Journal of Earth Sciences and Geotechnical Engineering, vol.7, no. 1, 2017, 191-214
ISSN: 1792-9040 (print version), 1792-9660 (online)
Scienpress Ltd, 2017

Quantification of the effect of WLTP introduction on passenger cars CO_2 emissions

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Abstract

In 2014 the United Nations Economic Commission for Europe (UNECE) adopted the global technical regulation No.15 concerning the Worldwide harmonized Light duty Test Procedure (WTLP) while the European Commission is now aiming at introducing the new test procedure in the European type-approval legislation in order to replace the New European Driving Cycle (NEDC) as the certification test. The current paper aims to assess the effect of WLTP introduction on the reported CO_2 emissions from passenger cars presently measured under the NEDC and the corresponding test protocol. The most important differences between the two testing procedures, apart from the kinematic characteristics of the respective driving cycles, is the determination of the vehicle inertia and driving resistance, the gear shifting sequence, the soak and test temperature and the post-test charge balance correction applied to WLTP. In order to quantify and analyze the effect of these differences in the end value of CO_2 emissions, WLTP and NEDC CO_2 emission measurements were performed on 20 vehicles. WLTP CO_2 values range from 125.5 to 217.9 g/km, NEDC values range from 105.4 to 213.2 g/km and the ΔCO_2 between WLTP and NEDC ranges from 4.7 to 29.2 g/km for the given vehicle sample.

Keywords: NEDC, WLTP, CO_2, Fuel Consumption, European Regulation.

1 Introduction

Road transport currently accounts for approximately 23% of all carbon dioxide (CO_2) emissions in the European Union (EU), of which about 2/3 come from passenger cars. Emissions from road transport have been increasing until recently

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(European Environment Agency 2014) undermining reductions made by other sectors and hampering the EU ability to meet its greenhouse gas emission commitments under the Kyoto protocol. Regulation (EC) No 443/2009, setting the target of 95 gCO_2/km for passenger cars to be achieved by 2020, aims at incentivizing investments by the car industry in new technologies and thus continue improving fuel consumption efficiency and decrease CO_2 emissions.

One of the key challenges for the European legislator is to ensure that reductions in light-duty vehicle emissions at type approval (TA) are representative of those experienced during real world driving and that the fuel consumption values communicated to the customers lay as close as possible to those actually experienced when driving the car. In parallel, the certification procedure has to provide a level playing field for competition of the various OEMs and reflect accurately the competitive advantages of different vehicles in order to support and promote the cars that exhibit better energy efficiency. Several studies have shown that actual on-road emissions and fuel consumption might be substantially higher than values reported during the type approval testing on a chassis dynamometer in testing laboratories (Weiss, Bonnel et al. 2011, Ntziachristos, Mellios et al. 2014, Tietge, Zacharaof et al. 2015, Transport & Environment 2015). One of the reasons for the discrepancy between certified and actual emissions is considered to be the current test cycle, the New European Driving Cycle (NEDC), employed for the TA tests for emissions certification of light-duty vehicles.

The existing TA test in the EU was established in the 70s to measure at the time regulated pollutant emissions but not CO_2 or fuel consumption. The testing of the latter was introduced in the 80s. It is based on the NEDC, which has received a lot of criticism and is currently considered outdated (Mock, German et al. 2013). NEDC does not represent real driving behaviour of a vehicle in actual traffic and thus, does not accurately reflect pollutant emissions and fuel consumption (Joumard, André et al. 2000). NEDC consists of smooth accelerations and decelerations which fail to reflect modern driving patterns (Kågeson 1998, Dings 2013, Marotta, Pavlovic et al. 2015). In addition, the test protocol disregards various real-world conditions like additional weight, number of passengers, use of A/C, realistic gear shifting, cold starts, operation at higher velocities and congestion (Ligterink 2012, Tutuianu, Bonnel et al. 2015), while it examines only a small area of the operating range of the engine (Kågeson 1998).

On top of that, the penetration of modern technologies and alternative drivetrains further aggravate the situation (Millo, Rolando et al. 2014, Rangaraju, De Vroey et al. 2015). The existing test procedure prescribed for plug-in hybrid vehicles mainly considers the CO_2 produced by the engine, while the CO_2 related to the electricity used to charge the battery is only partially taken into account. An experimental investigation on a downsized Euro 5 turbocharged diesel engine managing high/low pressure EGR systems revealed that brake specific fuel consumption decreases around 5-9.5% at low speed/load, 1.7-3.3% at intermediate conditions, both well represented in the NEDC, while no advantages are achieved in higher speed/load conditions (Zamboni, Moggia et al. 2016). Finally, tests in the emissions of petrol and diesel Euro 4, 5 and 6 cars at low temperatures (-7 ^{o}C), indicate that current test procedure potentially requires revisions (Dardiotis, Martini et al. 2013).

Apart from the above, specific provisions or interpretations of the current certification procedure, or absence of those, result in the measurement of lower CO_2 emission values. A series of test margins or elasticities have been identified to date like those applied on the speed profile of the test cycle, the test temperature definition, the calculation of vehicle resistances, the vehicle preparation, etc., which make the certified CO_2 value less representative (Kadijk, Verbeek et al. 2012).

The European Commission is currently addressing these open issues by leading the development of a new World-wide harmonized Light duty Test Cycle (WLTC) and a new World-wide harmonized Light-duty Test Procedure (WLTP) and by preparing the ground, including the time-frame, for their introduction in the European TA procedure.

The development of the WLTC has been carried out under a program launched by the World Forum for the Harmonization of Vehicle Regulations (WP.29) of the United Nations Economic Commission for Europe (UNECE) through the working party on pollution and energy transport program (GRPE). The aim of this project was to develop a harmonized light duty test cycle, that represents the average driving characteristics around the world and to have a legislative world-wide-harmonized TA procedure put in place from 2017 onwards.

The first roadmap for the development of the new driving cycle and test procedure was presented in 2009 and it consisted of three phases:

i. Phase 1 (2009 – 2014): development of the worldwide harmonized light duty driving cycle and associated test procedure for the common measurement of criteria pollutants, CO2, fuel and energy consumption (Type 1 test of EU type approval procedure).

ii. Phase 2 (2014 - 2018): low temperature/high altitude test procedure, durability, in-service conformity, technical requirements for on-board diagnostics (OBD), mobile air-conditioning (MAC) system energy efficiency, off-cycle/real driving emissions.

iii. Phase 3 (2018+): emission limit values and OBD threshold limits, definition of reference fuels, comparison with regional requirements.

After the finalization of WLTP (Tutuianu, Marotta et al. 2013, Tutuianu, Bonnel et al. 2015), the European Commission decided to propose its introduction in the TA procedure of light duty vehicles already in 2017. This has however an effect on the European Regulations since current CO_2 targets, established for years 2020 and 2021 based on the experience and practices of the old protocol (NEDC), must be adjusted to account for the different severity and boundary conditions of the new test procedure (Ciuffo, Marotta et al. 2015).

In order to tackle this obstacle from 2017 onwards new vehicle registrations will either be measured in both WLTP and NEDC for CO_2 monitoring purposes or it is likely that a back translation of the WLTP measured CO_2 values to their NEDC equivalent will be performed by means of computer simulation, using a dedicated software tool. In order to support this process and provide a first assessment of the impact of the introduction of WLTP in the certification system a series of measurements on real vehicles were performed under both the NEDC and WLTP protocol.

The current paper starts from the results of these measurements and focuses on quantifying the effect of WLTP Regulation, when compared to the NEDC. The results presented here refer to the higher driving resistance configuration of the WLTP (WLTP-High).

2 Methodology

For the scope of this study, and in order to analyze the effect of the introduction of the new test procedure to the European legislation, a series of pollutant and CO_2 emission tests have been performed for a total of 20 passenger cars under the two protocols, NEDC and WLTP-High. The complete test protocol and specifications for some of the tested vehicles can be found in (Tsokolis, Tsiakmakis et al. 2015). In the current paper, a wider vehicle sample is presented, focusing only on CO_2 emissions. The specifications of the vehicles are given in Table 1.

Table 1: Specification of the measured vehicles in NEDC and WLTP-High.

Fuel	**Vehicle**	**Emission Standard**	**I*/A**/T*** **	**Start/Stop**	**Displacement [cc]**	**Max Power [kW]**	**Max Torque [Nm]**	**Curb mass [kg]**
Gasoline	G01	EURO5	PFI/NA/MT6	YES	1368	125	250	1290
	G02	EURO5	DI/T/MT6	YES	1798	125	318	1450
	G03	EURO6	DI/T/MT6	YES	1600	100	240	1300
	G04	EURO5	DI/T/AT8	YES	1995	180	350	1510
	G05	EURO5	PFI/NA/MT5	YES	875	77	145	930
	G06	EURO5	PFI/NA/MT5	YES	1368	57	115	1025
	G07	EURO5	DI/T/MT6	YES	999	92	170	1179
	G08	EURO5	DI/T/AT7	YES	3498	200	370	1635
	G09	EURO5	PFI/NA/AT5	YES	999	52	92	750
	G10	EURO5	DI/T/AT6	NO	2497	187	360	1456
	G11	EURO5	DI/T/MT5	NO	1197	66	160	1102
	G12	EURO5	DI/T/AT6	YES	1390	110	240	1623
Diesel	D01	EURO5	DI/T/AT8	YES	2967	190	580	1880
	D02	EURO5	DI/T/MT6	YES	1995	120	380	1465
	D03	EURO5	DI/T/MT5	NO	1248	55	190	1090
	D04	EURO5	DI/T/AT7	NO	2030	120	360	2030
	D05	EURO5	DI/T/MT5	YES	1248	70	190	1393
	D06	EURO5	DI/T/AT6	NO	1686	95	300	1309
	D07	EURO6	DI/T/MT6	YES	1598	90	320	1601
	D08	EURO5	DI/T/MT6	YES	1560	82	270	1293

***I** = Injection: DI = Direct Injection; PFI = Port Fuel Injection
****A** = Aspiration: T = Turbo; NA = Naturally Aspirated
*****T** = Transmission: ATn = Automatic Transmission with n gears, MTn = Manual Transmission with n gears

The above measurements are complemented with a step-by-step simulation exercise, allowing the better identification of the sources of differences between the two test protocols, and a further quantification and assessment of the individual effects. The simulation tool used is the AVL's CRUISE, a tool to perform vehicle CO2 emission simulations and powertrain analysis (AVL 2016). For this activity, two out of thirteen validated vehicle models were used; one small size gasoline (G11) and one medium-large size diesel passenger car (D02), considered to be representative for the current European fleet.

The simulation approach adopted is as follows: both vehicle models are set up to run a WLTP-High. Then, one at a time, a test parameter is modified according to the NEDC protocol, and a new simulation run is performed; i.e. first the test mass is changed, then the RL coefficients, then the driving profile, the gear shifting sequence etc.

3 Results and discussion

The following paragraphs present the main results in terms of the effect on CO_2 emissions between the two protocols as regards the most influential differences between the NEDC and WLTP which are: the driving profile, the vehicle mass (inertia) and road load determination, the chassis preconditioning, the gear-shifting procedure, the temperature, and the REEES (Rechargeable Electric Energy Storage System) Charge Balance (referred to as RCB) correction.

Measurement results

Figure 1 presents the median cold WLTP-High CO_2 bag results vs the median cold NEDC CO_2 bag results for all measurements conducted for the two driving cycles. The pool of tested vehicles included diesel and gasoline fueled engines, with direct or port fuel injection, turbo or naturally aspirated, equipped with manual or automatic transmission, conventional or mild hybrid equipped with Start/Stop (S/S) and regenerative breaking. The presented NEDC and WLTP-High results are not corrected for RCB. As explained above, it is expected that the WLTP-High CO_2 values will be higher, if the RCB correction is included, while no RCB correction is foreseen for NEDC.

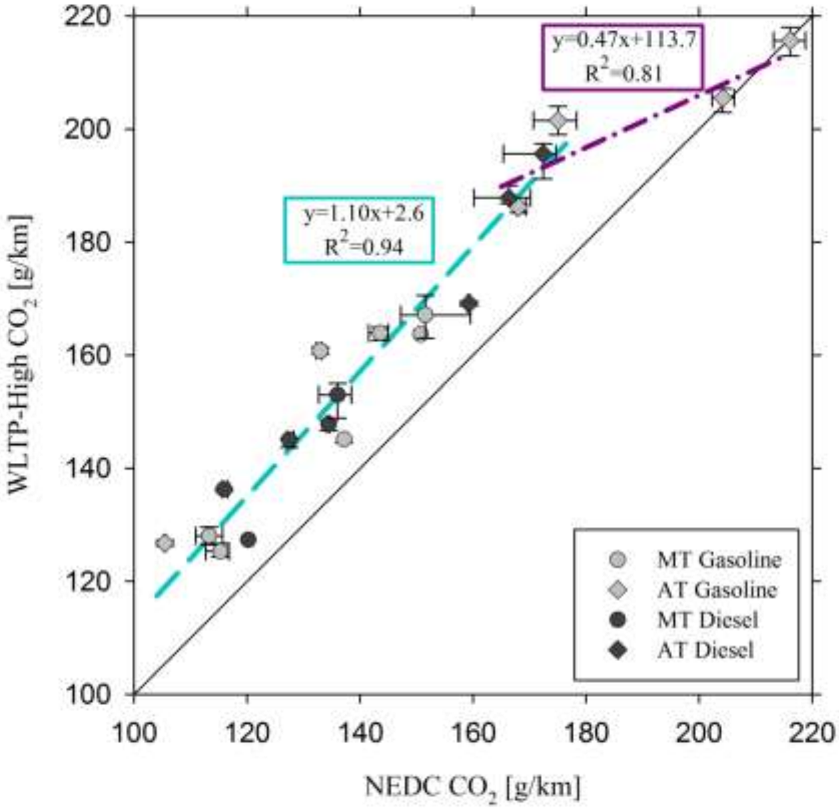

Figure 1: WLTP-High vs NEDC CO_2 measurements for 20 different passenger cars. The points correspond to the median of one to five measurements. The standard deviation of vehicle can also be seen. The dashed trend line corresponds to the increasing trend of WLTP-High vs NEDC CO_2 emissions, while the dotted line corresponds to the decreasing trend.

The WLTP-High vs NEDC CO_2 results can be divided in three main areas according to their NEDC value. The first consists of small, medium and medium-large vehicles with measured CO_2 emissions from 100 to 160 g/km; the second narrow region consists of medium-large and large vehicles with emissions from 160 to 180 g/km and the third consists of executive vehicles with measured NEDC emission values above 180 g/km. In the first area, almost all vehicles were equipped with manual transmission, while the rest were equipped with automatic transmission exclusively.

The WLTP-High results in the range from 100 to 180 g/km demonstrate an increasing trend over the y=x line, especially determined by the vehicles that belong to the second area which can be characterized as "transitional". Currently, vehicles equipped with automatic transmission are optimized, in terms of gear shifting strategy, to perform best over the NEDC. The measured CO_2 emissions from these vehicles is expected to deliver higher NEDC and lower WLTP values in the future, assuming that the automatic gear shifting strategy will be optimized for the WLTP. Thus, two trends are observed: an increasing trend in the area with WLTP-High CO_2 emission values from 100 to 180 g/km with characteristic y=1.10x+2.5, R^2=0.94 and a decreasing trend in the area from 180 to 220 g/km with characteristic y=0.47x+113.7, R^2=0.81.

Driving profile analysis

A significant improvement in the WLTP Regulation is that, in contrast to the NEDC, the driving profile is different for the various vehicles according to their Power to Mass ratio (PMR), which is defined as the ratio of rated power (in Watts) to the curb mass (in kg). Two driving profiles characteristic for low powered vehicles are defined for PMR ≤ 22 (WLTC class 1) and 22 < PMR ≤ 34 (WLTC class 2). For the rest, vehicles with PMR > 34, WLTC class 3 should be used (Tutuianu, Marotta et al. 2013). Most passenger cars fall in the WLTC class 3 category. Since some vehicles close to the borderline PMR values may present drivability problems in high speeds, a downscaling is applied to the speed profile further enhancing the closer-to-reality features of the new approach.

The kinematic characteristics of NEDC and WLTC (Demuynck, Bosteels et al. 2012, Kühlwein, German et al. 2014), as well as their potential effect on pollutant formation (Joumard, Rapone et al. 2006, Sileghem, Bosteels et al. 2014) and CO_2 emissions (Bielaczyc, Woodburn et al. 2014, Mock, Kühlwein et al. 2014) have been sufficiently covered by the scientific community so far. The basic characteristics of NEDC and WLTC class 3, are described in

Table 2. Compared to WLTC, NEDC is characterized by shorter duration and distance, longer idling and cruising time and lower speed and acceleration (Figure 1). In addition, a single vehicle operates in lower engine speed and load over the NEDC, which is not representative of real world driving. Although WLTC driving profile is more transient than NEDC, when these two cycles are been tested under the same driving resistance in Euro 5 vehicles, then in most cases WLTC delivers CO_2 results that do not significantly differ from NEDC’s (Favre, Bosteels et al. 2013, May, Bosteels et al. 2014, Bielaczyc, Woodburn et al. 2015). The same trend stands for Euro 6 vehicles (Andersson, May et al. 2014, Bielaczyc, Szczotka et al. 2015) and different ethanol fuel blends on gasoline vehicles (Suarez-Bertoa, Zardini et al. 2015).

Table 2: Basic characteristics of NEDC and WLTC class 3.

	NEDC	**WLTC class 3**
Distance [km]	11.023	23.262
Duration [s]	1180	1800
Idle time [s]	280	235
Phases [#]	2	4
Average speed /w idle (w/o idle) [km/h]	33.6 (44.7)	46.5 (53.5)
Max speed [km/h]	120.0	131.3
Max acceleration [m/s^2]	~1.0	~1.7

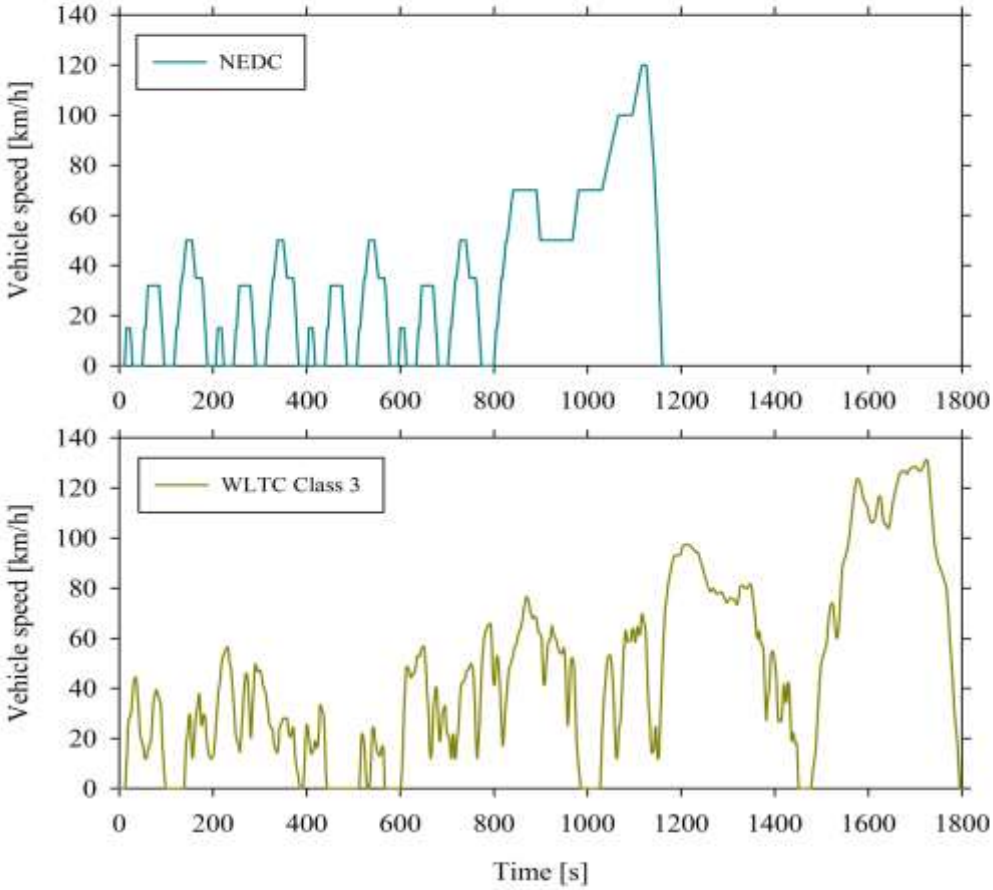

Figure 2: NEDC and WLTC class 3 driving profiles over time.

Test protocol

WLTP substantially differs from the NEDC in the preparation of the vehicle for testing and the post-test management. The latter mainly concerns the corrections applied in the CO_2 values to account for the different contribution of each vehicle's electrical system; a correction which is of crucial importance given the high penetration of micro and mild hybridization systems to modern cars.

A summary of the differences between WLTP and NEDC is given in Table 3. Each of these differences is explained in the following paragraphs.

Table 3: Differences between the NEDC and WLTP measurement protocol.

		NEDC	WLTP
Mass	**Test**	Reference mass: Unladen + 100 kg	TMH ("worst" case) and TML ("best" case) defined from min/max unladen mass and max laden mass

	Inertia	Inertia classes	Inertia mass = Test mass
	Rotating parts	Not applied	+1.5% for 1-axle chassis dyno
Road load	**Origin**	Provided by manufacturer – derived by the coast-down method	Calculated from NEDC RL taking into account masses, Cd*A, tyres – derived by the coast-down method in future
	Preconditioning	Vehicle and gear box type dependent (typical values 0 to 20 N)	
Driven wheels	**4WD**	1-axle dyno allowed	2-axle dyno mandatory
Engine	**Preconditioning**	1 NEDC + 1 EUDC (gasoline) 3 EUDC (diesel)	WLTP
Gear shifting		Fixed points	Vehicle specific - derived from a function of mass, RL, drivetrain, full load curve
Temperature	**Soak**	20 to 30 °C	23 °C ± 3 °C
	Oil, coolant	± 2°C to soak temperature	23°C ± 2°C
	Test initiation	25 °C ± 3 °C	23 °C ± 3 °C
RCB Correction		Not applied	Post-test correction

Mass, road load and driven wheels

The procedure which determines the road load (RL) or driving resistance coefficients over the NEDC presents a series of flexibilities which allow lower driving resistances to be applied for the test (Tietge, Zacharaof et al. 2015). These RL coefficients are characteristic for the total driving resistance provided by Equation (1).

$$F = F_0 + F_1 \cdot V + F_2 \cdot V^2 \tag{1}$$

where F represents the total driving resistance in N, F_0 the constant coefficient in N, F_1 the linear coefficient in N/(km/h), F_2 the quadratic coefficient in $N/(km/h)^2$ and V the vehicle velocity in km/h.

Achieving lower driving resistance can become feasible by using e.g. low resistance tires or the best aerodynamic and most light weighted version of the same vehicle model during coast down. Additionally, the test mass in NEDC is determined by inertia classes which creates discontinuities in a physical quantity that in reality is continuous and which has significant influence on CO_2 emissions. In WLTP, the RL coefficients for a single vehicle are produced by taking into account its minimum and maximum unladen mass, which is defined as the vehicle's standard weight without driver, fluid or any additional equipment, the maximum permissible weight, the difference in rolling resistance between different tire versions, as well as the difference in aerodynamic resistances expressed as the product of the drag coefficient and the frontal area ($C_d \cdot A$) between the vehicle model with the best and worst aerodynamics. Then, two sets of RL and test mass values are produced; one set characteristic of the best case vehicle (WLTP-Low or WLTP-L), which is the vehicle that is expected to have the lowest energy demand, and one of the worst case vehicle (WLTP-High or WLTP-H), the vehicle of highest energy demand. The equations that were used to calculate the RL coefficients for WLTP can be found in the respective Regulation (Tutuianu, Marotta et al. 2013).

Figure 3 presents different coast down curves for a medium size vehicle. With the NEDC inertia mass and RL coefficients, this vehicle decelerates from 135 km/h to 0 in 215 seconds. Similar coast down time to NEDC is calculated for the WLTP-Low case. In contrast, WLTP-High is associated with lower deceleration time, approximately 180 s. Additionally, individual coast down test performed indicate total deceleration time 20% less than NEDC. The divergence between these individual tests and WLTP-High may be attributed to the experimental difficulties of performing such tests, since they are not fully controlled and identical (wind intensity and direction, road slope, road surface quality, type of tires used etc). Still, a part of the discrepancy between WLTP-High and the real world is expected to remain in the future and possibly rise further (Tietge, Zacharaof et al. 2015).

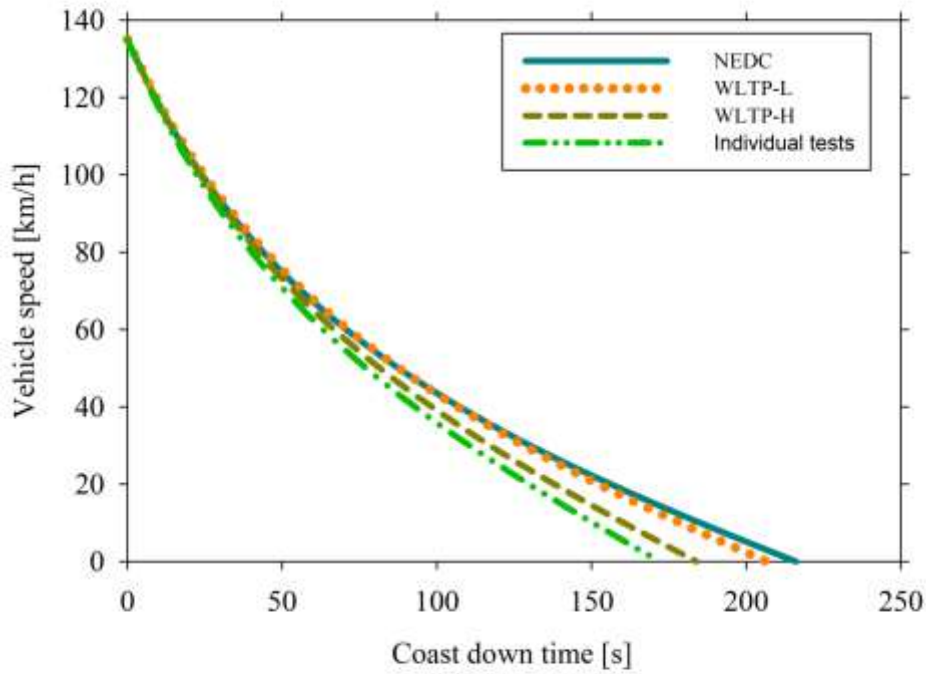

Figure 3: Coast down time for a medium size vehicle.

Chassis preconditioning

Throughout the course of this work, as refereed for example in (Tsokolis, Tsiakmakis et al. 2015), it was found that the preconditioning of the chassis dynamometer and the vehicle, during the adjustment of the driving resistance on the dyno, plays a non-negligible role on the CO_2 emissions of the tested cycle. This comes as a direct result of the different resistance that is applied on the vehicle over a driving cycle.

This driving resistance consists of two components: the resistance applied by the electric system ("electric force", F_{el}) and the friction ("friction force", F_{fr}). The latter comes from the internal dyno components (such as bearings, the friction of which cannot be zeroed) and the drivetrain of the vehicle (mainly the gearbox, the differential and the tires). Hence, the total force is:

$$F_{tot} = RL = F_{el} + F_{fr} \tag{2}$$

While the former part, F_{el}, depends only on the parameters of the electrical machines, F_{fr} is a function of the thermal state of the test installation. Thus, the hotter the dyno and the vehicle the lower the friction force.

This can be better explained if the two cycles of interest, NEDC and WLTC, are considered. Since WLTC has longer duration and reaches higher speed than NEDC, a single vehicle will be warmer after WLTC than after NEDC (evidently after a start at the same conditions). Since the target is to apply the same F_{tot} in the chassis dyno, different result will be obtained if the chassis setup is performed after a NEDC or a WLTC (or another driving cycle).

Figure 4 shows the effect of different preconditioning on CO_2 emissions. In one case the vehicle was preconditioned by running a NEDC cycle, while in the other case by running for 1180 s at an approximately constant speed in the range 35 - 40 km/h. The results indicate that the average effect in terms of CO_2 emissions is 5 g/km. In the constant speed preconditioning, in fact, the vehicle reached higher temperature, translated in lower F_{fr}, and thus the applied F_{el} by the dyno is higher, so as to achieve the same F_{tot}. This explains the higher CO_2 emissions during the testing of the same driving cycle.

Running as preconditioning a complete WLTC (longer and more dynamic cycle), the results present higher variability for the specific combination of vehicle and tires. An average difference of around 1 gCO_2/km is measured, but for some vehicles this figure goes up to 3-4 gCO_2/km.

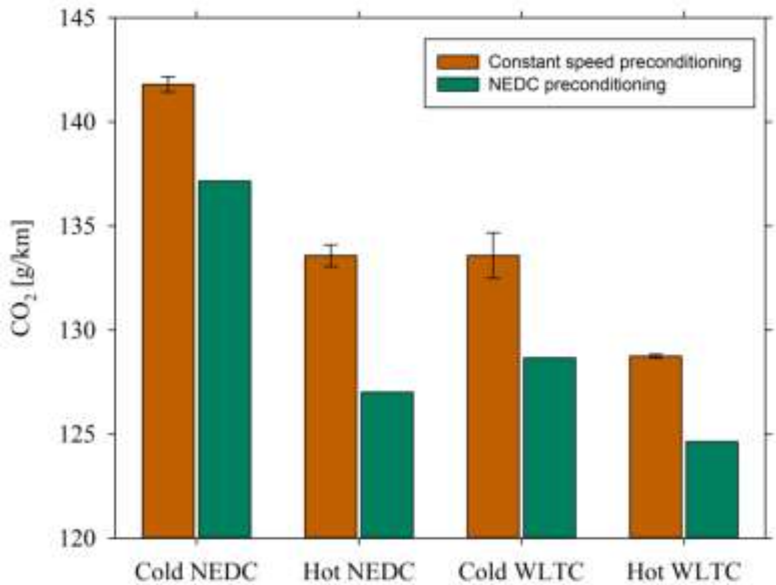

Figure 4: CO2 effect of different chassis preconditioning in NEDC and WLTC for a small 5-gear MT gasoline vehicle.

Gear shifting

This refers to the procedure that defines the gear shifting in WLTP for manual transmission (MT) vehicles; in automatic transmission (AT) vehicles this procedure is not applicable. In NEDC, fixed gear shifting points are defined, without taking into account the different drivetrain configurations. In WLTP first the required (from the driving profile) and available (from the vehicle) power are calculated, then a predefined algorithm decides which gear should be used (Tutuianu, Marotta et al. 2013). This algorithm was designed in a way to emulate the gear shifting experienced in real world driving from normal drivers. As a result, it is highly unlikely for the gear shifting sequence of two randomly selected vehicles to be exactly the same, similar to reality. The generated gear shifting sequence for one diesel and one gasoline vehicle with the characteristics shown in Table 4 is illustrated in Figure 5. Although the driving pattern is the same, the exact shifting points are different due to the differences in the vehicle drivetrain configurations.

Table 4: Vehicle characteristics for the calculation of gear shifting in WLTP-High for two medium size vehicles. For the mass and road load parameters, the delta between these two vehicles is presented if the diesel parameters are used as baseline.

Gear shifting input	Diesel vehicle	Gasoline vehicle
Idle engine speed [RPM]	830	750
Engine speed at maximum power [RPM]	4000	5500
Maximum power [kW]	120	125
Engine to vehicle speed ratio for 1st gear	98.92	134.85
Engine to vehicle speed ratio for 2nd gear	54.14	73.23
Engine to vehicle speed ratio for 3rd gear	33.69	51.31
Engine to vehicle speed ratio for 4th gear	24.06	38.59
Engine to vehicle speed ratio for 5th gear	19.25	31.02
Engine to vehicle speed ratio for 6th gear	15.88	26.52
Delta in curb mass [kg]	-	-200
Delta in WLTP-High mass [kg]	-	-231
Delta in WLTP-High F0 [N]	-	-5.8
Delta in WLTP-High F1 [N/(km/h)]	-	0.0561
Delta in WLTP-High F2 [N/(km/h)^2]	-	0.0025

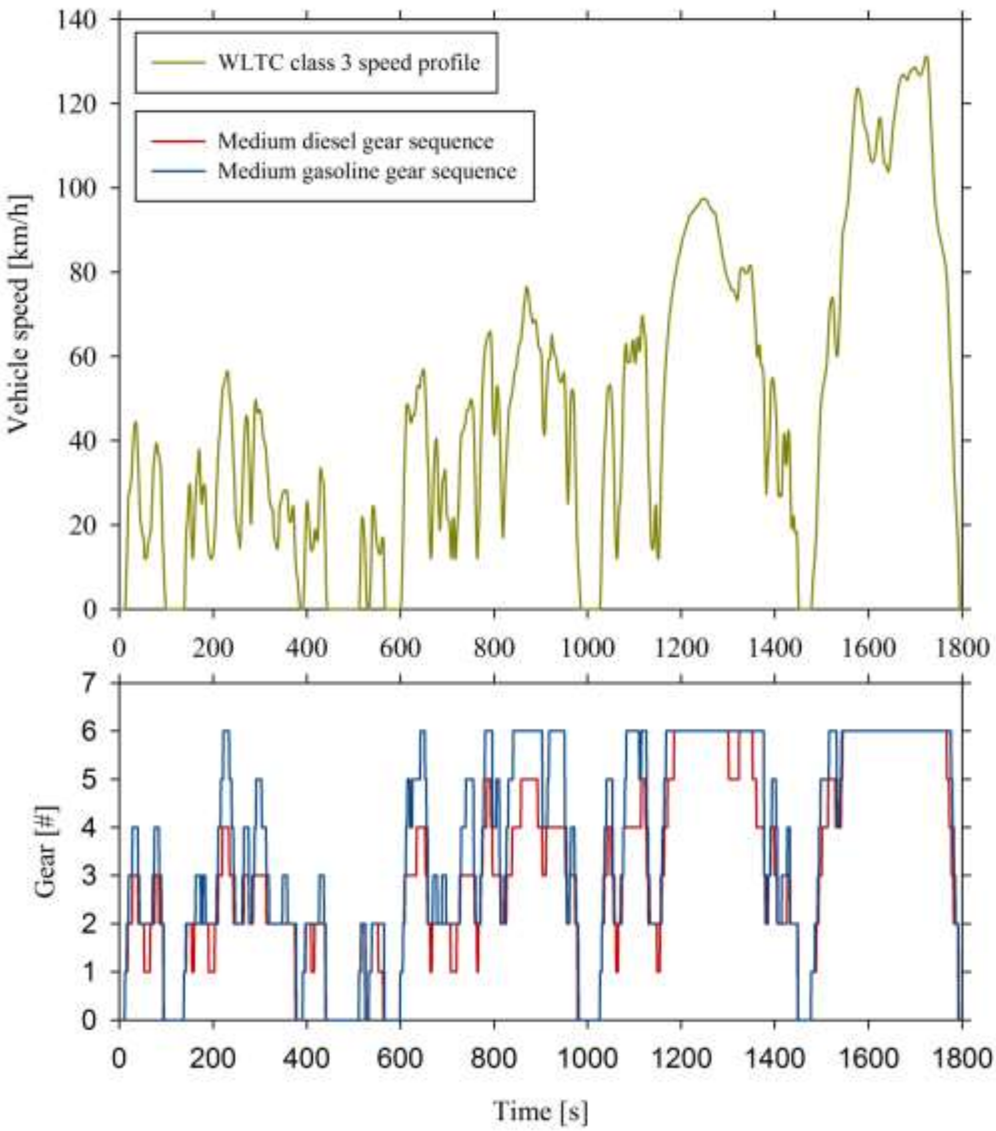

Figure 5: Gear shifting sequence in WLTC for one medium diesel and one medium gasoline vehicle.

One way to investigate the gear shifting effect on WLTP CO_2 emissions is to perform for the two vehicles described in Table 1 (G11, D02), two series of simulations; one with the WLTP-generated gear shifting profile and another with fixed points similar to the NEDC regulation. In both simulations, the total CO_2 emissions were found 1 g/km for the diesel and 6 g/km for the gasoline higher when the NEDC fixed gear shifting points were used. Since the generated gear shifting profile is a function of vehicle specific parameters, it is not odd that the simulated CO_2 effect is not the same for these two case studies.

Temperature

While in NEDC the soak and the test temperature is set between 20 and 30 ^{o}C, in WLTP the respective figure is 23±3 ^{o}C for both temperatures. These temperatures are not representative of Europe's average annual temperature and even less when compared to Northern Europe's annual average temperature (European Environment Agency 2015). EU is planning to adopt a WLTP test with initial test temperature set at 14 ^{o}C, which is closer to the European average.

The temperature difference is expected to have an impact mainly on cold start, which for NEDC is more pronounced given the overall shorter duration of the cycle and the milder driving profile during its first part.

RCB correction

Another parameter that is different between the two procedures is the RCB correction applied to WLTP. So far, the type approval measurement is performed in charge depleting mode because the NEDC regulation does not give any specific prescriptions concerning the state of charge of the battery at the commencement of the test. Therefore, it is common practice to fully charge the battery before the test in order to minimize any extra fuel consumption due to the electrical system. In WLTP, a post-test correction is applied to the measurement, correcting the final CO_2 emissions and fuel consumption value with the total charge balance. The RCB correction is described in Equation (3).

$$RCB\ CO2\ correction = \frac{\Delta RCB \cdot V_{bat} \cdot Willans\ Factor}{1000 \cdot Alternator\ Efficiency\ \cdot Distance} \quad (3)$$

where the RCB correction is expressed in g/km, ΔRCB is the RCB difference before and after the measurement in Ah, V_{bat} the nominal voltage of the battery in V, the fuel specific Willans Factor in gCO_2/kWh and the Distance expressed in km. For the Alternator Efficiency typical values are in the order of 0.66-0.67.

Results from four WLTP measurements for a single vehicle and the respective RCB corrections are shown in Figure 6. The tests were performed starting with fully charged battery, discharging during the measurement. When the contribution of the battery is taken into account, the declared value over WLTP is higher than the measured due to the RCB correction. The extra CO_2 produced due to the correction is also shown as charge balance equivalent. The extra consumption due to the battery operation of these tests was on average 9 Ah or 4.6 gCO_2/km. Since this correction was not performed in the NEDC, it is expected that manufacturers will optimize the operation of the electrical system in such a way, as to minimize any additional CO_2 and at the same time maximize the gain from electrical systems such as the Break Energy Recuperation System. The contribution of the electrical system is expected to be different among individual vehicles due to the different requirements and operation strategies.

Simulation results

In order to quantify the differences between the two test procedures, simulation models have been set up, and run sequentially changing one parameter at a time. The delta between WLTP-H and NEDC (ΔCO_2) which is produced from modifying one parameter is shown in Figure 7 for a small gasoline vehicle and in Figure 8 for a medium-large diesel vehicle.

For both vehicles, the largest proportion of the overall ΔCO_2 between WLTP-High and NEDC is due to the change in the RL; 42% for the diesel vehicle and 50% for the gasoline vehicle. If chassis preconditioning is added to RL differentiation, the proportions become 55% and 74% respectively. Significant is also the impact of the different test mass used in WLTP-High, which is calculated to 21% for the diesel and 31% for the gasoline vehicle.

Test parameters such as the driving profile, the gear shifting and the RCB correction may have a negative impact on ΔCO_2. The sum of the contributions of RL, test mass and chassis preconditioning, exceeds 100% in the case of gasoline vehicles. Although it was expected that with a more aggressive driving profile, compared to NEDC, the divergence between type approval and real world fuel consumption would drop, it was proven otherwise in both EURO 5 (Favre, Bosteels et al. 2013, May, Bosteels et al. 2014, Bielaczyc, Woodburn et al. 2015) and EURO 6 vehicles (Andersson, May et al. 2014, Bielaczyc, Szczotka et al. 2015), as well as when alternative fuels were used (Suarez-Bertoa, Zardini et al. 2015). This may be attributed to the fact that the vehicles are generally driven in a more fuel efficient area for a longer period, which for WLTP is a function of the drivetrain, the engine map, the RL and the generated gear shifting. For the small gasoline vehicle the driving profile had an absolute impact of 0.2 gCO_2/km whereas for the diesel vehicle the impact was 2.1 gCO_2/km. On the other hand, the WLTP gear shifting reduced CO_2 emissions for the gasoline vehicle by 0.9 g/km, while in the diesel vehicle the same figure was less than 0.1 g/km. This was investigated by running WLTC with the NEDC gear shifting strategy.

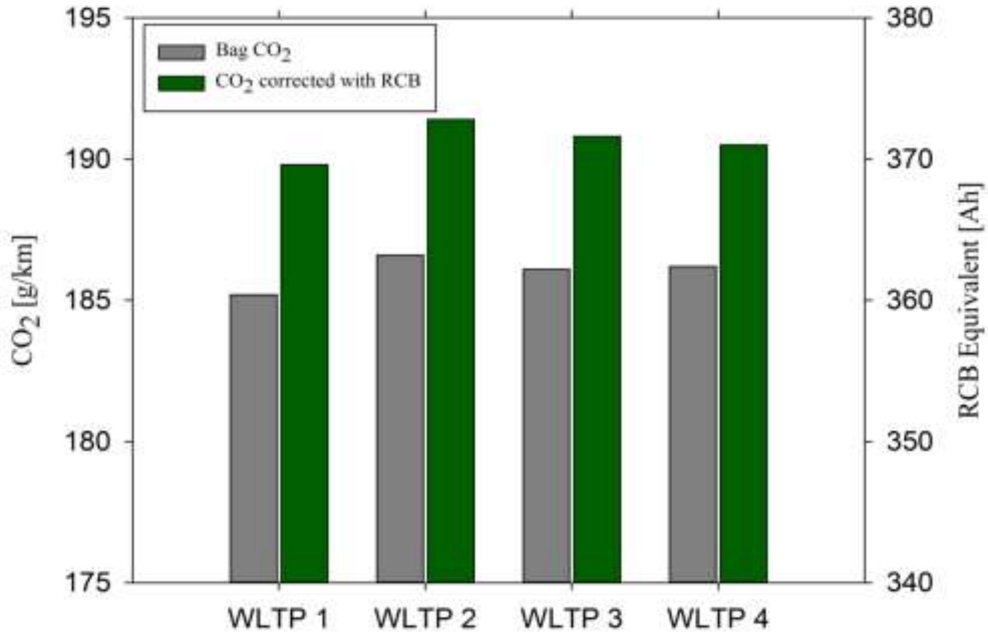

Figure 6: WLTP measurements corrected with RCB for a large gasoline vehicle.

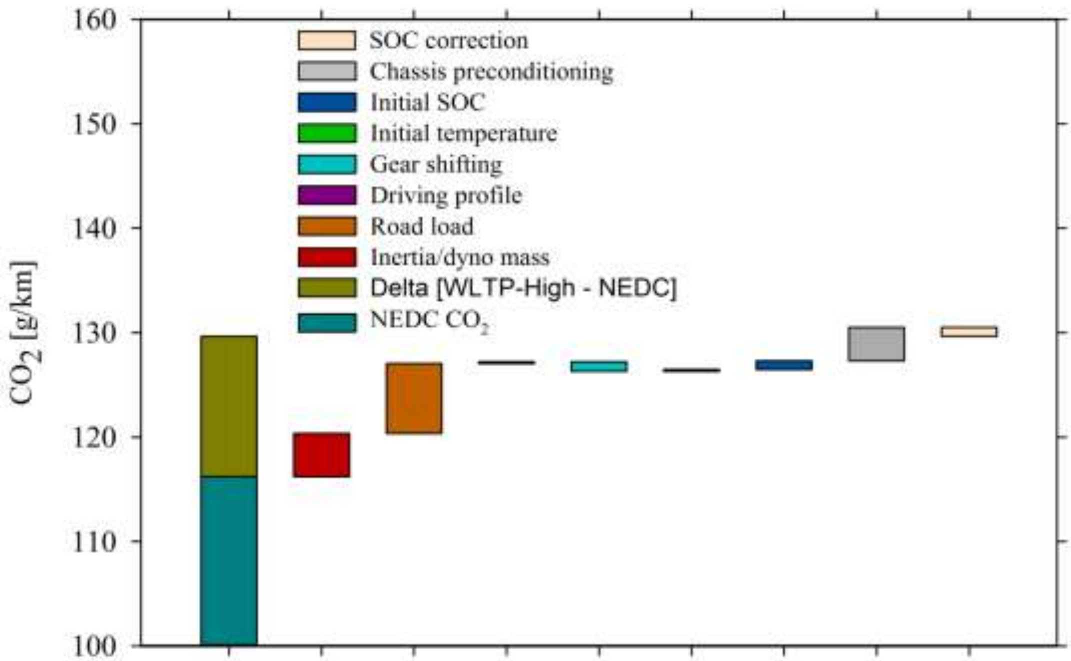

Figure 7: Step-by-step simulated ΔCO_2 between WLTP and NEDC for a small gasoline passenger car.

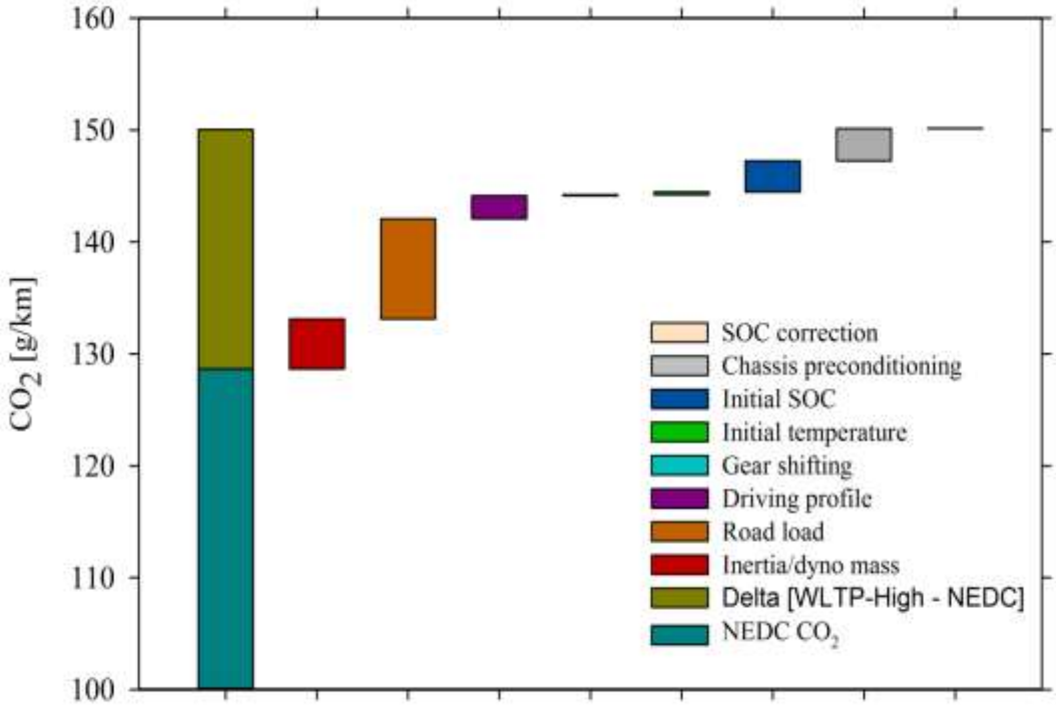

Figure 8: Step-by-step simulated ΔCO_2 between WLTP and NEDC for a medium-large diesel passenger car.

In the specific simulations, the battery SOC effect is investigated by changing its initial value from maximum, which is used in NEDC, to the battery's charge sustain mode operation value, which it is believed that will be used in WLTP. This modification in the simulations has an effect of 13% for the diesel vehicle and 6.1% for the gasoline vehicle in ΔCO_2. If the final CO_2 values are corrected with RCB from Equation (3), the overall effect for the diesel vehicle remains constant, while surprisingly the effect of the gasoline vehicle is -6.5%, despite the fact that the same electrical system was used for the two vehicles. This highlights the fact that a detailed investigation regarding the optimum initial SOC should be conducted for the gasoline vehicle, in order to minimize the CO_2 correction. Finally, in both vehicles the effect of decreasing the initial test temperature from 25 ^{o}C to 23 ^{o}C, accounts for less than 1% in the overall ΔCO_2.

4 Conclusion

CO_2 emission tests for 12 gasoline and 8 diesel passenger cars were performed under the NEDC and WLTP. These tests were used for the calibration and validation of a simulation tool used in the context of the WLTP-NEDC correlation exercise. The current work analyses the differences between the two protocols, and starting from the test results, quantifies the effect of WLTP on CO_2 emissions from passenger cars and comparing it with those of the NEDC.

The two measurement protocols differ in the driving profile and kinematic characteristics, in the determination of the test mass and applied driving resistance, in the gear shifting sequence and RCB correction and in the initial and soak temperature. From the above, the dominant reason for the difference between the WLTP-High and the NEDC was found to be the different test mass and the applied RL coefficients in the chassis dynamometer. These parameters, based on a simulation exercise in a small gasoline and a medium-large diesel car, were found to account for up to 74% in the observed ΔCO_2 between WLTP-High and NEDC.

Comparing cold start WLTP-High against NEDC, two trends were identified as characteristic for the vehicle sample; an increasing trend above the y=x line for emissions from 100 to 180 g/km over NEDC and a decreasing trend from 180 to 220 g/km over the NEDC. In the area of 160-180 g/km belong medium-large automatic transmission vehicles, whose gear-shifting strategy is currently optimized over the NEDC and in the future is expected to be optimized over the WLTP; thus this area is characterized as “transitional”. The delta between CO_2 emissions over WLTP-High and NEDC is decreasing as the CO_2 emissions values over NEDC are increasing.

The increase of certified CO_2 emissions when moving from NEDC to WLTP originates from a driving cycle and an overall test procedure, which more closely represents realistic vehicle operation. Introducing WLTP in the type-approval of light duty vehicles therefore represents an important step-forward in the direction of decarbonizing the road transportation sector and of providing customers with more reliable information. Optimizations towards the new procedure by vehicle manufacturers will still be possible, and possibly the overall increase in CO_2 will slightly decrease. But since vehicles will need also to comply with the Euro 6 emission limits on WLTP (for which no adjustment will be carried out) and on the RDE (although with some additional margins), flexibilities will in any case be limited.

Acknowledgments

The authors would like to acknowledge the contribution of the following institutes and their associated personnel in the framework of the NEDC-WLTP correlation exercise: European Commission, TNO, DEKRA, FIAT, Horiba, VELA labs at JRC-Ispra, TU Graz, TUV Nord and UTAC.

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