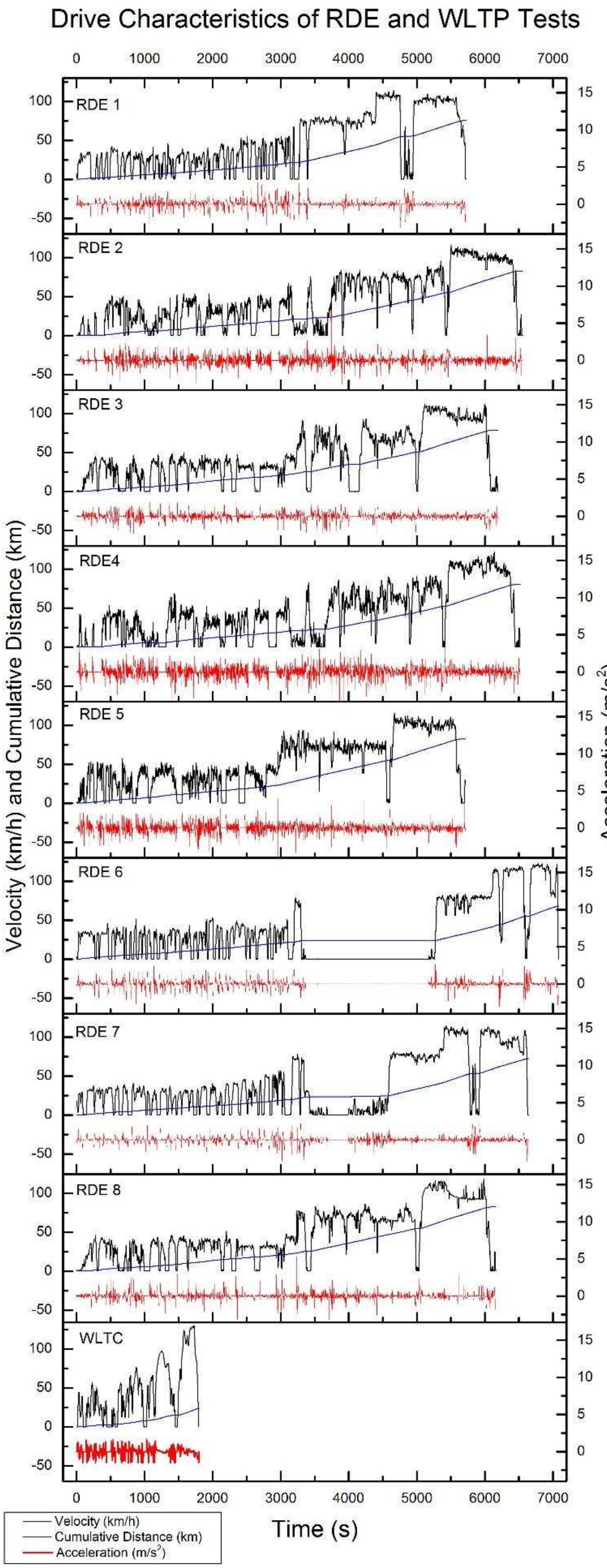

Figure 3. Velocity, acceleration and cumulative distance distributions of all RDE tests and the WLTP test performed.

As discussed in the methodology, a comparison of various drive characteristics was performed, looking at the raw RDE data, the "MAW unapplied with RDE exclusions" data, and the WLTC properties. Average values were taken in each test mode (urban, rural or motorway), and then the distance-based average of these individual sections gave the average value. For some examples, the sum of individual modes gave a total value instead.

Figure 4 displays the average velocities across different modes. One can see that the average velocity is slightly higher under the "MAW unapplied with RDE exclusions" than the WLTC for all drive modes, being 62 km/h compared to 60km/h. The average velocity is increased from 59km/h by the application of the RDE exclusions, indicating that these exclusions are the main cause of the difference.

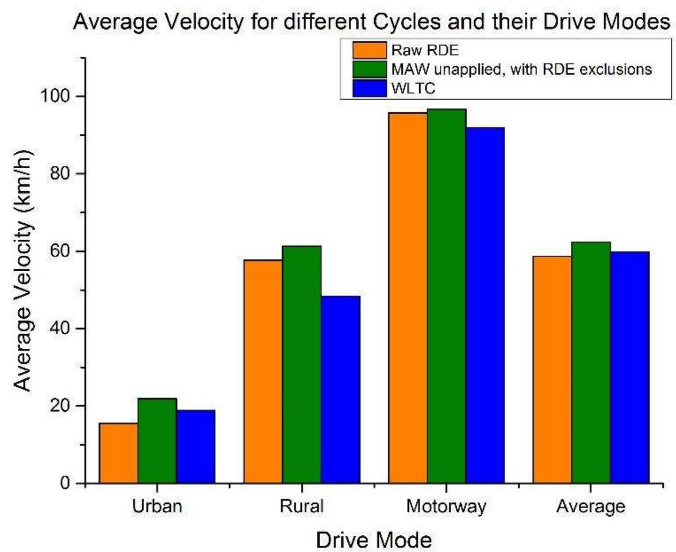

Figure 4. Average velocities for the raw RDE, MAW unapplied with RDE exclusions, and WLTC tests, divided into their relative drive modes.

Figure 5 shows the maximum velocities across the different modes. It indicates that the maximum velocities are marginally lower for the RDE cycles than the WLTC cycle in this case, except for the urban section. The reason for this may lie in the visual selection of the drive modes, described in the methodology.

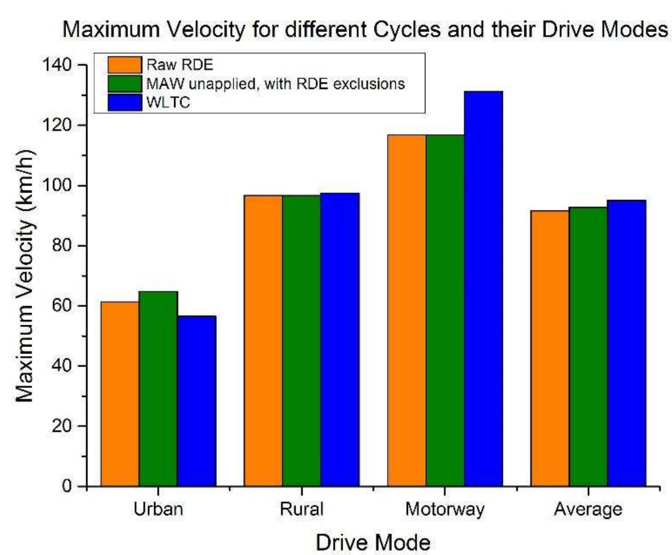

Figure 5. Maximum velocities for the raw RDE, MAW unapplied with RDE exclusions, and WLTC tests, divided into their relative drive modes. The total value is an average of all modes.

Figure 6 displays the average acceleration over different cycles, and results indicate that the RDE cycles have lower acceleration in general, except for the rural drive mode. Average "MAW unapplied with RDE exclusions" values were marginally lower than the WLTC. Figure 7 shows the average magnitude of deceleration, with the WLTC having the greater average deceleration for all modes. One can also conclude that the exclusions employed by the RDE legislation increase the average values of acceleration and deceleration, taking the average acceleration from 0.33 m/s^2 – 0.36 m/s^2.

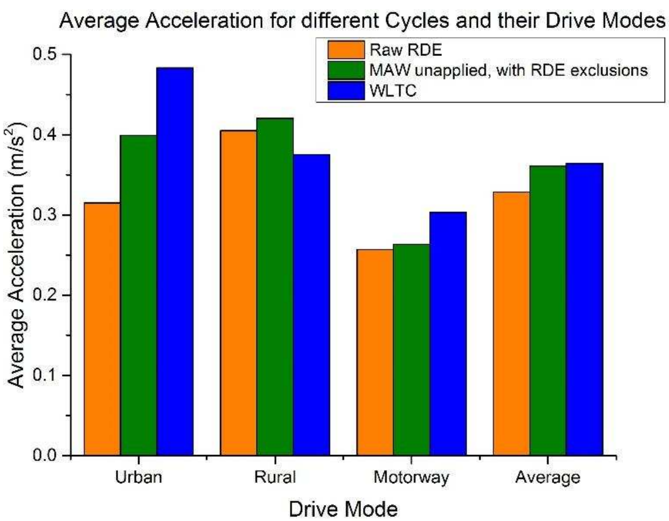

Figure 6. Average accelerations for the raw RDE, MAW unapplied with RDE exclusions, and WLTC tests, divided into their relative drive modes.

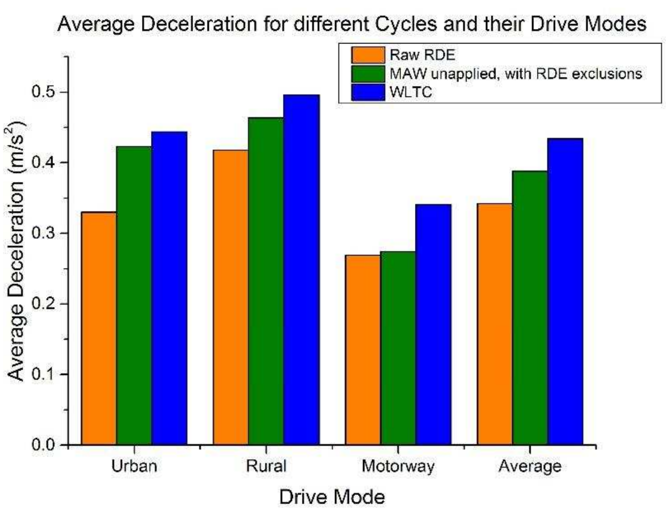

Figure 7. Average decelerations for the raw RDE, MAW unapplied with RDE exclusions, and WLTC tests, divided into their relative drive modes.

Figures 8 and 9 show that concerning the maximum rate of acceleration and deceleration, the RDE tests have a 2.5 times greater magnitude than the WLTC. These findings are in contrast to the average accelerations and decelerations seen, indicating that the maximum values may not be a good indicator of the respective general behaviors.

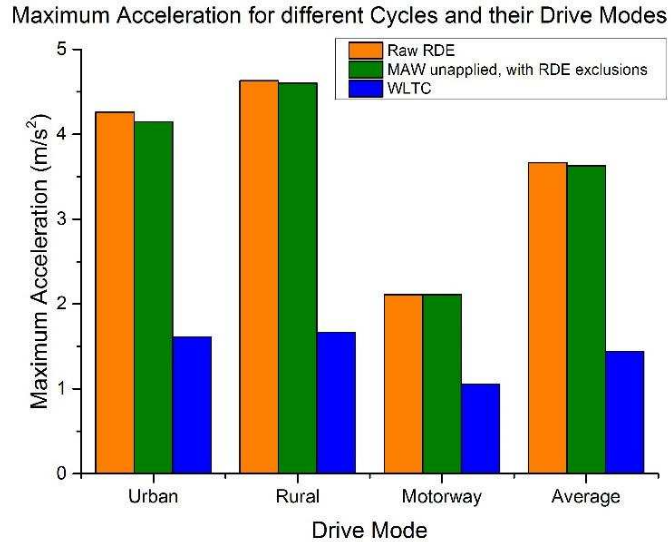

Figure 8. Maximum accelerations for the raw RDE, MAW unapplied with RDE exclusions, and WLTC, divided into their relative drive modes. The total value is an average of all modes.

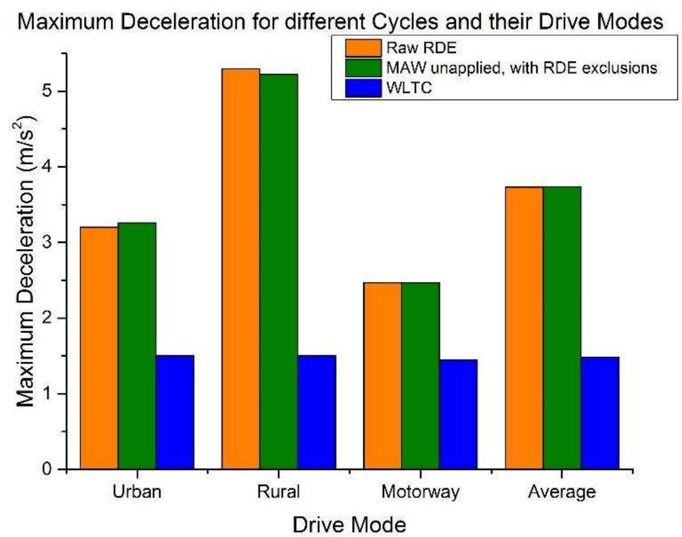

Figure 9. Maximum decelerations for the raw RDE, MAW unapplied with RDE exclusions, and WLTC tests, divided into their relative drive modes. The total value is an average of all modes.

Whereas the average acceleration was smaller for the RDE cycles than the WLTC cycle, the RPA shows more similar values. The RPA in the rural section of the RDE is greater than the WLTC, while the urban and motorway sections show the opposite trend to a small degree, giving an average value only marginally greater for the RDE than WLTC (0.15 m/s^2 compared to 0.14 m/s^2). This relationship is displayed in figure 10. The average RPA values are clearly larger than the average RPA values calculated for the on-road tests by May et al. [15], who reported 0.117 m/s^2.

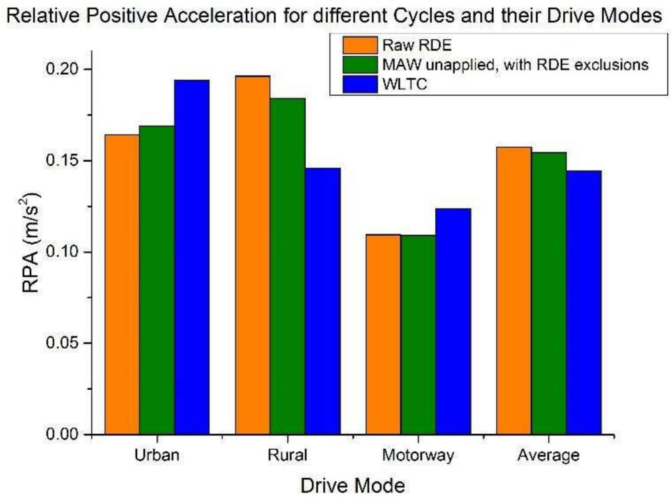

Figure 10. Relative Positive Accelerations (RPA) for the raw RDE, MAW unapplied with RDE exclusions, and WLTC tests, divided into their relative drive modes. The total value is an average of all modes.

Figures 11 and 12 display the average number of stops per kilometer and the average stop duration per kilometer, respectively. One can see that there are certainly far fewer stops involved in the RDE tests than the WLTC test, but that the average time stopped per kilometer remains approximately equal. This indicates that the duration of individual stops may be greater for the RDE test. Of course, with the idle exclusions involved in the "MAW unapplied with RDE exclusions" results, these values decrease to zero. It would be interesting to investigate whether the longer stops involved in the RDE testing may cause a noticeable cold start effect, and if so, whether this lingers beyond the time the vehicle is travelling below 1km/h and so affects the legislated RDE emissions measurement.

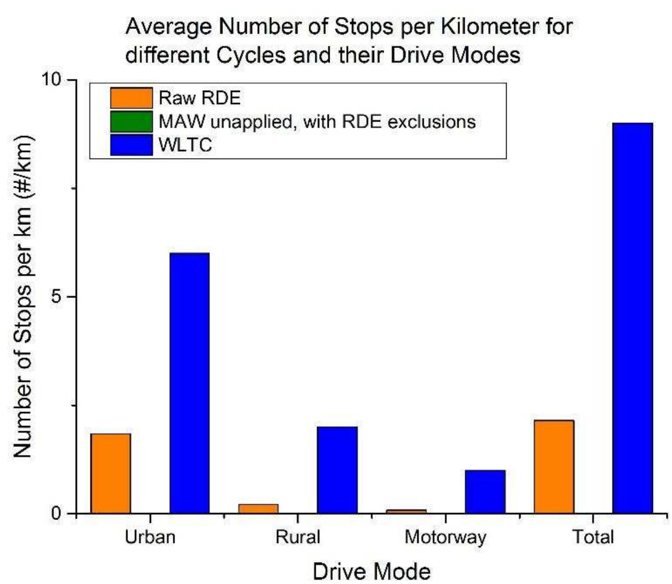

Figure 11. Average number of stops per kilometer for the raw RDE, MAW unapplied with RDE exclusions, and WLTC tests, divided into their relative drive modes. The total value is a total of all modes.

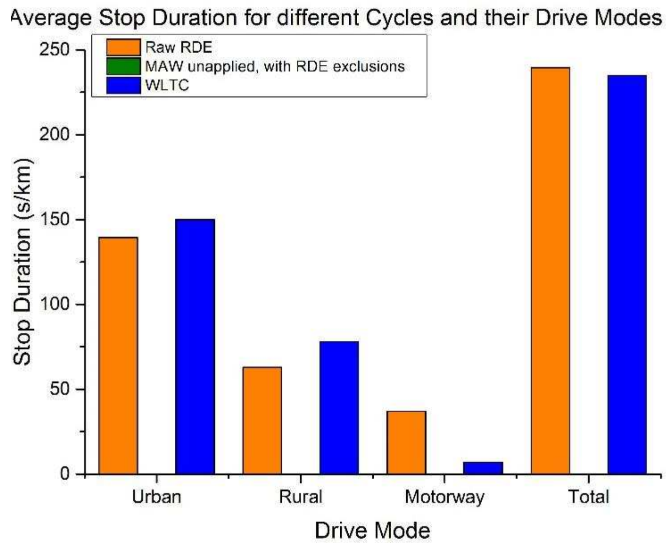

Figure 12. Total duration of stops per kilometer for the raw RDE, MAW unapplied with RDE exclusions, and WLTC tests, divided into their relative drive modes. The total value is a total of all modes.

Emission Comparisons

Figure 13 shows that the CO_2 emissions across all sections of the RDE and WLTC cycles are above the EU passenger cars 2015 CO_2 target (130 g/km). It should be noted that the target value of 130 g/km is based on the NEDC cycle which is less aggressive than WLTP and RDE, and is for new cars sold in 2015 in the EU. The RDE cycles appear to produce slightly lower levels of CO_2, being 4% lower than the WLTP cycles. The RDE exclusions clearly appear to have contributed to this reduction in the urban drive mode. Comparing the patterns between RDE and WLTC results across the modes for figures 6 and 13, it appears that CO_2 may be positively correlated with the average acceleration, but the correlation is weak.

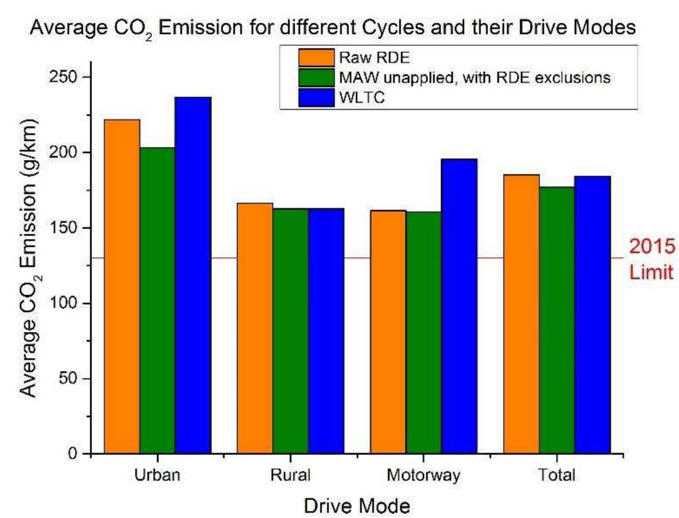

Figure 13. Average CO_2 emission per kilometer for the raw RDE, MAW unapplied with RDE exclusions, and WLTC tests, divided into their relative drive modes. The total value is a distance-weighted average of all modes. A horizontal line at 130 g/km delineates the 2015 CO_2 limit.

Figure 14 shows that the CO emissions of the RDE cycles appear to be 60% lower than the WLTC, and well below the Euro 5 legislated emission limit of 1 g/km. The rural section, however, gave larger CO emissions for the RDE cycle, which would be interesting to investigate in more detail in future work. Again, it is clear that the official RDE exclusions of cold start and idling have an effect on the level of emission in the urban section, decreasing the value by 4%. One can see some similarities between the pattern of CO emissions across modes with that of the average acceleration and RPA in figures 5 and 9, when comparing the RDE and WLTC trends. Increases in RPA and average acceleration may contribute to CO emission.

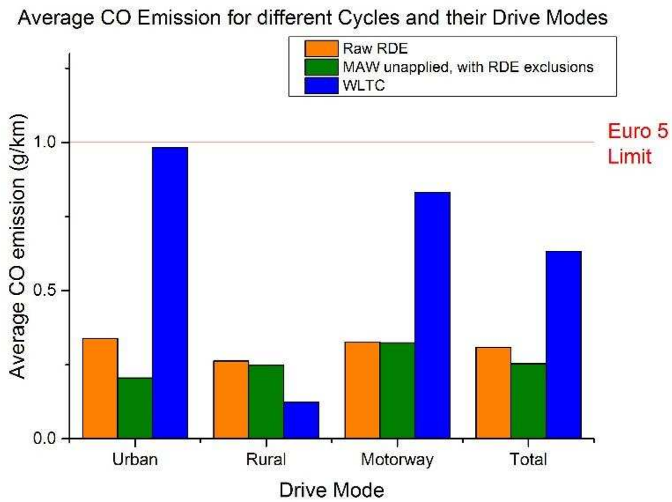

Figure 14. Average CO emission per kilometer for the raw RDE, MAW unapplied with RDE exclusions, and WLTC tests, divided into their relative drive modes. The total value is a distance-weighted average of all modes. A horizontal line at 1g/km delineates the Euro 5 legislated emissions limit.

The RDE emissions of NO_x were 34% lower than the WLTC emissions, as shown in figure 15. The difference is greatest for the urban drive sections, and this is, of course, where the RDE exclusions also appear to have had the greatest impact, reducing NO_x emissions by 41%. However, it is clear that this is not the sole cause of the decrease in NO_x emission. The rural section shows a different trend, with NO_x emissions having similar values. It appears that NO_x emission may be positively correlated with average acceleration (figure 5), indicating that the higher engine speeds required for acceleration may increase combustion temperatures, leading to increased NO_x emission.

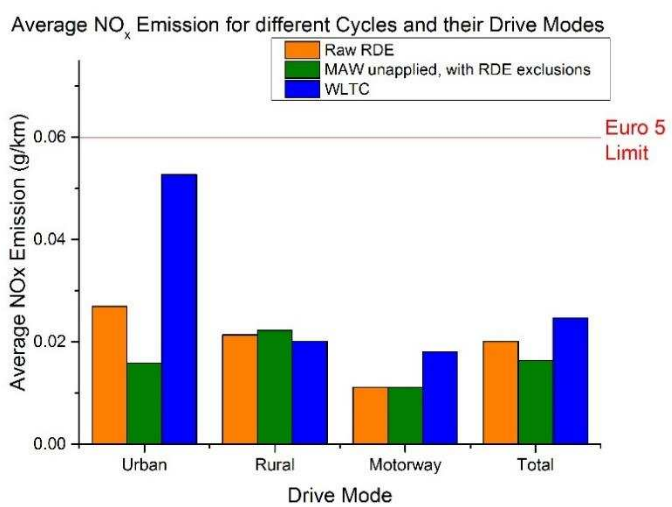

Figure 15. Average NO_x emission per kilometer for the raw RDE, MAW unapplied with RDE exclusions, and WLTC tests, divided into their relative drive modes. The total value is a distance-weighted average of all modes. A horizontal line at 0.06g/km delineates the Euro 5 legislated emissions limit.

Looking at the patterns in the emissions studied, it appears that none of them are correlated in any way with the maximum acceleration and deceleration. This would indicate that these parameters, though useful in defining the type of cycle, are not indicative of the emissions behavior of such cycles. The emissions results tend to agree with those of Merkisz et al. [13] regarding the decrease in on-road emission factors compared to those of chassis dynamometer tests, but are in contrast to those of Merkisz et al. [16] and May et al. [15]. This is particularly interesting given that the average RPA of the current work was found to be greater than in the latter of these two studies. This may be explained by large differences in other characteristics between tests and the greater number of cars used in the current study. The findings regarding the association of CO and NO_x to average acceleration also agree with the findings of Merkisz et al. [13]. It should be noted, however that none of these studies used the same RDE legislation as is presented in the current work, and so cannot be fully compared.

A Closer Investigation of Emission trends with RPA

RDE and WLTC Distance-based Emissions

The CO_2, CO and NO_x grams per kilometer for each vehicle and each drive mode (urban, rural and motorway) were plotted for the RDE and WLTC data. The RDE data used abides by the official RDE requirement of exclusion of cold start and idling.

Looking at figures 16, 17, 18, 19, 20 and 21, little correlation for CO_2, CO and NO_x with RPA is observed. There is an increase in the range of RPA values attained through RDE testing compared to WLTC testing, and average RPA is highly variable across different RDE tests. It is also interesting to see that many individual cars exceeded the NO_x limits for some drive modes of the WLTC test. One can conclude from the results displayed below that RPA is an unreliable indicator for distance-based CO_2, CO and NO_x emissions.

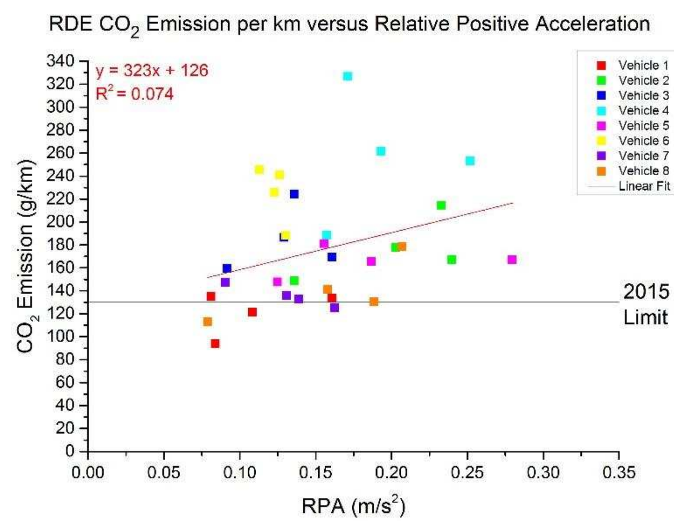

Figure 16. Average CO_2 mass per km for different modes of the RDE cycle (MAW unapplied, with RDE exclusions) plotted against RPA. A horizontal line at 130 g/km delineates the 2015 CO_2 limit.

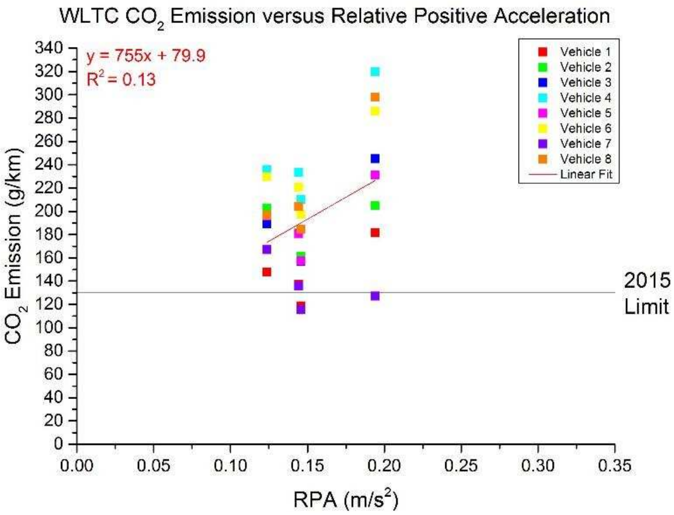

Figure 17. Average CO_2 mass per km for different modes of the WLTC cycle plotted against RPA. A horizontal line at 130 g/km delineates the 2015 CO_2 limit.

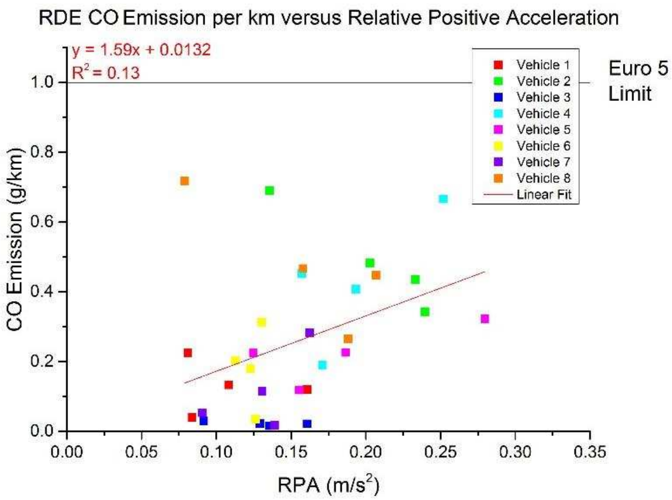

Figure 18. Average CO mass per km for different modes of the RDE cycle (MAW unapplied, with RDE exclusions) plotted against RPA. A horizontal line at 1 g/km delineates the desired fleet-average limit.

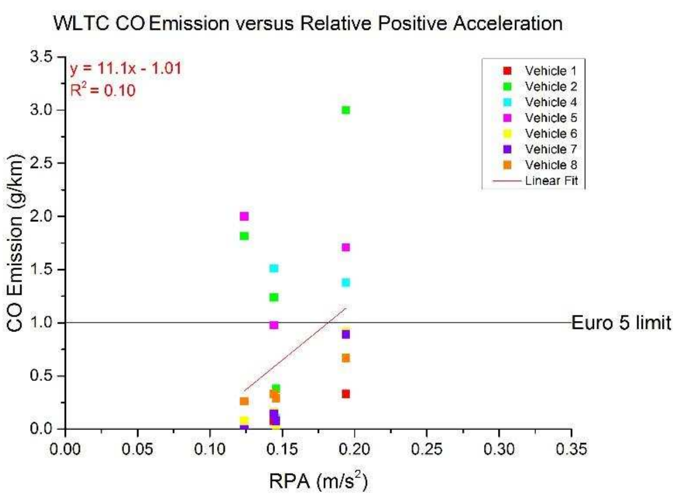

Figure 19. Average CO mass per km for different modes of the WLTC cycle plotted against RPA. A horizontal line at 1 g/km delineates the desired fleet-average limit.

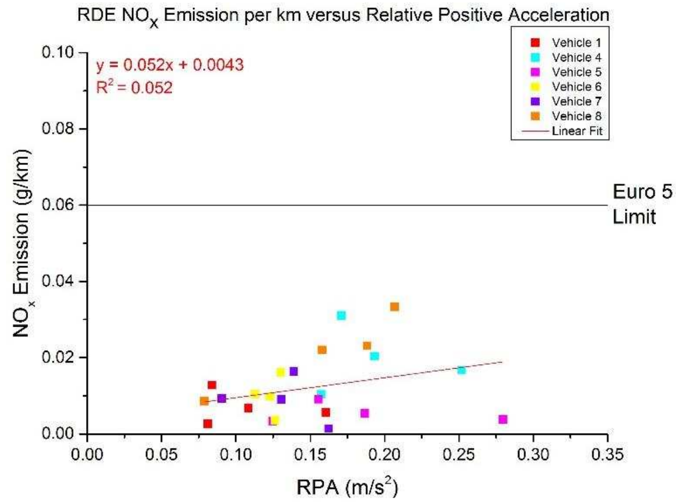

Figure 20. Average NO_x mass per km for different modes of the RDE cycle (MAW unapplied, with RDE exclusions) plotted against RPA. A horizontal line at 0.06 g/km delineates the desired fleet-average limit. The values for Vehicle 2 have been removed as were anomalous.

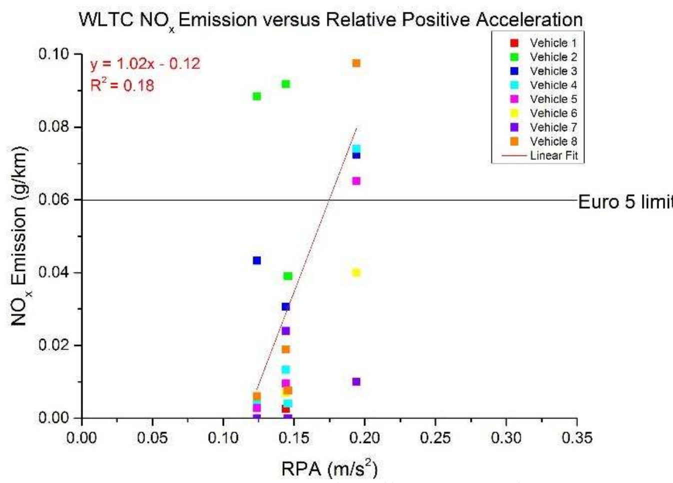

Figure 21. Average NO_x mass per km for different modes of the WLTC cycle plotted against RPA. A horizontal line at 0.06 g/km delineates the desired fleet-average limit.

RDE Mass Emission Rate

The mass emission rate (g/s) for each vehicle and each drive mode was plotted against RPA for the RDE tests as shown in figures 22, 23 and 24 for CO_2, CO and NO_x respectively. It appears that there is no correlation between RPA and emission rates of CO_2, CO and NO_x. It can therefore be inferred that RPA is not an indicator for mass emission rates of CO_2, CO or NO_x.

A possible reason for lack of correlations between the RPA and emissions (g/km or g/s) is that the emissions were the average values for each mode (urban, rural and motorway) which mingled the acceleration and deceleration movements. It would be worthwhile to separate acceleration and deceleration events and this is planned for the future work.

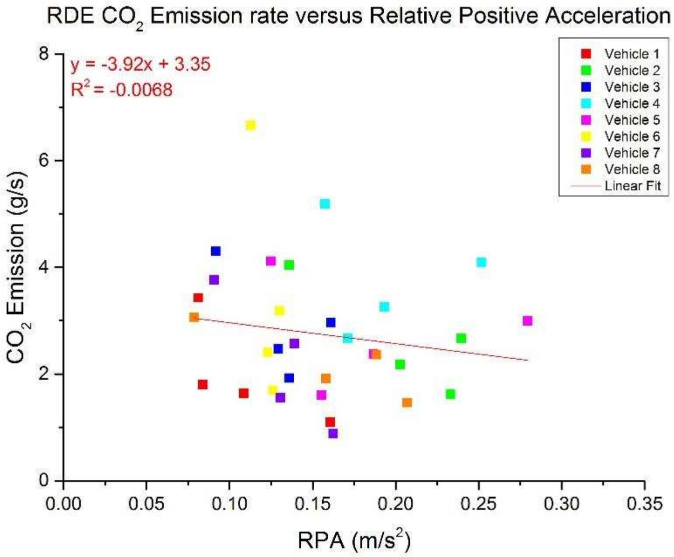

Figure 22. Average CO_2 mass per s for different modes of the RDE cycle (MAW unapplied, with RDE exclusions) plotted against RPA.

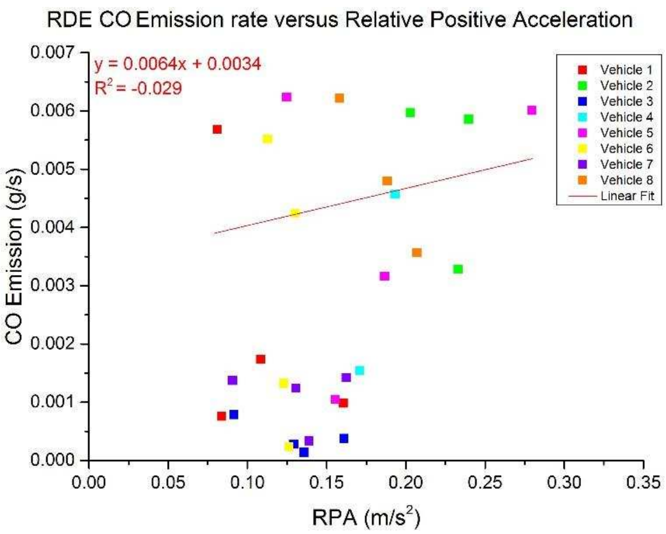

Figure 23. Average CO mass per s for different modes of the RDE cycle (MAW unapplied, with RDE exclusions) plotted against RPA.

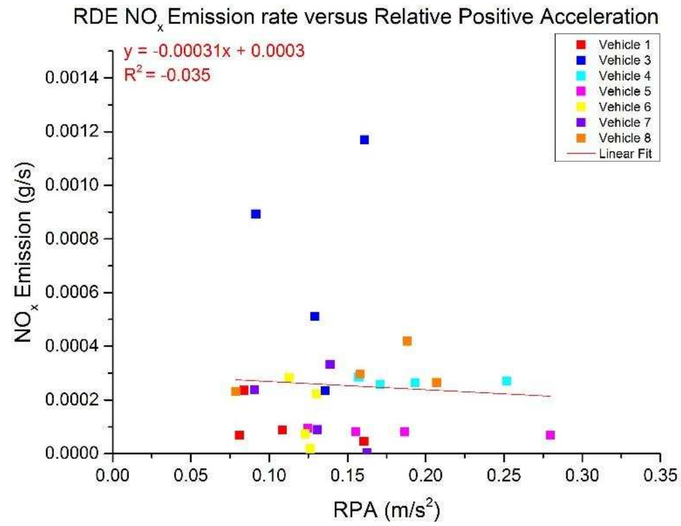

Figure 24. Average NO_x mass per s for different modes of the RDE cycle (MAW unapplied, with RDE exclusions) plotted against RPA.

Effect of the MAW technique on Emissions

The MAW applied RDE values of emissions across the different drive modes were compared to the MAW unapplied RDE values. This allows deeper analysis of how the employment of the MAW method alters the perceived levels of emissions. The plot for CO_2 in figure 25 indicates that the use of the MAW method has minimal effect on the overall CO_2 emissions, but does act to normalize the data by way of minimizing differences between modes. Again, all values are above the desired fleet-average values.

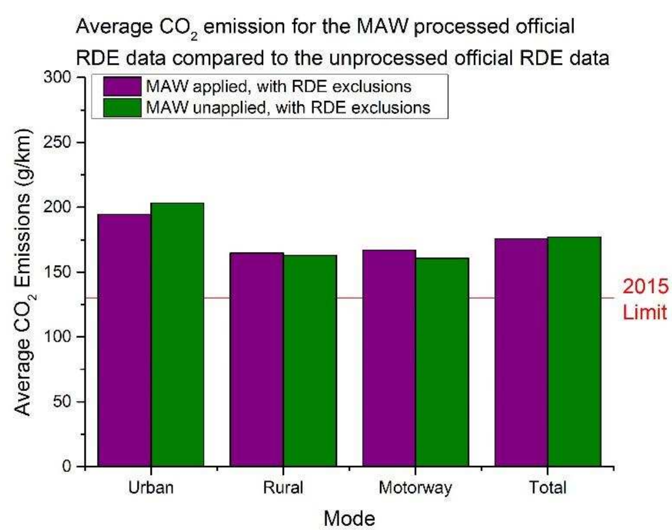

Figure 25. Average CO_2 concentrations resulting from the MAW applied data compared to that with the MAW unapplied (both with the RDE official exclusions employed). A horizontal line at 130 g/km delineates the 2015 CO_2 limit.

Figure 26 shows that the MAW is reducing the average CO emissions for the RDE test, acting primarily in the motorway and urban modes to reduce the overall value by 12%.

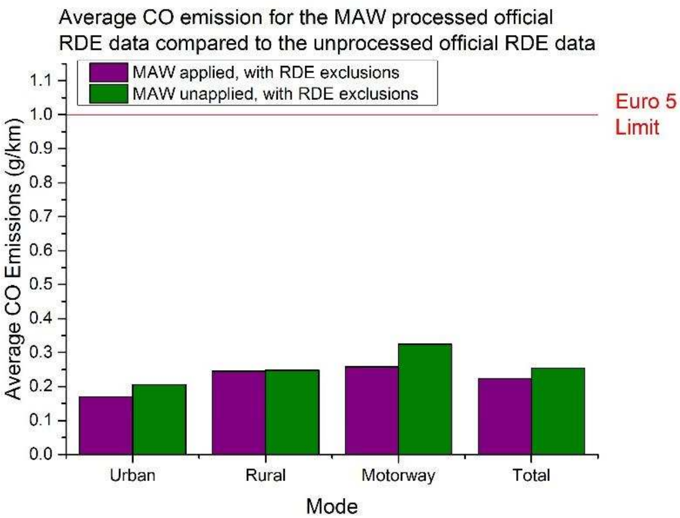

Figure 26. Average CO concentrations resulting from the MAW applied data compared to that with the MAW unapplied (both with the RDE official exclusions employed). A horizontal line at 1g/km delineates the Euro 5 legislated emissions limit.

The NO_x emissions, displayed in figure 27, show a stronger trend of decreasing values under the use of MAW processing. This time most change comes from the rural section, followed by the motorway section, giving an overall reduction of 21%.

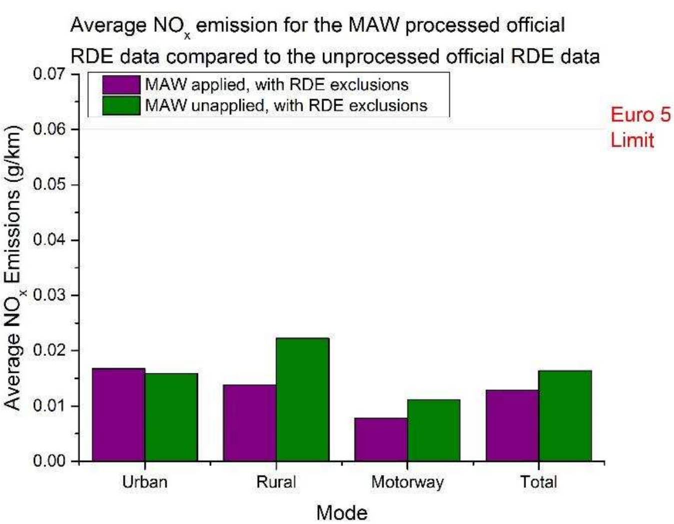

Figure 27. Average NO_x concentrations resulting from the MAW applied data compared to that with the MAW unapplied (both with the RDE official exclusions employed). A horizontal line at 0.06g/km delineates the Euro 5 legislated emissions limit.

In all cases, the use of the MAW processing method appears to smooth out differences between driving modes, which is not surprising given the nature of the technique. It would be interesting to further investigate exactly why the use of the MAW technique decreases some of the perceived CO and NO_x emission levels, and why this is accompanied by a normalization of those results between vehicles.

Conclusions

In summary, the legislated RDE test results from 8 different spark ignition vehicles were compared to corresponding WLTC test results for the same vehicles. The effect of the official RDE exclusion of cold start and idling was simultaneously investigated. Specific attention was paid to differences in drive characteristics and the effect this appeared to have on the CO_2, CO and NO_x emissions. The relationship between RPA and the emissions of CO_2, CO and NO_x was investigated in more depth. Finally, the MAW technique was applied to investigate how this changes the perceived levels of CO_2, CO and NO_x emissions.

The investigation found that the average velocity is 4% greater under the legislated RDE test than the WLTC test, with the exclusion of cold start and idling appearing to be the main cause of this increase. The maximum velocity, however, was 2.4% lower for the RDE test than the WLTC test, with the exception of the urban drive mode, for which there was an increase. The average acceleration and deceleration were lower for the RDE than the WLTC, while the maximum acceleration and deceleration were greater. The effect of the RDE exclusions was to increase the average values seen by around 10%, while it had negligible effect on the maximum values. The values of RPA between the RDE and the WLTC tests showed little variation on average, nor did the difference between the "raw RDE" and "MAW unapplied with RDE exclusions" values. There are fewer stops per kilometer on average for the "raw RDE" than the WLTC, but a longer stop duration per kilometer, indicating that the average time per stop in the RDE is greater.

When studying the CO_2 emissions pattern, it seems that the RDE produces 4% lower values of CO_2 per km than the WLTC, and that the official RDE exclusions of cold start and idling decrease the emission of CO_2 in the urban drive mode by 8%. The RDE showed a large decrease in distance-based CO emissions of 60% compared to the WLTC, with the RDE exclusions leading to 18% of this decrease. The remainder is due to the differences in the driving characteristics of the RDE tests compared to WLTC test. Some correlations between CO emissions and average acceleration and RPA were seen from the results. NO_x emissions were 33% lower under RDE testing than WLTC testing, with 18% of this decrease again attributable to the official RDE exclusions. NO_x emissions also appeared to be related to the average acceleration. No pollutants were correlated with the maximum acceleration and deceleration, indicating that, although a useful cycle characteristic, these variables are not suitable indicators for pollutant emission.

There were hardly any correlations observed between the RPA and CO_2, CO and NO_x distance-based emission factors. This was the case for both RDE and WLTC results. The range of RPA values was much greater for the RDE than the WLTC test, and different RDE tests showed a large variation in values. No correlation was seen between the RPA and mass emission rates for any of the pollutants, indicating that RPA is not correlated with emission rates. The use of the MAW technique had minimal effect on the distance-based CO_2 emissions, but did appear to decrease the CO and NO_x results by 12% and 21% respectively. For all three pollutants the MAW acted to decrease the variation between drive modes.

Recommendations

In future work it would be interesting to more closely study the variation in emissions with drive characteristics by looking at each vehicle test individually. It would also be desirable to investigate whether other drive characteristics are more closely affecting the pollutant emission, such as vehicle specific power (VSP). A more thorough study into the effect the MAW technique has on the pollutant emission values is also necessary, in order to see why the CO and NO_x decreased under its use. The cold start and idling exclusions for the official RDE test is a topic of hot debate currently, and so further investigation into the effects of these exclusions would be prudent.

References

1. Vlachos, T.G., Bonnel, P., Perujo, A., Weiss, M., Villafuerte, P.M., and Riccobono, F., "In-Use Emissions Testing with Portable Emissions Measurement Systems (PEMS) in the Current and Future European Vehicle Emissions Legislation: Overview, Underlying Principles and Expected Benefits," SAE Int. J. Commer. Veh. 7(1):199–215, 2014, doi:10.4271/2014-01-1549.

2. AVL Emission Testing Systems, AVL Emission Testing Handbook – 2016, 80, 2016.

3. Marotta, A., Pavlovic, J., Ciuffo, B., Serra, S., and Fontaras, G., "Gaseous Emissions from Light-Duty Vehicles: Moving from NEDC to the New WLTP Test Procedure," Environ. Sci. Technol. 49(14):8315–8322, 2015, doi:10.1021/acs.est.5b01364.

4. Dings, J., "Mind the Gap! Why official car fuel economy figures don't match up to reality?," 2013.

5. Kadijk, G., Verbeek, M., Smokers, R.T.M., Spreen, J., Patuleia, A., Ras, M. van, Norris, J.O.W., Johnson, A., O'Brien, S., Wrigley, S., Pagnac, J., Seban, M., and Buttigieg, D., "Supporting analysis regarding test procedure flexibilities and technology deployment for review of the light duty vehicle fleet CO2 regulations," Brussels, 2012.

6. Mock, P., German, J., Bandivadekar, A., and Riemersma, I., "Discrepancies between type- approval and 'real-world' fuel- consumption and CO 2 values: Assessment for 2001-2011 European passenger cars," Berlin, 2012.

7. Tutuianu, M., Bonnel, P., Ciuffo, B., Haniu, T., Ichikawa, N., Marotta, A., Pavlovic, J., and Steven, H., "Development of the World-wide harmonized Light duty Test Cycle (WLTC) and a possible pathway for its introduction in the European legislation," Transp. Res. Part D Transp. Environ. 40:61–75, 2015, doi:http://dx.doi.org/10.1016/j.trd.2015.07.011.

8. Ciuffo, B., Marotta, A., Tutuianu, M., Anagnostopoulos, K., Fontaras, G., Pavlovic, J., Serra, S., Tsiakmakis, S., and Zacharof, N., "Development of the Worldwide Harmonized Test Procedure for Light-Duty Vehicles: Pathway for Implementation in European Union Legislation," J. Transp. Res. Board (2503):pp 110–118, 2015, doi:10.3141/2503-12.

9. Kageson, P., "Cycle-Beating and the EU Test Cycle for Cars," Eur. Fed. Transp. Environ. 98/3(November 1998):10, 1998.

10. Weiss, M., Bonnel, P., Hummel, R., Provenza, A., and Manfredi, U., "On-road emissions of light-duty vehicles in Europe," Environ. Sci. Technol. 45(19):8575–8581, 2011, doi:10.1021/es2008424.

11. Johnson, T. V, "Vehicular Emissions in Review," SAE Int. J. Engines 9(2):1258–1275, 2016, doi:10.4271/2016-01-0919.

12. Els, P., "Random Cycle Test vs . Portable Emission Measurement System," 2013.

13. Merkisz, J., Fuć, P., Lijewski, P., and Bielaczyc, P., "The Comparison of the Emissions from Light Duty Vehicle in On-road and NEDC Tests," SAE Tech. Pap. 2010-01–12:1–12, 2010, doi:10.4271/2010-01-1298.

14. Weiss, M., Bonnel, P., Hummel, R., and Manfredi, U., "Analyzing on-road emissions of light-duty vehicles with Portable Emission Measurement Systems (PEMS)," ISBN 9789279190728, 2011, doi:10.2788/23820.

15. May, J., Bosteels, D., and Favre, C., "An Assessment of Emissions from Light-Duty Vehicles using PEMS and Chassis Dynamometer Testing," SAE Int. J. Engines 7(3):1326–1335, 2014, doi:10.4271/2014-01-1581.

16. Merkisz, J., Pielecha, J., Bielaczyc, P., and Woodburn, J., "Analysis of Emission Factors in RDE Tests as Well as in NEDC and WLTC Chassis Dynamometer Tests," SAE Tech. Pap. 2016-01-0980, 2016, doi:10.4271/2016-01-0980.Copyright.

17. Department for Transport, "Vehicle Emissions Testing Programme," 2016.

18. European Parliament and Council of the European Union, "Commission Regulation (EU) 2016/427 of 10 March 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6) (Text with EEA relevance)," Off. J. Eur. Union 82(31/03/2016):1–98, 2016.

19. United Nations, "Addendum 15 : Global technical regulation No . 15 - Worldwide harmonized Light vehicles Test Procedure," Glob. Regist. ECE/TRANS/:1–234, 2014.

20. European Commission, "ANNEXES to the Commission Regulation supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and," 2007.

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Definitions/Abbreviations

CO	Carbon monoxide
CO_2	Carbon dioxide
DI	Direct injection
EU	European Union
GPS	Global positioning system
MAW	Moving averaging window
NA	Naturally aspirated
NEDC	New European drive cycle
NO_x	Nitrous oxides
OBD	On board diagnostics
PEMS	Portable emissions measurement system
PFI	Port fuel injection
RDE	Real driving emissions
RPA	Relative positive acceleration
T	Turbocharged
TWC	Three way catalyst
USB	Universal serial bus
VSP	Vehicle specific power
WLTC	World harmonized light duty test cycle
WLTP	World harmonized light duty test procedure
SI	Spark ignition

Appendix

Table A1. Characteristics of vehicles tested.

Vehicle	1	2	3	4	5	6	7*	8
Engine Capacity (mL)	1498	1199	1600	1998	1598	1998	1800	1800
Engine Maximum Power (kW)	96	100	81	108	90	162	-	118
Maximum GVW (kg)	1775	1721	1750	2000	1770	2720	-	2060
Maximum no. People	5	5	5	5	5	7	5	5
Emission Compliance	5	5	5	5	5	5	2	5
Injection	DI	DI	PFI	PFI	PFI	PFI+DI	PFI	DI
Transmission	CVT	6AT	6AT	4AT	CVT	6AT	CVT	7DCT
Curb Weight	1205	1305	1250	1510	1285	1925	1350	1580
T or NA	NA	T	T	T	T	-	NA	NA

*Vehicle 7 is a hybrid electric vehicle

Table A2. Ambient conditions and trip properties. All values reported were measured during testing, except where otherwise indicated. The values over all WLTC tests performed in a single test center were very similar to each other, so an average value for each city test center is reported for the WLTC tests.

Test	RDE 1	RDE 2	RDE 3	RDE 4	RDE 5	RDE 6	RDE 7	RDE 8	WLTC	WLTC
Location	Beijing	Xiamen	Xiamen	Xiamen	Xiamen	Beijing	Beijing	Xiamen	Xiamen	Beijing
Average ambient temp (°C)	10.25	21.35	27.64	21.26	25.95	15.05	5.75	27.65	22.39	24.56
R.H. (%)	23.1	56.8	50.94	57.23	41.5	28.7	37.9	50	48.63	48.42
Pressure (kPa)	103	101.8	101.55[a]	101.7[a]	101.8	102.2	102.9	101.6	101.677	100.64
Altitude (m)	30.2	17.6	18.93[b]	18.93[b]	17.4	29.7	24.8	21.8	18.93[b]	28.23[b]

[a] values inferred from the RDE official report for that vehicle.
[b] values estimated as the average value for all other trips in that location.

Table A3. Trip drive characteristics and properties. All values reported were measured during testing and taken from the official RDE output report, except where otherwise indicated. Because the WLTC test is a predefined cycle, the values for this are taken from literature.

Test	RDE 1	RDE 2	RDE 3	RDE 4	RDE 5	RDE 6	RDE 7	RDE 8	WLTC
Average velocity (km/h)	47	45.2	44.95	43.92	51.7	34.1	38.8	48	46.54[a]
Average engine speed (rpm)	1392	1510	1580.06	1589.19	1641	1239	-	1561	-
Average engine power (kW)	6.2	8.5	-	-	8.8	8.6	5.9	6.8	-
Total distance (km)	75.892	82.454	78.4	80.18	82.364	68.094	72.407	82.256	23.27[a]
Total work (kWh)	11.166	16.528	-	-	15.322	18.258	11.526	13.277	-
Total duration (s)	5813	6563	6194	6316	5733	7181	6720	6166	1800[a]
Stop duration (s)	772	773	-	-	490	2616	1310	618	242[a]
Number of stops (#)	25	18	15	23	12	27	32	22	7[a]
Maximum speed (km/h)	114.18	115.88	-	-	115.59	123.09	114.31	117.81	131.3[a]

[a] values given in Tutuianu et al. [7].
A dash (-) indicates that the information was unavailable.