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Gaseous Emissions from Light-Duty Vehicles: Moving from NEDC to the New WLTP Test Procedure

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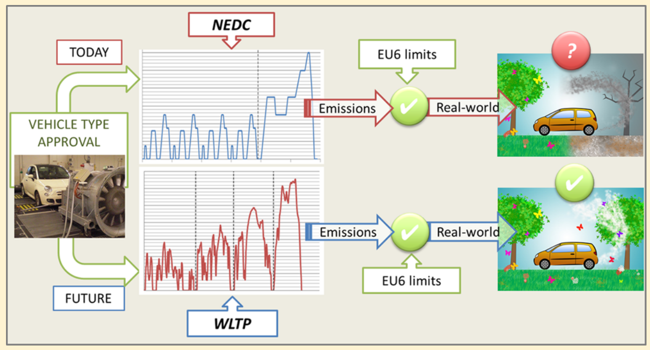
ABSTRACT: The Worldwide Harmonized Light Duty Test Procedure (WLTP), recently issued as GTR15 by UNECE-WP29, is designed to check the pollutant emission compliance of Light Duty Vehicles (LDVs) around the world and to establish the reference vehicle fuel consumption and CO_2 performance. In the course of the development of WLTP, the Joint Research Center (JRC) of the European Commission has tested gaseous emissions of twenty-one Euro 4–6 gasoline and diesel vehicles, on both the current European type approval test procedure (NEDC) and the progressive versions of the WLTP. The results, which should be regarded just as an initial and qualitative indication of the trends, demonstrated minimal average differences between CO_2 emissions over the NEDC and WLTP. On the other hand, CO_2 emissions measured at JRC on the NEDC were on average 9% higher than the respective type approval values, therefore suggesting that for the tested vehicles, CO_2 emissions over WLTP were almost 10% higher than the respective NEDC type approval values. That difference is likely to increase with application of the full WLTP test procedure. Measured THC emissions from most vehicles stayed below the legal emission limits and in general were lower under the WLTP compared to NEDC. Moving from NEDC to WLTP did not have much impact on NO_x from gasoline vehicles and CO from diesel vehicles. On the contrary, NO_x from diesel vehicles and CO from low-powered gasoline vehicles were significantly higher over the more dynamic WLTP and in several cases exceeded the emission limits. Results from this study can be considered indicative of emission patterns of modern technology vehicles and useful to both policy makers and vehicle manufacturers in developing future emission policy/technology strategies.



1. INTRODUCTION

For emissions certification of light-duty vehicles (LDVs) various driving cycles and type approval test procedures are employed around the world. For example, in Europe the New European Driving Cycle (NEDC) is used for the certification, whereas the JC 08 Cycle is used in Japan. Existing driving cycles differ in their representativeness and completeness, or in other words, in their ability to statistically represent the real-world conditions and diversity. The NEDC is a cold-start driving cycle used for emission type-approval of all Euro 3 and later LDVs in Europe and has been criticized for not being representative of real-world vehicle operation.[1,2] The JC 08 represents driving in congested city traffic, including idling periods and frequently alternating acceleration and deceleration, but does not cover motorway driving behavior.

Several studies have shown that actual on-road emissions and fuel consumption can be substantially higher than values reported during the type approval testing on a chassis dynamometer in certified testing laboratories.[2−4] The CADC (Common Artemis Driving Cycle) is a real-world simulation driving cycle[5] that aims to represent average driving conditions in Europe. Studies have shown that its higher dynamicity resulted also in higher emissions compared to the NEDC.[6−8] Furthermore, the emissions of passenger cars measured over the newly developed Worldwide Motorcycle Test Cycle (WMTC) were closer to real world driving emissions.[9] Portable Emissions Measurement Systems (PEMS) were also developed and used to measure emissions during real driving over preselected routes. These on-road emission tests showed that the current laboratory emission testing fails to reliably capture on-road emissions, especially in the case of nitrogen oxides (NO_x).[3,10,11] Therefore, in many countries around the world there has been a growing interest to develop a new driving cycle and test procedure more representative of real-world driving conditions and emissions.

The World Forum for the Harmonization of Vehicle Regulations (WP. 29) of the United Nations Economic Commission for Europe (UNECE), through its working party on pollution and energy (GRPE), in 2009 launched a project with the aim to develop a worldwide harmonized light duty test cycle (WLTC) and test procedure (WLTP). Two working groups were established; the first group in charge of the development of harmonized cycle (DHC) and the second group working on development of test procedures (DTP). The JRC has been deeply involved in both groups, participating to

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Table 1. Characteristics of the Gasoline and Diesel Vehicles Tested

fuel	vehicle	emission standard	displacement (cc)	I[a]/A[b]/T[c]	power (kW)	inertia class (kg)
gasoline	G01	EURO5A	1600	DI/T/MT	75−100	1360
	G02	EURO5A	2000	DI/T/AT	>100	1810
	G03	EURO5	900	DI/T/MT	50−75	1020
	G04	EURO5	1500	PFI/NA/MT	75−100	1250
	G05	EURO5B	4600	DI/NA/AT	>100	2040
	G06	EURO6	2000	DI/T/AT	>100	1700
	G07	EURO5A	1600	DI/T/AT	>100	1470
	G08	EURO5A	1600	PFI/NA/MT	75−100	1250
	G09	EURO5A	1200	PFI/NA/AT	50−75	1020
	G10	EURO5A	1200	PFI/NA/MT	50−75	1020
	G11	EURO5B	1400	DI/T/AT	>100	1250
	G12	EURO5A	1200	DI/T/AT	50−75	1360
diesel	D01	EURO5A	2000	DI/T/MT	>100	1470
	D02	EURO5A	2000	DI/T/AT	>100	1470
	D03	EURO4	2200	DI/T/MT	>100	1930
	D04	EURO4	2200	DI/T/MT	50−75	1810
	D05	EURO5	1250	DI/T/MT	50−75	1250
	D06	EURO6	3000	DI/T/AT	>100	2960
	D07	EURO4B	2500	DI/T/MT	>100	2140
	D08	EURO5	1450	DI/T/MT	50−75	1250
	D09	EURO5A	1450	DI/T/MT	50−75	1130

[a]I = injection: DI = direct injection; PFI = Port Fuel Injection. [b]A = air aspiration: T = turbo; NA = naturally aspirated. [c]T = transmission: AT = automatic transmission; MT = manual transmission.

the design, validation, and revision of the new test cycle, described in details by Tutuianu et al.,[12] and in developing, testing, and adjusting the new test procedures.

During this period, from 2010 to 2015, JRC has tested the various versions of the new test cycle and test procedure on a number of vehicles that were also tested under NEDC conditions. The result is a remarkable amount of experimental data regarding the regulated gaseous pollutants and fuel consumption on more than 20 vehicles. During this experimental campaign particulate matter (PM) mass measurements were routinely carried out, however nothing worth mentioning was found, as most of the diesel vehicles were Euro 5 and thus equipped with diesel particulate filter (DPF).

So far a very limited number of experimental results have been published that evaluate the impact of the introduction of WLTP on gaseous emissions[7,13−16] and mostly these studies had a focus on CO_2 emissions.[16−18] The objective of the present paper is to show the results of gaseous emissions (CO_2, NO_x, CO, and THC) from Euro 4, 5, and 6 vehicles measured at JRC under the NEDC and WLTP, and to provide some qualitative trends, also in comparison to the little available literature data.

2. EXPERIMENTAL CAMPAIGN

2.1. Test Vehicles. Twenty-one vehicles from different manufacturers and with a wide variety in terms of mass, power, engine displacement and technology were tested. The idea behind the choice of the vehicles selected during the period 2010−2014 was to try to cover as many segments of the European market as possible, in order to make sure that the WLTP was suitable for all types of European LDVs. The main characteristics of the tested vehicles can be found in Table 1. Twelve of these vehicles were gasoline fueled while the remaining nine were diesel fueled. Two vehicles were type approved for the EURO 6 standard, three vehicles for the EURO 4, while all other met EURO 5 standard requirements (the most common and easily procurable). Two vehicles (D04 and D03) were of categories N_1 class II and III, respectively, while all other vehicles were of category M_1. The average NEDC inertia mass was 1522 kg, the average engine capacity 1847 cc, and the average engine maximum power 106.5 kW.

2.2. Description of the Test Procedures. The NEDC cycle includes four urban driving segments (UDC) characterized by low vehicle speed, low engine load, and low exhaust gas temperature, followed by one extra-urban driving segment (EUDC) to account for more aggressive and higher speed driving. Figure 1 shows the speed profiles of the two cycles. The WLTC assigned to the highest power to mass ratio (PMR) vehicle category (class 3), which represents the vast majority of European vehicles, is composed by four speed phases (low, medium, high and extra-high). The WLTC lasts for 1800 s, features a more dynamic speed profile, a higher mileage than NEDC, and thus the engine cold start CO_2 emissions have a lower impact on the overall fuel economy. In addition, the WLTC has the vehicle accelerating or decelerating 84% of the time over the whole cycle, with only 13% at idle and 4% at constant cruise driving, while 40% of the NEDC is at a steady state cruise condition, 24% is at idle, and the remaining 36% is spent accelerating or decelerating. Table 2 quantifies the main parameters related to dynamics of the two cycles. Additional details about the WLTC development, validation, and comparisons with the NEDC can be found in Tutuianu et al.[12]

The NEDC tests were performed in line with the existing UNECE Regulation 83.[19] For most vehicles the manufacturer's road load (RL) coefficients were used. In few cases, where these values were not available, the default coefficients included in Regulation 83 were applied.

Concerning the tests carried out over the WLTC/WLTP (note: the first indicates only the speed profile and gear shift strategy, the second implies that the WLTC is executed

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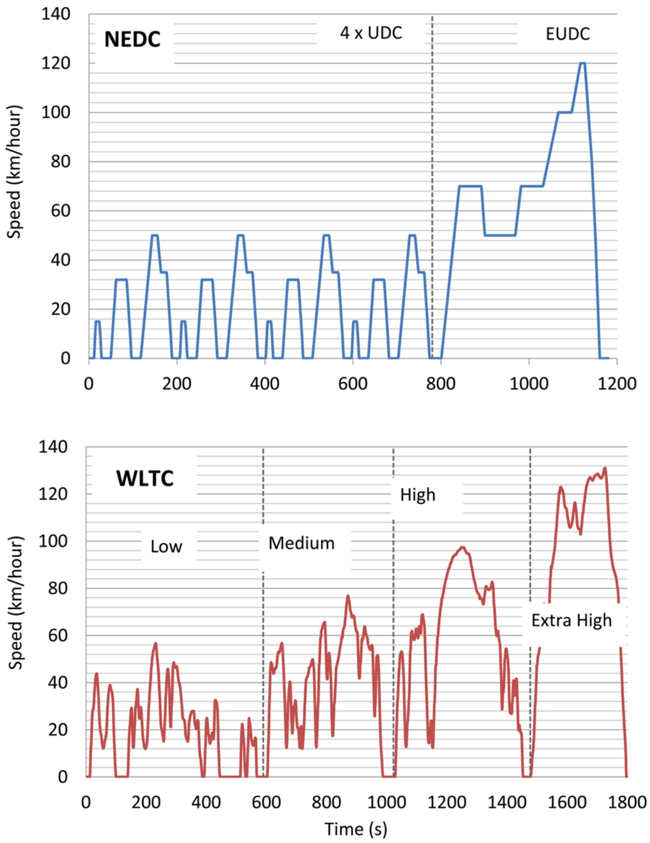

Figure 1. Speed profiles of NEDC and WLTC driving cycles.

Table 2. Key Parameters of the Driving Cycles NEDC and WLTC

parameters	NEDC	WLTP
duration (s)	1180	1800
distance (km)	11.03	23.27
average speed (km/h)	33.6	46.5
maximum speed (km/h)	120.0	131.3
stop duration (%)	23.7	12.6
constant driving (%)	40.3	3.7
acceleration (%)	20.9	43.8
deceleration (%)	15.1	39.9
average positive acceleration (m/s^2)	0.59	0.41
maximum positive acceleration (m/s^2)	1.04	1.67
average positive “speed·acceleration” (m^2/s^3)	1.04	1.99
maximum positive “speed·acceleration” (m^2/s^3)	9.22	21.01
average deceleration (m/s^2)	−0.82	−0.45
minimum deceleration (m/s^2)	−1.39	−1.50

together with a partial or complete set of parameters that characterize the new test procedure) it is necessary to explain the following.

The WLTC/WLTP tests carried out at the JRC, which started in 2010 and are still continuing in 2015, were aimed at developing, validating and confirming the new Worldwide Harmonized Light Duty Vehicle Test Procedure. The speed profiles of this new procedure evolved from 2010 (WLTC ver.2) to 2014 (WLTC 5.3, now called WLTC Class 3.2) and that is described in more detail in Tutuianu et al.[12] Initially, some WLTC tests were performed with NEDC RL (indicated in this paper as WLTC-TM-NEDC), but the majority of vehicles were tested following the evolving requirements of the WLTP, in terms of test temperature, test mass, RL, from the first tentative proposals to the latest provisions as prescribed in the official, recently released UNECE GTR15.[20] In particular, the test temperature for WLTP was set at 23 °C during the initial discussions and has remained fixed. Concerning the test mass, the WLTP sets two test mass values, a Test Mass High (TMH) and a Test Mass Low (TML), with correspondingly increased RL compared to NEDC. The TMH and TML are calculated according to the Annex 4 of the UNECE GTR15[20] as

$$\mathrm{TMH} = \mathrm{MRO} + \mathrm{OM} + 25 + \varphi \times \mathrm{MVL} \tag{1}$$

$$\mathrm{TML} = \mathrm{MRO} + 25 + \varphi \times \mathrm{MVL} \tag{2}$$

where MRO is mass in running order, OM is mass of optional equipment, MVL is maximum vehicle load and is equal to LM − MRO − OM − 25 where LM is technically permissible maximum laden mass. φ is the percentage of the vehicle load included in the definition of the test mass, and is equal to 15% for M1 category (passenger cars) and to 28% for N1 category vehicles (light commercial vehicles). For regulated (criteria) pollutants selected vehicles representative for one vehicle family (with identical engine capacity and technology, transmission type and a number of gears, charging system, maximum number of seating places, number of powered axes, MRO, and LM) will be tested under both test masses and RL conditions and in both cases they must comply with legislated emission standards. The final result for regulated pollutant emissions shall be the average of these two measurements. For CO_2 certification the procedure is a bit different. For a given vehicle family TMH will be used for the worst case scenario of CO_2 emissions as well as to determine WLTP road load coefficients for the same scenario, while TML will be applied for the best case CO_2 emissions for that same vehicle family. Based on TML and TMH results a linear regression for CO_2 emissions over cycle energy (which is calculated from vehicle test weight and RL) will be determined. This regression line will be used to determine CO_2 emissions of all other vehicles within the respective vehicle family without type approval certification if their mass is between TML and TMH.[21]

The WLTC/WLTP tests at JRC were carried out using up to 3 test masses: the NEDC test mass (WLTC-TM-NEDC); the TMH (WLTP-TMH) and the TML (WLTP-TML) as described above. For WLTP Road Load, as no real measurement results were available at the time when tests were performed, the values were decided on the basis of common sense. The F_0 values were corrected for the increase of test mass from NEDC to WLTP TML and TMH. The F_0 increase was between 11 and 14% of the difference in test mass as proposed in the scientific literature.[22] In addition to that, on some vehicles, a parametric study was performed where F_0 and F_2 (F_1 was kept constant) varied between NEDC values and +25% with an intermediate step of +12.5%. It is clear that these values do not represent the WLTP Road Load values that would be expected from applying the GRT15 Road Load determination procedure; however they are in the direction of an increase that is, if not quantitatively, at least qualitatively valid.

The tests were carried out in the Vehicle Emission Laboratory (VELA) of the JRC. All vehicles were tested over the cold start cycle conditions according to the legislative procedures for type approval, including vehicle preconditioning and soak time. The cell temperature for all tests was between 22−25 °C for NEDC and 23 °C for WLTP tests. Regulated

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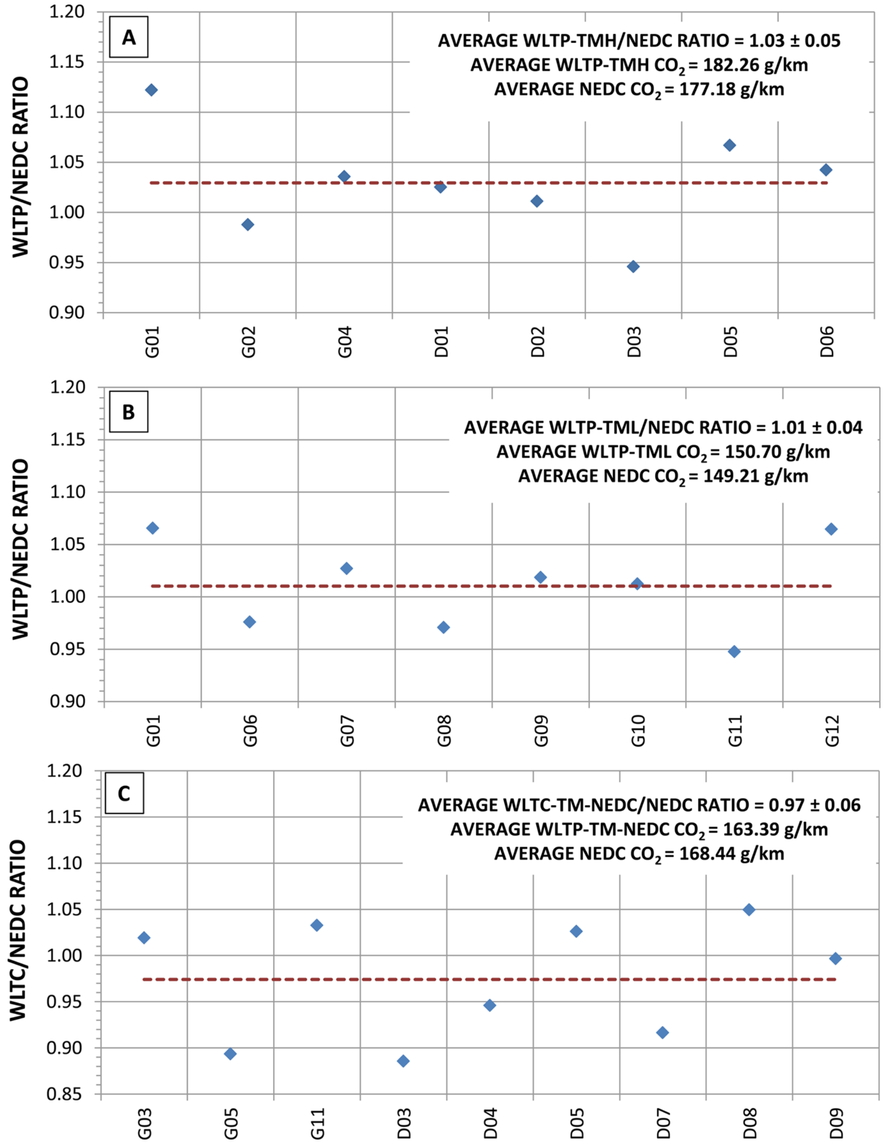

Figure 2. Ratio of CO_2 concentration measured under WLTC and NEDC for different gasoline and diesel vehicles in WLTP-TMH (A); WLTP-TML (B); and WLTC-TM-NEDC (C) conditions.

pollutant emissions from LDVs were measured using a chassis dynamometer and a conventional constant volume sampling (CVS) system with a critical flow venturi. The CVS was equipped with four critical orifices that allow the selection of the most appropriate flow rate. The roller bench of the chassis dynamometer was a 48″ single roller type. To follow the legislative cycle, the driver was assisted by a driver aid system. For gasoline vehicles the regulated gaseous emissions were measured using the bags as prescribed by the legislation. This means that a constant volume sample of the exhaust is collected in Tedlar bags during the test and the concentration of each pollutant measured inside these bags at the end of the test. The background level is determined by analyzing a sample of the dilution air collected in other bags. For the diesel vehicle, in agreement with the legislative procedure, the HC emissions were instead measured using an online heated flame ionization detector (FID) analyzer sampling directly from the dilution tunnel. The regulated emissions were measured as follows: CO and CO_2 with a nondispersive infrared (NDIR) analyzer, total unburned hydrocarbons (HC) with a flame ionization detector (FID), and oxides of nitrogen (NO_x) with a chemiluminiscense analyzer (CLA) using a NO_2 to NO converter.

3. RESULTS AND DISCUSSION

In the light of what has been explained in the previous paragraph concerning the limited number of vehicles tested and the incomplete experimental matrix, the results presented in the next paragraphs cannot be seen as a complete and exhaustive comparison between NEDC and WLTP. However, they show some interesting trends, in line with other similar studies, in particular for what concerns CO_2 emission and fuel consumption.

3.1. CO_2 Emissions. The selection of cars tested in this program provided a wide range of type approval CO_2 emissions, going from 90 g/km to 275 g/km. The CO_2 emissions measured in VELA at JRC on the NEDC were on average 9% higher than the respective type approval values, with a standard deviation of 8% (1.09 ± 0.08). Note that in the remainder of the text we will use the notation ($\mu \pm \sigma$) for all

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the results coming from the experimental campaign, where μ is the mean of the sample and σ the standard deviation

On the basis of all test results collected for the present study, the average ratio between CO_2 emissions over NEDC and over WLTP (carried out under different conditions) is around 1 (1.00 ± 0.06). Different WLTP conditions include tests with TMH (ratio shown in Figure 2A), TML (ratio shown in Figure 2B) and WLTC performed with NEDC test mass (ratio shown in Figure 2C). In addition, it should be noted again that for test conditions called "TMH" and "TML" not only test mass has been increased, but also road load coefficients as described earlier in this paper. As expected the average CO_2 results, and therefore the average WLTP/NEDC ratio as well, increase with higher test mass and road load applied to the WLTP tests. A statistical analysis (t test, one-sided, 95% confidence level) applied to these results showed statistically significant difference ($p < 0.05$) only when comparing ratios from WLTP-TMH/NEDC to WLTC-TM-NEDC/NEDC, whereas statistically insignificant differences were found when comparing ratios from WLTP-TMH/NEDC to WLTP-TML/NEDC or from WLTP-TML/NEDC to WLTC-TM-NEDC/NEDC.

In Figure 2C it is interesting to see the influence of only the driving cycle with the different gear shift strategy (while keeping the NEDC test mass and RL constant) on CO_2 emissions. Although more transient and demanding, WLTC tests resulted in lower average CO_2 emissions than NEDC tests. This can be attributed to two main effects: first, the smaller impact of the cold start emissions for WLTC, which is longer than NEDC; second, the higher efficiency of the engine while performing the WLTC, compared to the same engine performing the NEDC. Concerning the cold start effect, measurements of lube oil and coolant temperature during both NEDC and WLTC/WLTP tests showed that a period between 100 and 200 s was needed by the vehicles to reach warmed-up conditions. Assuming an average time of 150 s for the warm-up and comparing this time with NEDC total duration (1180 s) and WLTC total duration (1800 s), it turns out that the contribution of cold start emissions over NEDC is between 50% and 60% higher than for WLTC/WLTP. Some tests conducted in hot-start conditions at JRC (not reported here) confirmed this finding: the decrease in CO_2 emissions under hot-start NEDC tests was clearly higher than the decrease in the hot-start WLTC/WLTP tests. Similar trends in CO_2 results were reported by others[7,15−17] when NEDC and WLTC are run with the same vehicle inertia. In general, WLTC/NEDC CO_2 ratio was between 0.92 and 0.99,[7,15,16] which means that the CO_2 emission level is about 1% to 8% lower in WLTC than in NEDC. In addition, and consistent with this study results, it has been found that higher CO_2 emissions under WLTP are due to the higher vehicle inertia that is required in the new test procedure (WLTP) and not from the driving cycle itself.[7] On the other side, Andersson et al.[13] reported WLTP CO_2 values to be almost identical or lower than the NEDC results when WLTP inertia was increased to the requirements of TMH from GTR15. However, it should be noted that in both studies[7,13] only the WLTP inertia increased, whereas Road Load was kept the same for WLTP and NEDC and that could explain the lower WLTP CO_2 results and lower WLTP/NEDC CO_2 ratio than those found in the present study.

Figure 3A and B show the CO_2 emissions (g/km) of gasoline and diesel vehicles, respectively, as a function of vehicle test mass measured under two driving cycles/procedures. The average NEDC CO_2 emissions of all tested vehicles amount to

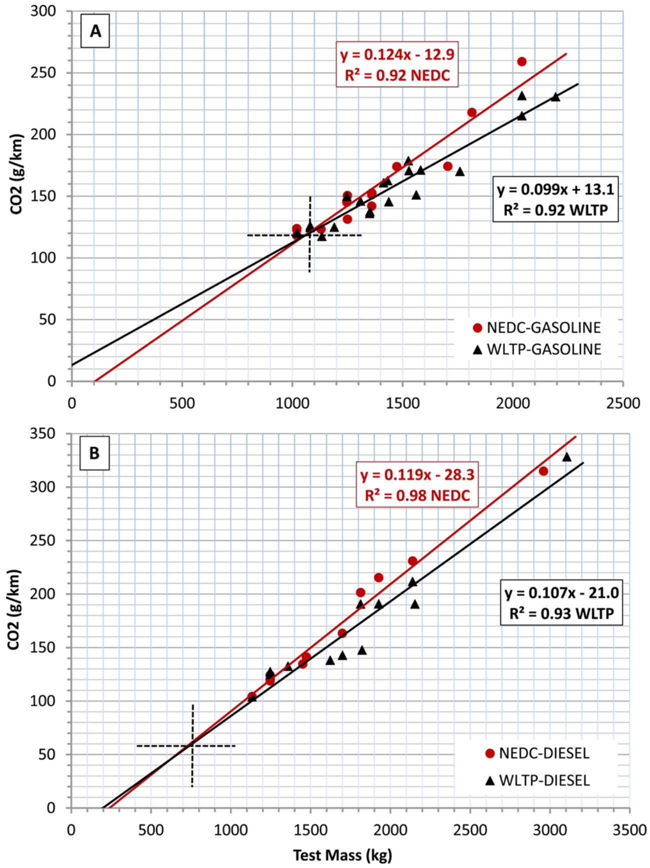

Figure 3. CO_2 emissions over NEDC and WLTP as a function of vehicle test mass for gasoline (A) and diesel (B) tested vehicles (cross points show the values where 2 lines intersect).

162 ± 49 g/km and the average NEDC tested mass is 1522 ± 470 kg. Interestingly, the average CO_2 emissions measured over the WLTP in the present study were 162 ± 45 g/km, and as expected the average WLTP vehicle inertia was higher (1627 ± 498 kg). The tested vehicles thereby exceeded, during both NEDC and WLTP, the current fleet-average performance requirements of Regulation EC 443/2009[23] by about 20%.

Although there is no statistically significant difference in slopes (t test, two-sided, 95% confidence level) for diesel and gasoline vehicles over NEDC and WLTP shown in Figure 3A and B ($p_{gasoline} = 0.06$ and $p_{diesel} = 0.30$), some general trends can be found and discussed. From Figure 3A it would appear that gasoline vehicles with test mass below about 1100 kg are penalized when moving from NEDC to WLTC/WLTP. Often gasoline vehicles with mass below 1100 kg are equipped with small engines, with limited max power. For these cars the change from NEDC to the more demanding WLTP can be quite challenging. In addition, the critical factor is not the absolute value of the vehicle mass, but the power-to-mass ratio (PMR). On the other hand, gasoline vehicles with higher test mass (and higher-powered engines) and all diesel fuelled vehicles would gain some benefit from the same transition. A similar trend was confirmed by the simulation runs for small gasoline vehicles with downsized engines (0.7L, 72 kW; 0.6L, 59 kW) that showed WLTP/NEDC CO_2 ratio of 1.14 and 1.16, respectively.[24] On the contrary, bigger gasoline and diesel vehicles in most cases (simulation and measurements) have lower CO_2 emissions in the WLTP compared to NEDC and WLTP/NEDC ratio is below 1.[13,24] Moreover, Figure 3

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suggests relatively good linear correlation between CO_2 emissions from gasoline and diesel vehicles over NEDC and WLTC on the one hand and vehicle test mass on the other hand (note the almost similar slopes of the gasoline and diesel vehicles for NEDC and WLTP vs test mass). Strong influence and correlation of vehicle test mass and CO_2 emissions were reported also before[6] when diesel and gasoline vehicles were tested under the NEDC conditions.

3.2. NO_x, CO, and THC Emissions. *3.2.1. Gasoline Fuelled Vehicles.* NO_x, CO, and THC emissions measured under the WLTP and NEDC requirements for gasoline vehicles are shown in Figure 4A–C. When more than one version of the WLTC/WLTP was measured, the emissions shown represent the average values. The NO_x emissions (Figure 4A) tested under the NEDC were between 5.8 and 37 mg/km, with an average value of 16.5 mg/km. All NEDC NO_x emissions remained below the Euro 5 and Euro 6 standard limit of 60 mg/km. The WLTP NO_x emissions for most gasoline vehicles were higher and between 7.2 and 189.6 mg/km with an average of 34.9 mg/km. However, with the exception of G01 vehicle, all WLTP NO_x emissions also remained below Euro 5/6 standard limits.

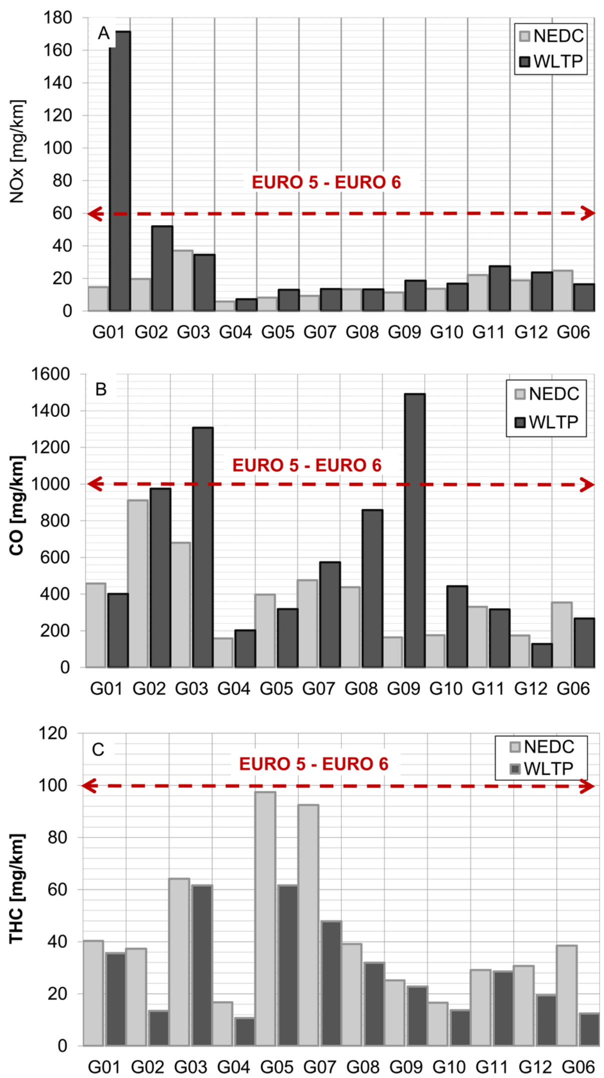

Figure 4. NO_x (A), CO (B), and THC (C) emission factors for gasoline vehicles tested under NEDC and WLTP.

The NEDC CO emissions of gasoline vehicles (Figure 4B) stay below the Euro 5/6 limit of 1 g/km and that is seen also in previous studies.[9,15,17] The average NEDC CO emissions were 392.9 ± 228.0 mg/km. The average WLTP CO emissions were 571.3 ± 423.1 mg/km and suggest an increase (~45%) in emissions due to the cycle and test procedure change. However, in the case of gasoline CO emission factors there is no clear evidence which factor (higher test mass and road load or driving cycle) have greater influence on the increase in emissions.

Some notable CO emission values above the type-approval limit were seen under the WLTP in the case of vehicles G03 and G09. These vehicles have relatively low PMR and, as previously suggested by others,[6] it is possible that their engines are tuned to low air-fuel ratio at high engine loads that are present in the new WLTP to a greater extent compared to NEDC. In line with that, bag data analysis showed significantly higher CO emissions during the WLTP's most energy demanding phase (extra high speed phase) compared to cold start and WLTP's "low" speed phase (more than 4.5 times higher emissions in the case of G09 vehicle).

THC emission levels of all gasoline vehicles tested under NEDC and WLTP (Figure 4C) remained below the Euro 5–6 type approval limits (Figure 4C). In addition to that, in almost all cases THC emissions were lower under the WLTP (average 30.2 ± 17.1 mg/km) compared to NEDC (43.9 ± 26.9 mg/km), suggesting lower weight of the cold start emissions on the WLTP compared to the NEDC emissions.

3.2.2. Diesel Fuelled Vehicles. The average NO_x, CO, and THC emissions of diesel vehicles tested under the NEDC and WLTP are shown in Figure 5A–C. The average NEDC NO_x emissions (Figure 5A) amount to 216.6 ± 90.9 mg/km with vehicles D03, D06, D07, and D08 exceeding the respective Euro limits. The average NO_x emissions of the same vehicles tested under the WLTP were significantly higher and are equal to 391.4 ± 171.3 mg/km. Under the WLTP, only the D02 stayed below the required regulation limits. It has already been reported that modern diesel cars (Euro 3–6 standards) often exceed legislated NO_x levels under normal driving condition,[3] or under laboratory test cycles different from NEDC.[6,9] Compared to these cycles, the WLTP is very similar since it has been developed to represent the real and average driving behavior of vehicles around the world. Higher NO_x emissions under the WLTP were therefore expected, additionally supporting the fact that vehicles are very likely optimized for the current type approval NEDC procedure, as also measured in previous studies.[7,13,15]

Concerning the diesel vehicles, with the exception of D04 and D05, CO emissions (Figure 5B) of all other vehicles tested under the NEDC complied with the respective Euro requirements for M_1 and N_1 vehicle categories. The average CO emissions under NEDC were 417.5 ± 228.6 mg/km. Interestingly, when diesel vehicles are tested under the WLTP the average CO emissions decrease by about 48% (average is 215.1 ± 148.8 mg/km). In addition, the vehicles D04 and D05 showed significant drop in CO emissions when tested under the WLTP and emissions stayed below Euro 4 and 5 limits. These results suggest importance of the role of cold start for diesel vehicles. In fact, the WLTP being longer and more dynamic than NEDC, has lower weight of the cold start emissions that are occurring during the warm-up phase of the oxidation catalyst, and therefore lower distance specific or total CO emissions. On the other hand, diesel vehicles never

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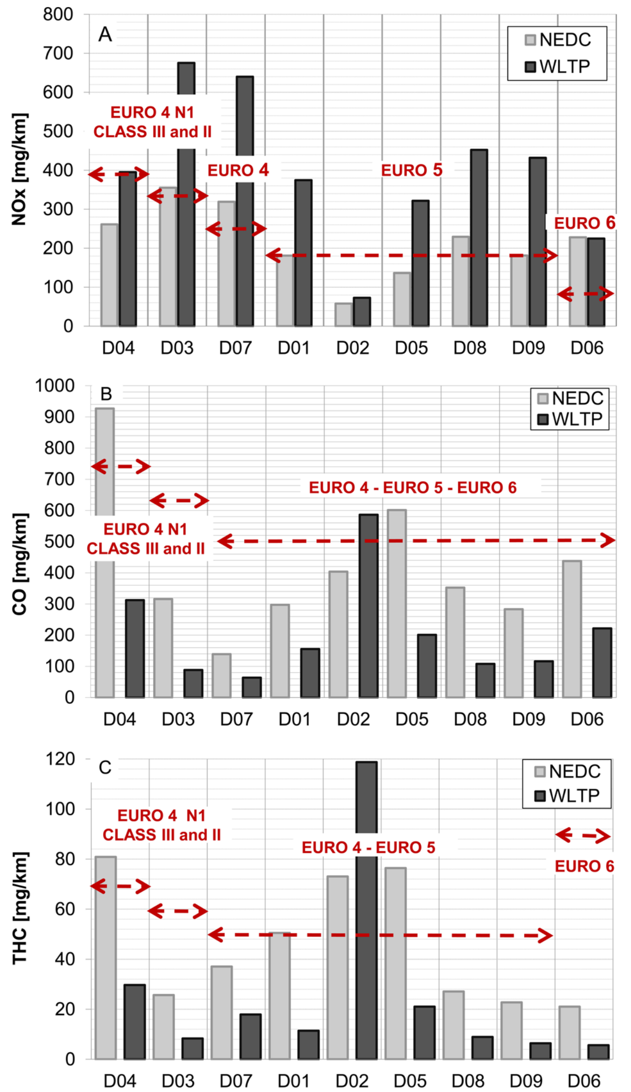

Figure 5. NO_x (A), CO (B), and THC (C) emission factors for diesel vehicles tested under NEDC and WLTP.

experience fuel rich conditions at high engine loads like the gasoline vehicles do (especially small PMR vehicles). Thus, the overall result is a net decrease of CO emissions under the WLTP (the only exception is vehicle D02, which showed a strange behavior also regarding THC emissions).

THC emissions of diesel vehicles under the NEDC and WLTP are shown in Figure 5C. Again, with the exception of vehicle D02, THC emissions under WLTP are lower than under NEDC.

This seems to suggest a general trend: for those pollutants whose emissions are mainly due to the cold start phase of the cycle (ex. THC on all vehicles, CO on diesel vehicles), moving from NEDC to WLTP brings an improvement due to the lower weight of the cold start emissions on the whole cycle and this has also been seen in previous research.[7,13,15] On the other hand, for pollutants that are emitted also during high engine load conditions (ex. NO_x on diesel vehicles and CO on gasoline vehicles) the change from NEDC to WLTP can lead to substantial emission increase.

As already mentioned, vehicle D02 showed a different trend than all other diesel vehicles tested and had higher CO and THC emissions under the WLTP. In addition, that vehicle under WLTP exceeded THC + NO_x regulatory limits. For that particular vehicle, CO and THC emissions were higher under the extra-urban phase of the NEDC and extra high speed phase of the WLTC, indicating a possible malfunction of the after-treatment system.

This study provides an initial assessment of the impact of newly developed WLTP on regulated gaseous pollutants from diesel and gasoline cars. Additional experimental data are needed to support findings presented here and to capture rapid evolutions made in the passenger car fleet. In addition, of significant interest are also future experimental activities that will evaluate influence of WLTP on particulate number emissions.

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Notes

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