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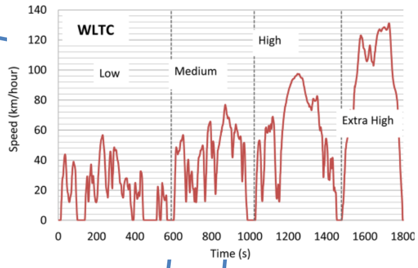

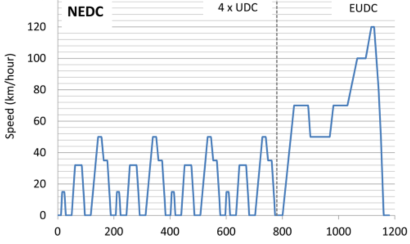

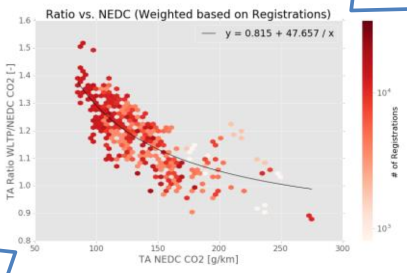

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From NEDC to WLTP: effect on the type-approval CO_2 emissions of light-duty vehicles

The present report summarises the work carried out by the European Commission's Joint Research Centre to estimate the impact of the introduction of the new type approval procedure, the Worldwide Light duty vehicle Test Procedure (WLTP), on the European car fleet CO_2 emissions.
To this aim, a new method for the calculation of the European light duty vehicle fleet CO_2 emissions, combining simulation at individual vehicle level with fleet composition data is adopted. The method builds on the work carried out in the development of CO2MPAS, the tool developed by the Joint Research Centre to allow the implementation of European Regulations 1152 and 1153/2017 (which set the conditions to amend the European CO_2 targets for passenger cars and light commercial vehicles due to the introduction of the WLTP in the European vehicle type-approval process).
Results show an average WLTP to NEDC CO_2 emissions ratio in the range 1.1-1.4 depending on the powertrain and on the NEDC CO_2 emissions. In particular the ratio tends to be higher for vehicles with lower NEDC CO_2 emissions in all powertrains, the only exception being with the plug-in hybrid electric vehicles (PHEVs). In this case, indeed, the WLTP to NEDC CO_2 emissions ratio quickly decreases to values that can be also lower than 1 as the electric range of the vehicle increases.

Contents

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Disclaimer

Executive summary

The present report presents the results of a study aimed at analysing the impact on the European light duty vehicle fleet CO2 emissions of the introduction of the Worldwide Light duty vehicle Test Procedure (WLTP) in the European vehicle type-approval process.

The calculations made in this report for conventional vehicles rely mainly on the use of the PyCSIS (Passenger Car fleet emissions SImulator) model, which was developed on the basis of CO2MPAS (CO2 Model for PAssenger and commercial vehicles Simulation), the model used in the phasing-in of the WLTP for the adaptation of the CO2 targets for light duty vehicles to the new test procedure[1]. However, while CO2MPAS depends on the test results of individual vehicles, PyCSIS makes use of limited information, referring mainly to already available data sources and using empirical models and information collected from measurements at the Joint Research Centre of the European Commission. The methodology was applied to assess the impact of the introduction of the new CO2 certification procedure in Europe on the vehicle fleet CO2 emissions. The main results of this calculation are reported in Table E.1 for passenger cars and in Table E.2 for light commercial vehicles. For conventional, internal combustion engine (ICEV) passenger cars, the PyCSIS model has been applied to all new registrations of year 2015. For battery electric, plug-in hybrid electric, and hybrid electric vehicles, a different approach has been used due to the limited number of such vehicles sold in the European market in 2015. For this reason, in the table below only the WLTP to NEDC ratio is shown for these vehicle segments and not the NEDC values.

Considering the certification values for CO2 emissions, results for ICEV passenger cars show an average WLTP to NEDC CO2 ratio of 1.21 (sales weighted average across the fleet). The ratio is higher for cars with lower NEDC emission values, while at very high emission levels (about 250 CO2 g/km) WLTP and NEDC lead to comparable results between the two procedures. Similar trends are found for light commercial vehicles, with a slightly higher average ratio for passenger cars (~1.3).

Results for battery electric (BEVs) and fuel cell vehicles (FCVs) show an expected average WLTP to NEDC electric energy ratio of approximately 1.28 and a pure electric range ratio of approximately 0.9 (approximately 0.8 for BEVs and 0.95 for FCVs). Differently from the case of the ICEVs, the ratio for EVs remains almost constant for vehicles of different size. In addition, the energy ratio is slightly higher for bigger vehicles than for smaller vehicles.

Results for hybrid electric vehicles (HEVs) show an average WLTP to NEDC CO2 ratio significantly higher than for ICEVs (approximately 1.33 for passenger cars and 1.4 for light commercial vehicles). Like in the case of ICEVs, the ratio is higher for vehicles with lower CO2 emissions.

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[1] European Commission Regulations 1152/2017 and 1153/2017

Table E.1: Relationship between WLTP and NEDC CO_2 emissions for different passenger cars

Passenger Cars		**NEDC Type Approval Emissions (g/km) (official 2015 data)**	**Ratio WLTP/NEDC**
All ICEV		123	1.21
Gasoline	**All**	125	1.22
	< 1.4 l	115	1.24
	1.4-2.0 l	148	1.15
	> 2.0 l	225	1.07
Diesel	**All**	121	1.20
	< 1.4 l	93	1.26
	1.4-2.0 l	114	1.21
	> 2.0 l	159	1.14
LPG		116	1.16
Gas		104	1.36
HEV Gasoline	**< 1.4 l**		1.37
	1.4-2.0 l		1.32
	> 2.0 l		1.23
HEV Diesel	**< 1.4 l**		1.38
	1.4-2.0 l		1.34
	> 2.0 l		1.30
PHEV			1.00
BEV/FCV*	**Small**		1.258
	Medium		1.283
	Large		1.299

Table E.2: Relationship between WLTP and NEDC CO_2 emissions for different types of light commercial vehicles

Light Commercial Vehicles	Ratio WLTP/NEDC
All ICEV	1.30
Gasoline	1.22
Diesel	1.31
LPG	1.16
Gas	1.36
HEV Gasoline	1.38
HEV Diesel	1.45
PHEV	1.00
BEV/FCV[2]	1.21

Finally, results for plug-in hybrid electric vehicles (PHEVs) show a peculiar trend. Due to the differences between the two test procedures (especially in the way they combine results from the charge-depleting and charge-sustaining tests), the WLTP to NEDC CO2 emissions ratio strongly depends on the capacity of the electric battery. The ratio quickly decreases as the battery capacity increases. For this reason, also considering the evolution in the battery capacity, an average ratio of 1 has been estimated for PHEVs.

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[2] The WLTP to NEDC RATIO for BEVs and FCVs refer to the electric energy consumption

1 Introduction

Light-duty vehicles only – passenger cars and vans – produce around 15% of the EU's CO_2 emissions [1]. Regulation (EU) No 443/2009 sets the target of fleet-wide sales weighted average CO_2 emissions from passenger cars to 130 gCO_2/km and 95 gCO_2/km, for years 2015 and 2020, respectively[3]. The aim is to curb transport generated greenhouse gas emissions and incentivize investments in new technologies that will improve fuel efficiency and fuel consumption [2]. In order to respect the competitiveness and diversity among different manufacturers, manufacturer-specific targets are defined according to a limit-value line, proportional to the sales-weighted average mass of their fleet while the fleet-wide emissions need to comply with the targets set in the Regulation [3]. Manufacturers failing to achieve their targets are subject to costly penalties.

The current test protocol and associated New European Driving Cycle (NEDC), on which the CO_2 targets are based, has received criticism regarding its effectiveness to reduce CO_2 emissions in real world operating conditions [4–10]. There are multiple reasons contributing to this, the NEDC itself [4,11], the flexibilities of the NEDC-based test procedure, i.e. the interpretation made on various loosely defined boundaries [12], and differences in the operation of the car under laboratory conditions compared to that over real life conditions [13].

In order to address these issues and to strengthen the effectiveness of existing policies, the European Commission is introducing a new, more realistic test procedure in the type-approval process. The new World-wide harmonized Light duty Test Cycle (WLTC) and the new World-wide harmonized Light duty Test Procedure (WLTP) were developed as a global standard for determining pollutant and CO_2 emissions. The objective of WLTP was to provide a more robust test-basis and a procedure which is more representative of actual on-road vehicle operation [14–17]. WLTP significantly differs from NEDC; its main differences affecting fuel consumption include the test cycle and gear-shifting sequence, vehicle mass definition, road load determination, chassis dynamometer preconditioning, temperature, and REESS (Rechargeable Electric Energy Storage System) Charge Balance correction.

The WLTP is introduced in the European type-approval process from September 2017 [18], in parallel with the introduction of the final Euro 6c emission limits [19,20] and following the recently established procedure for measuring Real Driving Emissions [21,22]. These three pillars create a robust framework for pollutant and CO_2 emission control in Europe. However, the WLTP introduction will have an effect on the monitored CO_2 emission values and consequently on the targets for the year 2021, as those are based on the NEDC. Through the correlation and target translation legislation, the WLTP procedure will be introduced without amending the targets set for the 2015-2021 period. Until 2021, the existing (NEDC) CO_2 targets will not change, and CO_2 emissions measured at type-approval using the WLTP procedure will be translated into the corresponding NEDC-based value using a technology-based vehicle simulation model, CO_2MPAS (CO_2 Model for PAssenger and commercial vehicles Simulation) [23], developed by the European Commission for the implementation of EU Regulations 1152/2017 [24] and 1153/2017 [25]. In 2020, the ratio between the average sales-weighted NEDC-simulated emissions and the manufacturer-specific target will be applied to the WLTP-measured, sales-weighted CO_2 emissions to identify, for each vehicle manufacturer, a specific WLTP-based target for 2021 and thereafter [26,27].

The exact effect of WLTP introduction on fleet-wide CO_2 emissions is difficult to estimate and limited literature on the topic is available. Most studies published to date estimate the effect of the WLTP introduction on individual cars, rather than the effect on the European fleet as a whole. The present report attempts an estimate of the impact of WLTP introduction on the officially reported CO_2 emissions from light duty vehicles. To achieve this the PyCSIS tool (Passenger Car fleet emissions SImulator) was used [28];

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[3] Regulation (EU) 510/2011 sets the targets for vans.

PyCSIS makes use of as limited information as possible, referring mainly to already available data sources and using empirical models and information collected from measurements at the Joint Research Centre of the European Commission in order to calculate CO_2 emissions over the two test protocols.

PyCSIS focuses mainly on conventional vehicles but the methodology based on PyCSIS was extended to cover electric vehicles (battery and fuel-cell vehicles), plugin-in hybrid electric vehicles and hybrid electrics in order to provide a comprehensive picture. The remainder of the report is structured as follows: initially, the methodology applied for the internal combustion engine vehicles is outlined. The outline of the PyCSIS tool is provided along with its main inputs, models and sub-models. The two main datasets used are presented together with the various data analysis steps. The results obtained with the model on the 2015 European fleet of passenger cars are presented. Next, the methodology is extended to cover electric powertrains. Simulation results obtained for conventional vehicles are coupled with powertrain specific assumptions and extended to cover the WLTP/NEDC ratio of battery electric and fuel-cell powered vehicles. Plug-in hybrid electrics' and hybrid electrics' operation is modelled using a simplified back-engineering approach starting from individual vehicles' laboratory measurement data. The approach is used to define the on-off operation of the internal combustion engine of an hybrid architecture. The approach is combined with the PyCSIS outputs for conventional internal combustion engine vehicles and, applying the respective legislations, calculates the respective CO_2 emission figures assuming that each vehicle operates as an hybrid.

2 Internal Combustion Engine Vehicles

2.1 Methodology

The following paragraphs provide a high level description of the PyCSIS model's structure (Figure 1). More information about PyCSIS and its sub-models can be found in [28]. The approach uses a methodology similar to the methodology of the CO_2MPAS Model [27,29], the open-source software developed by the Joint Research Centre of the European Commission to support the introduction of WLTP in the European Legislation and to allow the back-translation of a WLTP test to the equivalent NEDC CO_2 emission value [23].

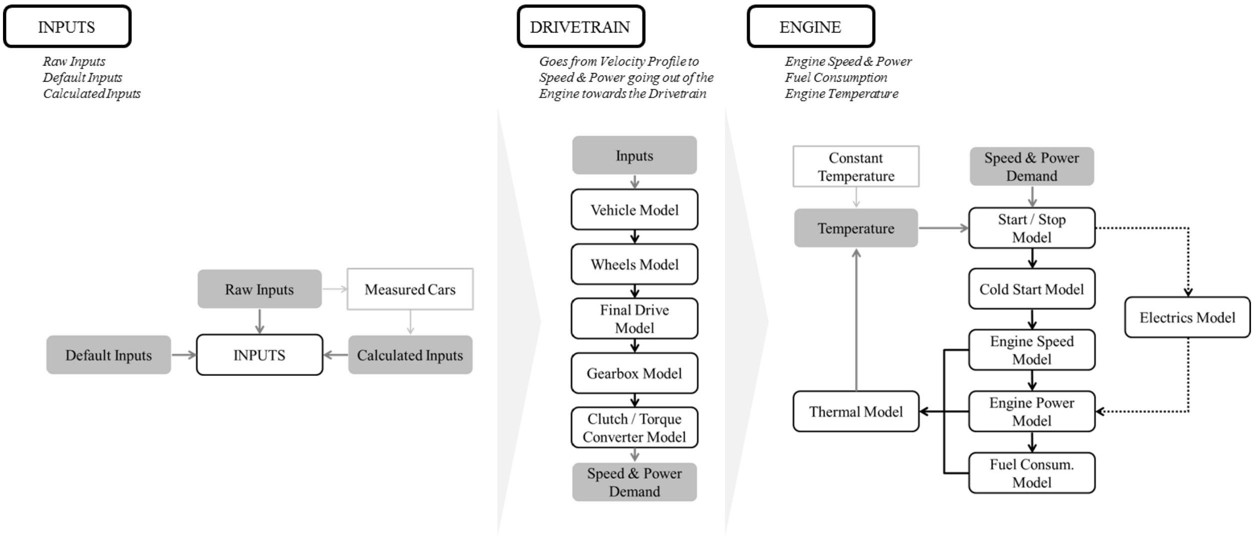

Figure 1: Outline of the Vehicle Simulation Tool and its key modules: the inputs module, the drivetrain module, and the fuel consumption module

Table 1 lists the main raw inputs of PyCSIS, the main parameters that define a single car. In addition, the tool uses a list of default values, plus a list of values calculated by empirical formulas derived from a pool of available measured cars (Annex 1).

Vehicle energy demand is calculated via simple vehicle longitudinal dynamics. The drivetrain module includes the various sub-models of the vehicle's drivetrain, excluding the engine. The calculation starts with a predefined velocity profile, and, respecting the energy equilibriums in the various steps, goes backwards from the forces applied to the vehicle and the wheels, to the final drive, the gearbox, the clutch or torque converter, up to the required engine's speed and power output. Engine power, engine speed, temperature and fuel consumption are then calculated by the engine module, using an extended Willans' lines approach [30,31] for the "fuel map" representation. A detailed description of the model and its sub-modules can be found in [28].

Table 1: Inputs of the Vehicle Simulation Tool

Name	Unit	Values / Comments
Aspiration Method	-	Turbo or Natural Aspiration / Turbo concerns all charging technologies
Dynamic Rolling Radius	Mm	Dynamic rolling radius of the wheel
Engine Capacity	Cc	Engine's capacity
Final Drive Ratio	-	Final drive ratio
Fuel	-	Fuel can be gasoline, diesel, etc.
Gearbox Ratios	-	Gearbox ratios
Gearbox Type	-	Manual or automatic
Mass in Running Order	Kg	As defined in Regulation No. 1230/2012 [32]
Nominal Power	kW	Nominal power of the ICE
Nominal Speed	RPM	Nominal speed of the ICE
Nominal Torque	Nm	Nominal torque of the ICE
Reference Mass	Kg	Vehicle's test mass
Start Stop Technology	-	Presence of a S/S system
Stroke	Mm	Cylinder's stroke
Unladen Mass	Kg	Vehicle's curb mass
Velocity Profile	km/hr, sec, -	Velocity, time, gear
Wheel Drive	-	2WD or 4WD

Table 2: Outputs of the Vehicle Simulation Tool used in the present study

Name	Unit	Values / Comments
Energy Demand	kJ	Overall and instantaneous energy demand for the simulated mission profile
Fuel Consumption	l	Overall and instantaneous fuel consumption for the simulated mission profile
CO_2 Emissions	g/km	Average CO_2 emissions for the simulated mission profile

2.2 Data Sources & Analysis

The official European Monitoring databases of CO_2 developed and maintained by the European Environmental Agency (EEA) [33,34] were used as a reference of this study. The databases, henceforward referred to as the "Fleet Datasets", collect the necessary information to assess vehicle manufacturers' compliance to the European CO_2 targets. Approximately 13 million new registrations of passenger cars and 1.5 million new registrations of light-commercial vehicles in the 27 Member States are grouped per vehicle type, variant, and version. For each entry the following information, among others, is provided: CO_2 emissions (g/km), mass in running order (kg), displacement (cm^3), engine power (kW), type of fuel, number of registrations in Europe for the specific year and vehicle footprint. Provisional data for the year 2015 were used for the present analysis.

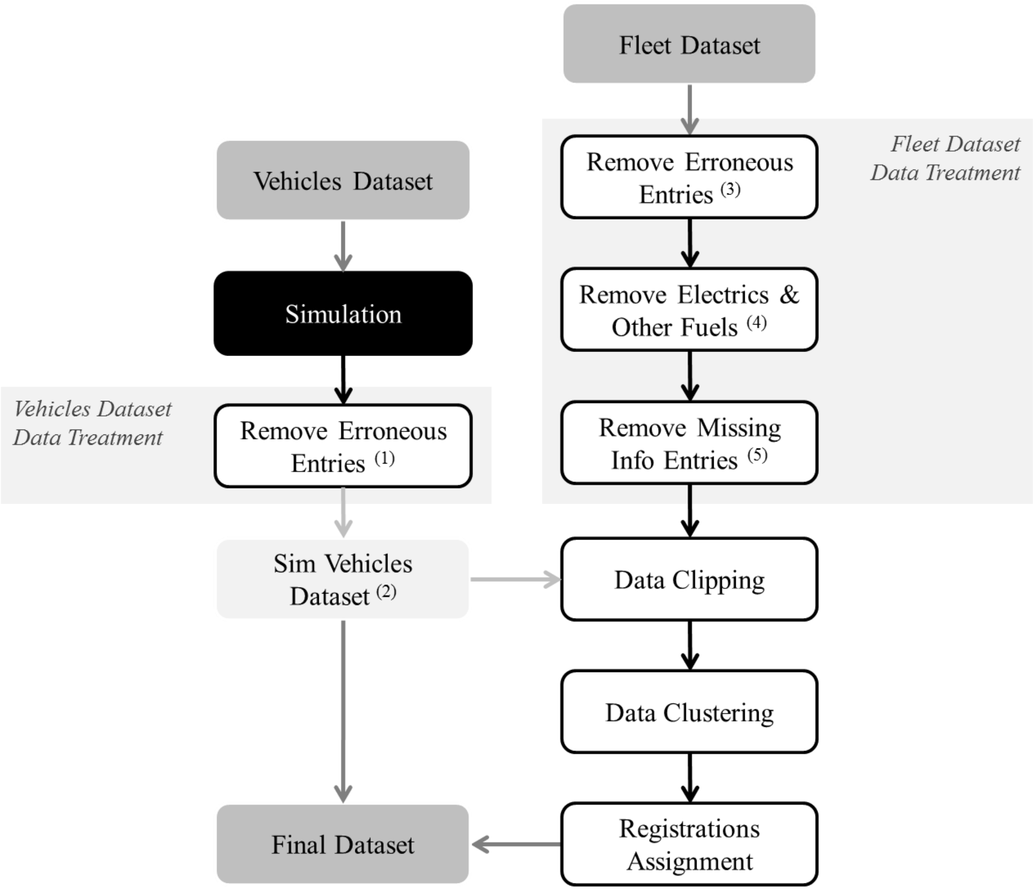

Figure 2: Flow-chart of the various data analysis steps performed to the two main datasets: the Vehicles Dataset and the Fleet Dataset (see footnote for notes[4])

The information included in each Fleet Dataset is not sufficient to run the model, as it provides no information on most vehicle characteristics, engine characteristics, road loads and on the type and the characteristics of the transmission. This information deeply affects the model's performance. Information from the official EEA database was combined with additional information retrieved from on-line publicly available sources (i.e. online databases like carfolio.com, cars-data.com, carspector.com, etc., and vehicle manufacturers' websites) which was used to formulate a second, more detailed database ("Vehicles Dataset"). This second database contains vehicle-specific information of approximately 1,200 vehicles, all available in the market in 2015, for both gasoline and diesel fuelled cars, with automatic and manual transmissions. Vehicles using other fuels and electric or electrified vehicles were excluded due to their very low share in vehicle sales. The Vehicles Dataset contains information regarding gearbox (gearbox ratios and

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[4] Notes: (1) Defined as entries with an error of Simulated vs. Reported NEDC CO2 Emissions value of < -10% or +30%; (2) The Sim Vehicles Dataset contains all entries of the Vehicles Dataset, plus two new entries: Simulated NEDC & Simulated WLTP CO2 emissions; (3) Defined as falling in one of the two following categories: (a) vehicles with carbon based fuels with no CO2 emissions, or (b) vehicles with CO2 emissions less than 70 g/km; (4) Other fuels include entries with either "hydrogen" or "others" in the fuel field of the raw dataset; (5) Defined as entries with no available data on at least one of the following fields: capacity, model, mass, CO2, power.

final drive), engine (capacity, bore, stroke), drive system, fuel, nominal power and engine speed, etc.), vehicle body dimensions (width, height, length), additional technologies (start-stop and engine aspiration), tyres, mass, type approved fuel consumption and CO2 emissions. A complete list of the fields included in the various datasets is available in the Annex 2.

The two datasets are combined into a single dataset (referred to as the Final Dataset) as shown in Figure 2 and described hereafter. The Fleet Dataset is initially created by removing erroneous data (i.e. vehicles with carbon based fuels and no CO_2 emissions, non-electrified vehicles with CO_2 emissions of less than 70g/km), entries representing electrics/electrified vehicles or vehicles fuelled with non-gasoline or diesel "equivalent" fuels (e.g. hydrogen or others), and finally entries missing key information, i.e. capacity, mass, CO_2, power and model. The Vehicles Dataset is used as an input to PyCSIS. The simulation results (namely the CO_2 emissions for NEDC and WLTP) are added to the Vehicles Dataset. All cases with a simulation deviation (namely the percentage difference between simulated and reported NEDC CO_2 emissions), falling outside the range of the average plus minus two standard deviations, are removed to minimize the uncertainty introduced by the simulation to the overall quality of the present exercise. This new dataset (referred to as "Sim Vehicles Dataset") constitutes the basis for further analyses including filtering, clustering and grouping. More information regarding the data treatment process can be found in [28].

2.3 Results

2.3.1 Passenger Cars

Figure 3 presents the simulated WLTP CO_2 emissions against the simulated official NEDC ones. WLTP CO_2 emissions result in higher values compared to the NEDC, reaching a range of 20-25 gCO_2/km for vehicles approaching 100 gCO_2/km. These values decrease as the CO_2 emissions increase (and become approximately null for WLTP CO_2 emissions of 250 gCO_2/km).

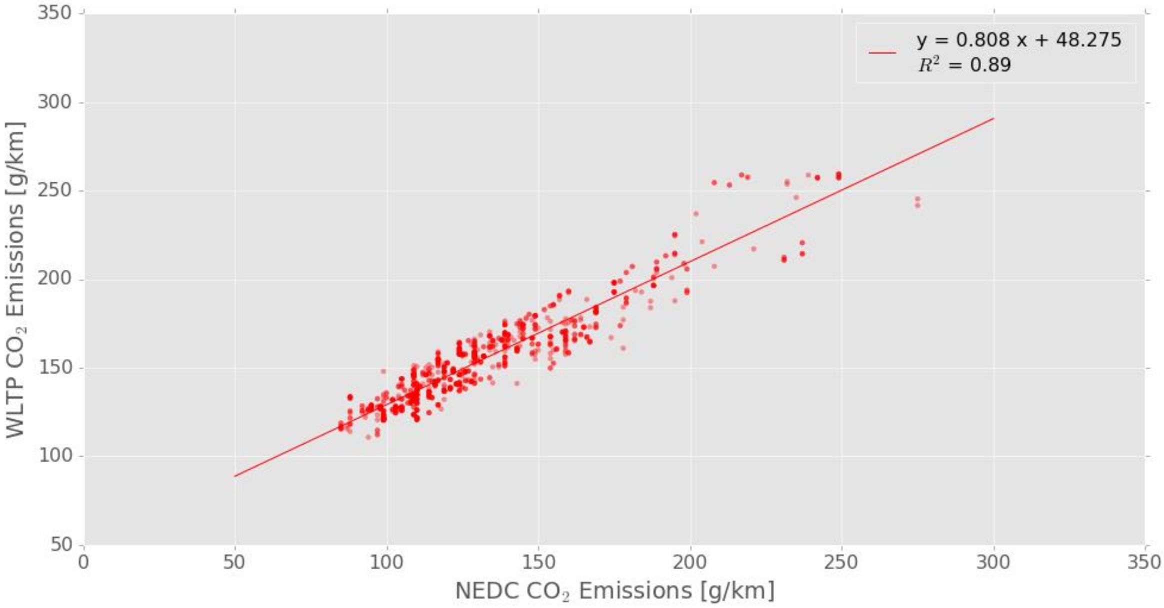

Figure 3: Simulated WLTP vs. Reported NEDC CO_2 emission values

In order to understand the implications of this observation a direct comparison is made against existing test-based datasets (Figure 4). In particular, Figure 4 shows the simulated WLTP/NEDC ratio (blue dots) as a function of the official NEDC reported values. In addition, Figure 4 also reports the equivalent ratio as derived from experimental data (red dots) originating from the latest update of the ADAC-EcoTest database [6]. The

ADAC EcoTest attempts to characterize the fuel consumption performance of passenger cars based on a series of tests performed over NEDC, WLTP and other ADAC developed realistic driving cycles. From this figure three main conclusions can be extracted: i) independently of the absolute accuracy of the simulations presented in this analysis, the proposed methodology manages to capture well the trends of the passenger car fleet, with the trend-lines of the two datasets coinciding in a large part of the range of data; ii) there is a clear decreasing trend of the WLTP/NEDC ratio as the NEDC value increases, confirming the observations drawn from Figure 3; iii) the WLTP/NEDC ratio tends towards very high values as the NEDC value decreases. Considering that different sources show an increasing gap between real-world and NEDC fuel consumption and CO_2 emissions [13], the fact that a similar trend is expected also between WLTP and NEDC confirms that the new test procedure should be more representative of real-world emissions. In this light, the recent introduction of WLTP in the EU emission type-approval of light duty vehicles seems crucial in order to reduce the gap between real-world and certification values.

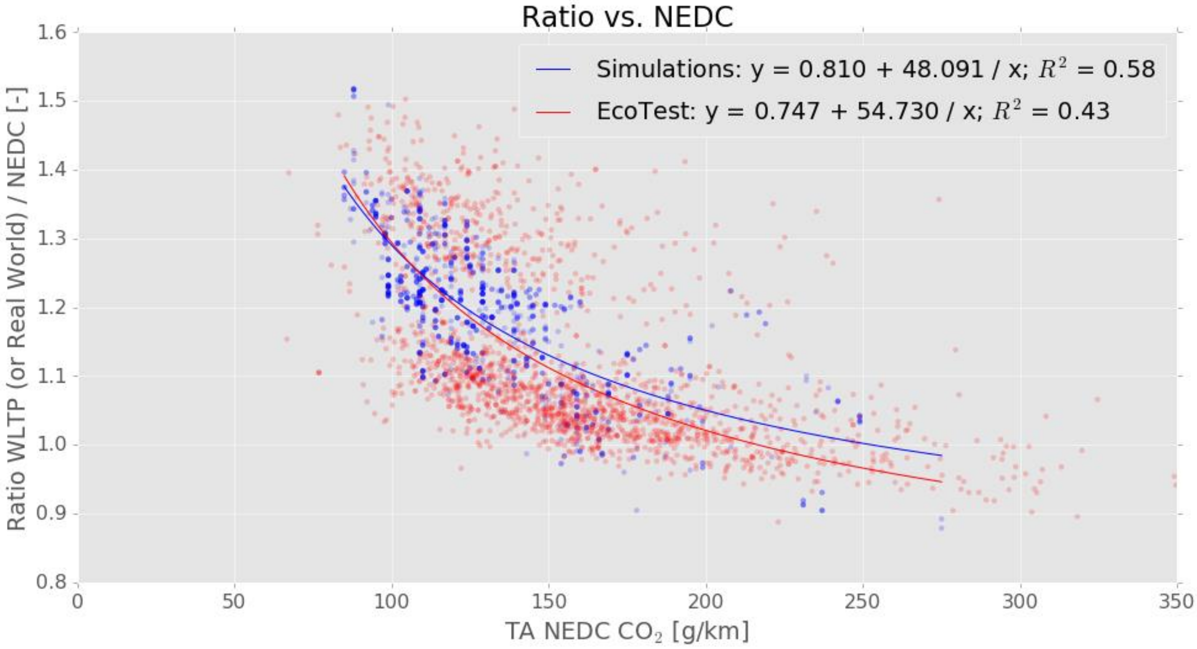

Figure 4: Correlation Factor, i.e. ratio, between WLTP/NEDC vs. Reported NEDC values

Finally, Table 3 summarizes the simulation results following the segmentation of COPERT [35] regarding fuel type and engine capacity. COPERT is one of the main methodologies used in Europe and in several non-European countries, for emissions monitoring and inventorying. For ICEV passenger cars, the overall (sales-weighted average) ratio between the two tests is equal to 1.21, which corresponds to an overall difference between the 2015 WLTP and NEDC CO_2 emissions of 23.5 gCO_2/km. Gasoline and diesel vehicles on average show almost the same ratio (1.22 vs 1.20) and the respective emissions' increases for 2015 are 25.0 vs. 22.2 gCO_2/km. This occurs independently of the capacity category. When capacity is taken into account, both for average and sales-weighted average values, segments of higher capacity show lower ratios as opposed to lower capacity ones. This finding is in line with the observation made previously that WLTP and NEDC emissions' difference reduces as CO_2 increases.

Table 3: Summary of the Average and Sales-Weighted (SW) Average values for various fuel / capacity segments among ICE passenger cars

		Type Approval Emissions [g/km]			
		NEDC (Type Approval 2015)	**WLTP[5] (Type Approval equivalent)**	**Delta WLTP-NEDC**	**Ratio WLTP/ NEDC**
All ICEVs	**Average**	131.9	153.9	22.0	1.19
	SW Average	122.6	146.1	23.5	1.21
Gasoline	**Average**	140.9	162.6	21.7	1.18
	SW Average	124.6	149.6	25.0	1.22
Gasoline <1.4 l	**Average**	118.1	143.5	25.3	1.23
	SW Average	115.2	141.8	26.6	1.24
Gasoline 1.4-2.0 l	**Average**	146.6	166.8	20.1	1.15
	SW Average	148.0	168.3	20.3	1.15
Gasoline >2.0 l	**Average**	210.2	223.3	13.0	1.07
	SW Average	224.6	237.8	13.2	1.07
Diesel	**Average**	123.6	145.7	22.1	1.19
	SW Average	121.2	143.5	22.2	1.20
Diesel <1.4 l	**Average**	92.9	116.1	23.3	1.26
	SW Average	92.9	116.1	23.3	1.26
Diesel 1.4-2.0 l	**Average**	115.4	137.6	22.2	1.20
	SW Average	114.3	136.7	22.4	1.21
Diesels >2.0 l	**Average**	157.4	178.7	21.3	1.15
	SW Average	159.3	180.4	21.1	1.14
LPG	**Average**	114.8	132.5	17.7	1.16
	SW Average	115.8	133.9	18.1	1.16
Gas	**Average**	91.1	127.9	36.8	1.43
	SW Average	103.9	137.8	33.9	1.36

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[5] WLTP Type Approval value equals to the simulated WLTP increased by 2% to account for a series of corrections (e.g. temperature, battery discharge, etc.) that are foreseen by the WLTP and take place after the official test is performed.

2.3.2 Light-Commercial Vehicles

Different from the passenger cars where all entries of the respective Fleet dataset have been considered, only the “top sellers” of each individual class[6] of the light-commercial vehicles’ respective Fleet dataset have been used in the present. The “top sellers” were defined as vehicles representing more than 10% of the sales in their equivalent class. The resulting WLTP to NEDC conversion factors for the two main fuel categories are provided in Table 4 below.

Table 4: Summary of average conversion factors for light-commercial vehicles

Avg. WLTP/NEDC for conventional LCVs	
Diesel	1.31
Gasoline	1.22

It shall be highlighted that the main difference in the CO_2 emissions calculation, as compared to the passenger cars, comes from the calculation of the road load coefficients. More specifically, and as described in Annex 3, different parameters and empirical relationships are considered regarding the masses, the aerodynamic drag, and the wheel rolling resistance definitions.

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[6] Classes are defined as: Class I: mass <= 1305 kg; Class II: mass 1305-1760 kg; Class III: mass >1760 kg

3 Electric powertrains

The calculations performed using PyCSIS for internal combustion engine based vehicles have been adapted in order to capture the effect of the WLTP introduction also on vehicles with electrified powertrains (i.e. HEV, BEV, FCV and PHEV). In particular, results from PyCSIS constituted the basis for various hypotheses and assumptions regarding the difference of an electric vehicle as compared with a conventional one in terms of the various efficiencies and losses, the fuel / energy storage systems, etc. The boundaries and provisions of the WLTP and NEDC type approval regulations were then applied to the sample, and the end results of CO_2 emissions, energy, and zero emissions vehicles range, for the two cycles were calculated. In the next sections, the approach used for the different types of electric vehicles is described in details.

3.1 Battery Electric & Hydrogen Fuel Cell Powered Vehicles

3.1.1 Methodology & Data Sources

WLTP to NEDC ratios for these two categories of vehicles are calculated on the basis of the conventional cars data, i.e. the vehicles included in the Vehicles Dataset as defined in section 2, and assuming that these would be run as BEVs and/or FCVs. This was necessary because using only the limited number of BEVs/FCVs included in the monitoring database could have produced a distorted picture.

In order to model a conventional vehicle as a BEV and/or FCV, specific assumptions are formed regarding the electrical efficiencies, battery sizes, etc., as it will be described below. As these vehicles have zero CO_2 emissions, two other environmental performance indicators are considered: the overall energy efficiency of the vehicle, and its pure electric driving range, starting with a full energy storage medium, i.e. battery or hydrogen tank.

Initially, the overall energy at the wheel is calculated by the Drivetrain Module of PyCSIS, both for NEDC and WLTP, for each individual vehicle of the sample, as if they were conventional internal combustion engine vehicles. Then, and since the overall distance driven is not the same between NEDC and WLTP, the energy at the wheel is normalized to, i.e. divided with, the total distance driven on each respective cycle. The ratio of the WLTP energy requirements per distance driven to the NEDC equivalent one provides a good estimate of the increased energy consumption of a vehicle over WLTP.

In order to calculate the driving range ratio between the two cycles when driven in pure electric, the overall available energy of the energy storage tank shall be defined. This figure is then compared with the energy demands of each cycle as defined above (energy on the wheel). In both cases, the overall energy storage capacity is calculated as a function of the energy storage system's mass and its energy carrier density. Initially, the energy storage system's mass is assumed to be a function of the vehicle mass:

$$m_{energy\ storage\ system} = a * m_{vehicle} \tag{1}$$

Where $m_{energy\ storage\ system}$ and $m_{vehicle}$ is the mass of the energy storage system and the vehicle, respectively. In order to guarantee a representative sample of both contemporary and future systems, parameter a is sampled from a uniform distribution from 15% to 35%. The energy storage capacity is then calculated multiplying the energy storage system's energy density with its mass. The energy storage system's energy density is sampled from a uniform distribution in the range of 100 to 150 Wh per kg. Lastly, the usable energy available from the energy storage system is assumed to be equal to 70% of the system's total storage capacity. The remaining 30% is accounted for the battery's depth of discharge, other losses, etc. The end driving range is then calculated dividing the usable energy available in the energy storage system by the normalized energy demand of the cycle. The latter, is further divided by the respective powertrain efficiency to estimate the exact energy requirements from the energy source and accounting for the differences between the two systems, BEVs and FCVs, as defined below:

- *Battery Electric Vehicles*: powertrain efficiency of 70% and 73% is assumed for the NEDC and the WLTP, respectively;
- *Hydrogen Fuel Cell Powered Vehicles*: powertrain efficiency of 27% for the NEDC and 32% for the WLTP is assumed.

Figure 5 provides a schematic representation of the various assumptions and steps to calculate the usable energy at the wheels.

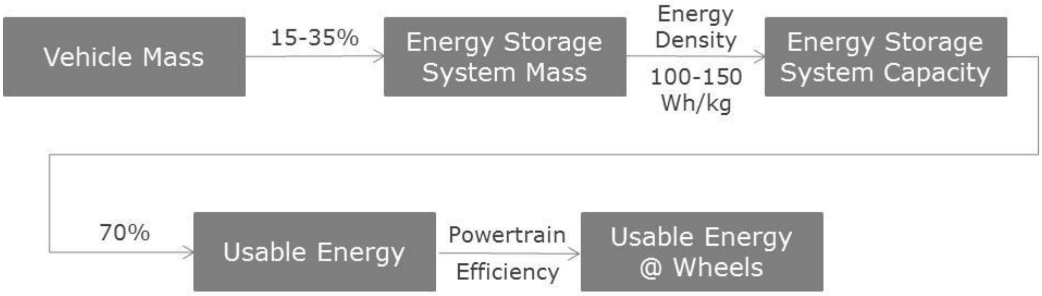

Figure 5: Schematic representation of usable energy at the wheels calculation

3.1.2 Results

Table 5 provides a summary of the resulting WLTP/NEDC energy and pure electric driving range ratio. Results are grouped based on the designated engine capacity segments of the respective conventional vehicles, which are used as an indicator of the vehicle's size and category.

Table 5: Energy & Range Ratio of WLTP vs. NEDC for Battery Electric & Hydrogen Fuel Cell Powered Vehicles

Category	Energy Ratio	Pure Electric Range Ratio	
		BEVs	**FCVs**
Small passenger cars	1.26	0.83	0.94
Medium passenger cars	1.28	0.81	0.92
Large passenger cars	1.30	0.80	0.91
Light-Commercial Vehicles[7]	1.21	0.86	0.98

3.2 Plugin Hybrid Electric Vehicles

3.2.1 Methodology & Data Sources

Plugin Hybrid Electric Vehicles (PHEVs) can operate in two different modes: a) In charge-depleting (CD) mode where the electric machine is responsible for propulsion and the internal combustion engine (ICE) is switched off, and b) In charge-sustaining (CS) mode where the ICE is used for propulsion and to maintain battery state-of-charge (SOC) within a small window.

For the calculation of the WLTP/NEDC CO_2 emission ratio for the PHEVs a different methodology, as compared to the BEVs and FCVs, is used. The calculation of the energy

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[7] A dedicated part of the Vehicles Dataset including the "top sellers" of light-commercial vehicles only (as described in section 2.3.2) is used for the present analysis

storage capacity is similar to the battery electric vehicles, except that the nominal capacity is assumed to be 1/3 as compared to the BEVs considering the smaller batteries used. The powertrain efficiencies over the two cycles are considered equal to the ones used for the battery electrics, i.e. 70% for the NEDC and 73% for the WLTP. In the case of PHEVs though, the usable energy available is assumed to be equal to 60% of the overall available, given the usually smaller depth of discharge of the batteries and the higher regeneration frequency.

Additionally, EC Regulation No 1151/2017 [18] prescribes a specific procedure for calculating the equivalent CO_2 emissions of a PHEV under WLTP and NEDC, respectively. A detailed description of the two different procedures, together with an experimental evaluation of the effect of the WLTP regulation regarding PHEVs, is provided in Annex 4 of the present document.

Procedural changes regarding the prescribed laboratory procedures and post-processing of the test data significantly affect the final PHEV CO_2 and fuel consumption figures. However, in order to perform the simulations of a PHEV and calculate the WLTP/NEDC correlation coefficients based on the prescribed procedure, modelling the behaviour of PHEVs was necessary. PHEV's modelling is based on a reverse engineering test campaign carried out on two different plug-in vehicles, characterized by the same hybrid architecture (Flywheel Alternator Starter or FAS, which is widely diffused between several PHEVs), the same electric machine (Max output power 70 kW) and different internal combustion engine size (respectively 3.0 and 1.4 litres spark ignition). The PHEV model aims at identifying and reproducing the typical operating conditions of a hybrid powertrain, namely:

- *Electric vehicle*: the internal combustion engine is off and all the power requested by the driver is supplied by the high voltage battery, allowing zero tail pipe emissions at the exhaust;
- *Regenerative braking*: the kinetic energy during the deceleration phases is recovered by the electric machine and stored in the high voltage battery;
- *Load point moving*: when the internal combustion engine is enabled (for example when the battery is depleted or the driver's power demand overcomes the physical limits of the electric powertrain) and used both to propel the vehicle and to charge the high voltage battery, increasing the overall powertrain efficiency;
- *Electric boost*: during aggressive transient phases, the internal combustion engine is on and it is supported by the electric machine.

The control logic for the simulation of the several test cases is the same and it reflects the behaviour identified from the two test campaigns. The model simulates both the CD and CS sustaining conditions, by supposing different initial battery State of Charge (SOC) at the beginning of the cycle and using the same simulation approach. The PHEV model simulates the engine on/off strategy using curves designed as function of the SOC, vehicle acceleration and motive power, as reported in Figure 6, based on the analysis of the experimental data. In Figure 6 the red line represents the engine-on curve, while the blue the engine-off one. The necessity to define two curves relies on the necessity to prevent frequent engine on/off, which are not representative of a realistic engine behaviour.

The efficiency of the powertrain during the regenerative braking and the electric drive is assumed to be constant and equal to 0.8, since the average efficiencies of a permanent magnet and of a mechanical transmission are around 0.9.

The enabling of the load point moving (or smart charge) or the electric boost is modelled using statistical analysis performed on the two reference vehicles tested at JRC. The load point moving/electric boost model correlates the battery SOC, the product between vehicle speed per acceleration and the motive power, obtaining the volume reported in Figure 7, where the green points stand for the load point moving while the magenta for the electric boost.

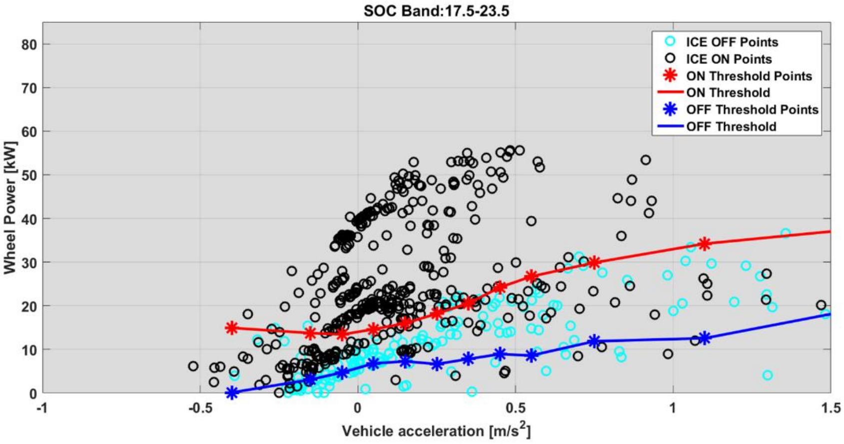

Figure 6: Engine on/off strategy for a PHEV as function of battery SOC, vehicle acceleration and wheel power

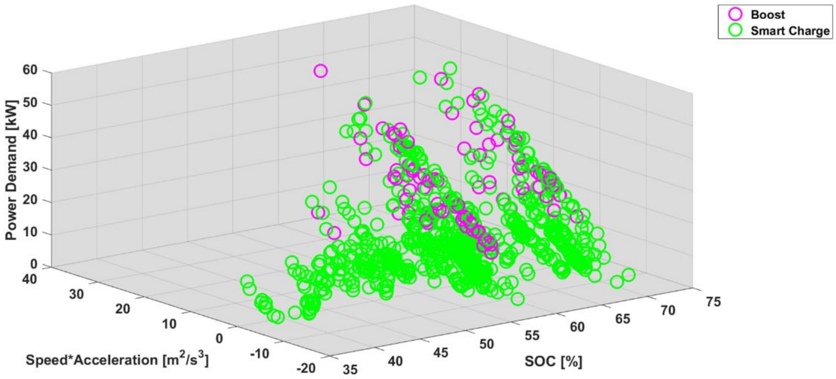

Figure 7: Powertrain operating volume of PHEVs when the internal combustion engine is enabled

During the simulation of the PHEV powertrain along the NEDC and WLTC cycles, the model evaluates the weight of the load point moving or electric boost depending on the SOC and vehicle kinematic parameters (speed, acceleration and motive power) at each instant of time, allowing the correct mode enabling.

The power adsorbed or released by the battery during these two modes is modelled through maps, detected during the reverse engineering activity, as shown in Figure 8. These two maps are effective for different size of the battery since the power adsorbed/released are strictly dependent on the maximum charge/discharge current of the cell, which chemistry is supposed to be similar for all the virtual prototypes and equal to the LiFePO4 [36], actually used by several PHEVs manufacturers.

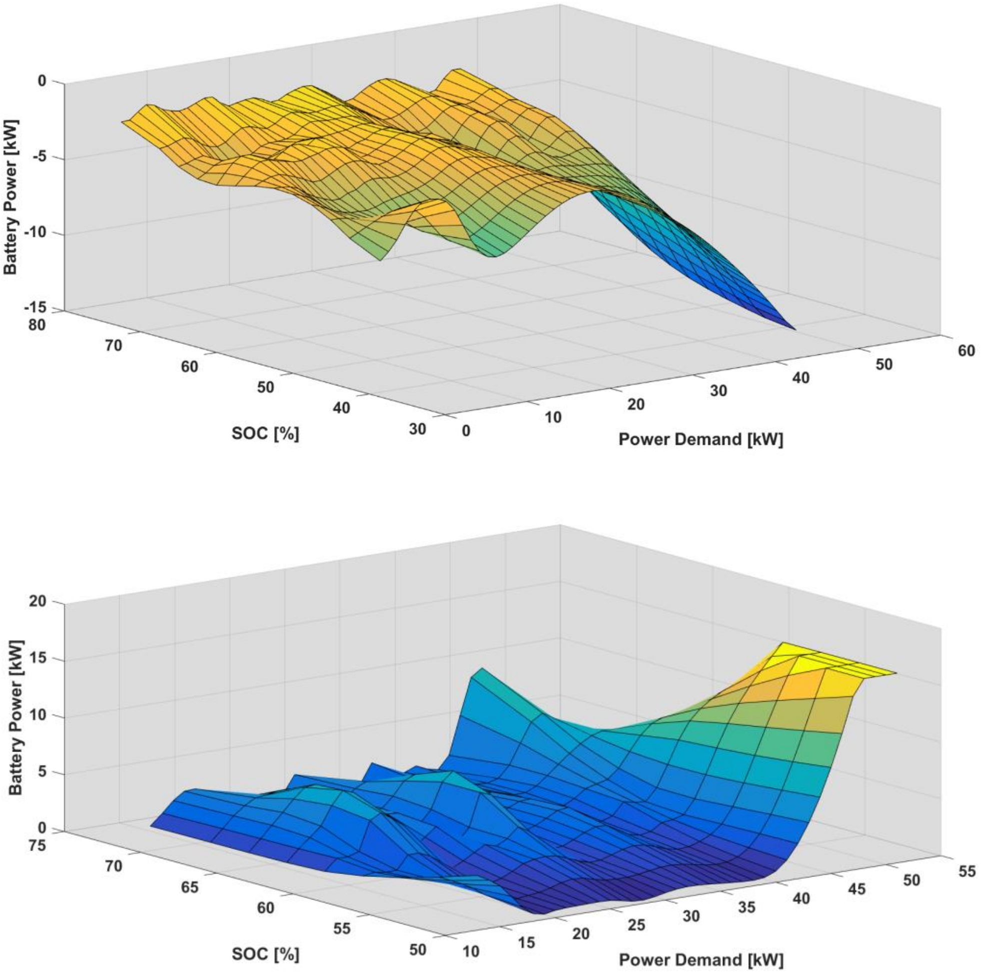

Figure 8: Load point moving (top) /Electric boost (bottom) for a PHEV

The battery modelling, necessary for the computation of battery current and consequently for the evaluation of SOC swing, is based on a 0-D circuital approach, reported in Figure 9. The computation of battery current is done using the Ohm's law using as Open Circuit Voltage (OCV) and Internal Resistance (R0) data representative of a LiFePO4 cell, which are variable as function of the battery SOC, as illustrated in Figure 10. Moreover, the battery cells are supposed to be connected in series similarly to the available hybrid technologies.

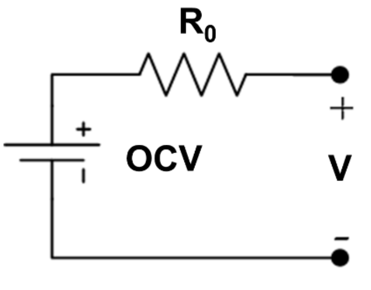

Figure 9: 0-D Battery model

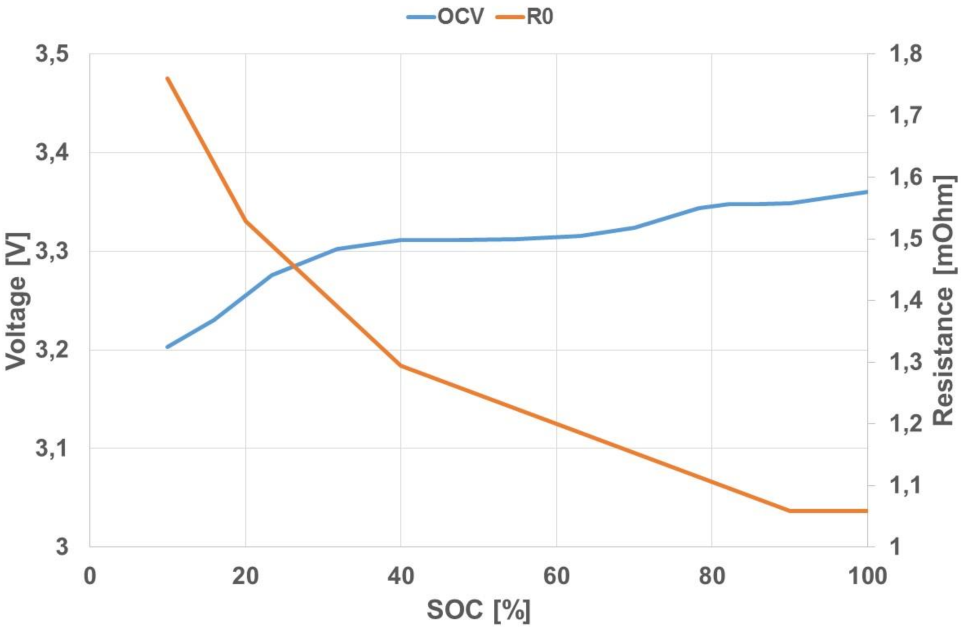

Figure 10: OCV and Internal resistance curves for a LiFePO4

Several sizes of the battery were considered during the simulation. The battery sizing for the different vehicles class was done as function of the three different electric distances (20, 40 and 80 km) and as function of the vehicle mass. Since the chemistry is the same for all vehicles and the cells are connected in series, the number of cells varies as function of the target electric range and of the vehicle mass. The definition of number of cells for different vehicle classes was done to satisfy the electric range requirements, through the evaluation of cycle energy demand along the NEDC cycle, since the actual hybrid portfolio is designed on the energetic requirements of the actual type approval procedure. An example of battery sizing for a target range of 40 km is reported in Figure 11.

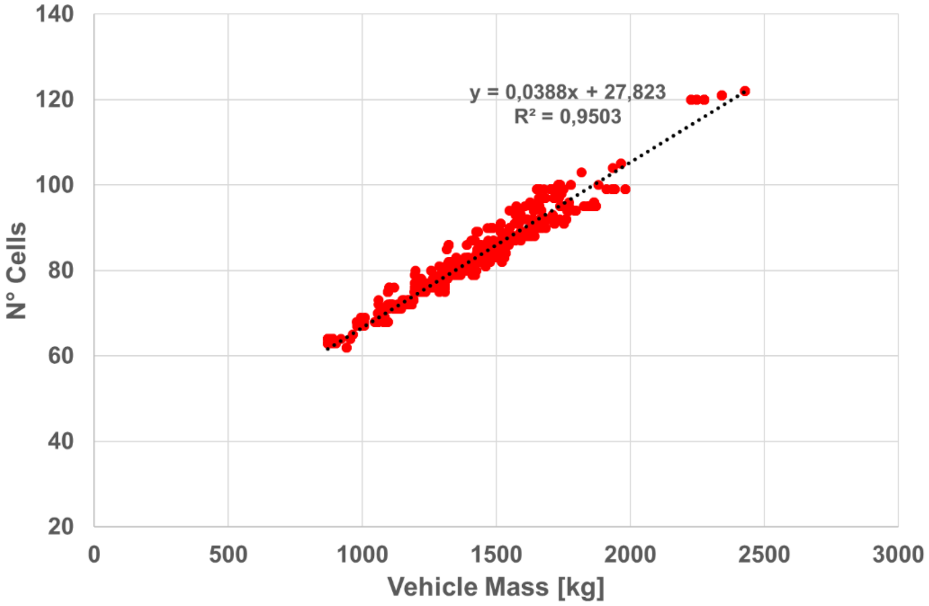

Figure 11: Battery size versus vehicle mass for a target electric range of 40 km on NEDC

3.2.2 Results

Considering the simulation results and the application of the specific procedural elements of the two Regulations, Figure 12 presents the resulting WLTP/NEDC CO_2 emissions ratios as a function of the size of the battery. As it can be seen on the graph, increasing the energy storage capacity, i.e. the battery size, leads to a decrease on the ratio as the WLTP procedure results more dependent on the electric range than the NEDC one (which uses a more simplistic and therefore less realistic approach in the combination of charge depleting and charge-sustaining conditions). In this light, from the results it seems clear that in the future, WLTP emissions are expected to be below the NEDC equivalent ones, confirming what was experimentally calculated (reported in Annex 4). It can be concluded that the energy storage system is thus of decisive importance both for environmental and economic reasons (batteries constitute one of the biggest elements in the cost structure of electric vehicles).

Given the approximation of the calculations carried out and considering 25kWh as a reasonable battery size after 2020, **a WLTP-NEDC correlation factor of 1 for plug-in hybrid vehicles (both passenger cars and light commercial vehicles) is considered appropriate in the present exercise**.

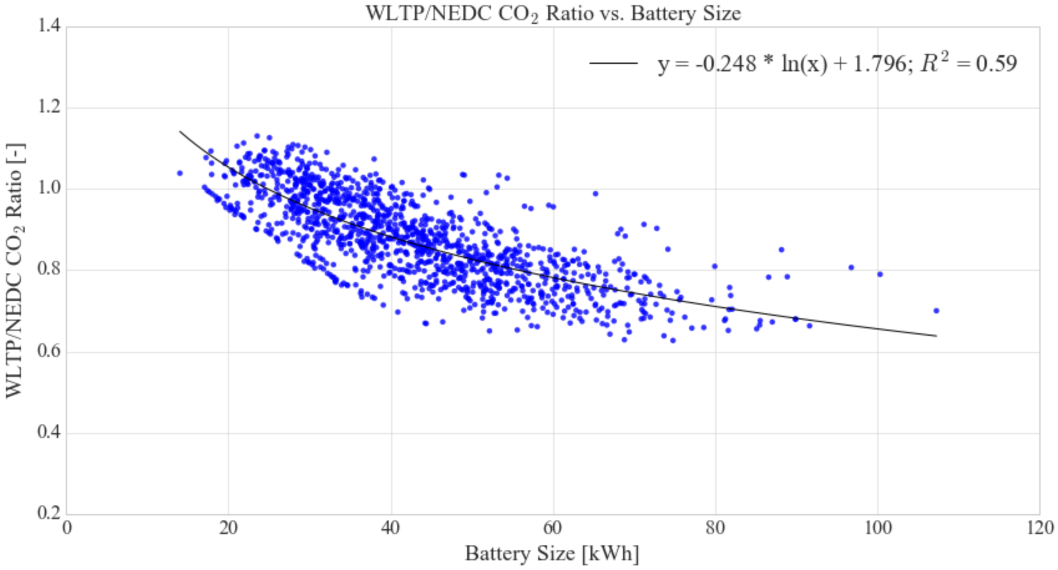

Figure 12: WLTP/NEDC ratio for Plugin Hybrid Electric Vehicles changing the battery size

3.3 Hybrid Electric Vehicles

3.3.1 Methodology & Data Sources

As opposed to the PHEVs, in Hybrid Electric Vehicles (HEVs) the high voltage battery represents an energy buffer, because the electric energy used during the discharge phase (for example during the electric drive) should be supplied afterwards through the engine load point moving or through the regenerative braking. For this reason, the tail pipe CO_2 emissions should be corrected, since the declared value should correspond to a neutral energy balance of the battery. This correction is necessary to take into account the effect of battery recharge made by the internal combustion engine, since HEVs do not allow the external recharge of the high voltage battery. The correction coefficient applied is called K-Factor. Thus, for HEVs tail pipe emissions should be corrected according to equation (2):

$$M_{CO2,corr} = M_{CO2} - K_{CO2} \times Q \qquad (2)$$

Where $M_{CO2,\ corr}$ are the corrected tail pipe CO_2 emissions, M_{CO2} are the raw CO_2 emissions measured during the chassis dyno test, K_{CO2} is the K-Factor calculated according to the WLTP legislation and Q is the integral of the battery during corresponding to M_{CO2} measurement. The K-Factor evaluation for both procedures requests at least two measurements performed at different starting battery SOC values.

One crucial difference among the WLTP and NEDC correction formulations is that the WLTP formulation uses the battery energy for the correction of tail pipe CO_2 emissions, allowing the car manufacturers to measure the voltage, while on the contrary, the NEDC assumes that the battery voltage is constant; therefore the correction uses the integral of the battery current.

For the evaluation of WLTP/NEDC ratios for HEVs, the battery voltage for the evaluation of the corrected CO_2 emissions along the WLTC cycle is assumed to be constant, according to Annex 8 - Appendix 3 paragraph 3, making the computational approach equivalent to Equation 2.

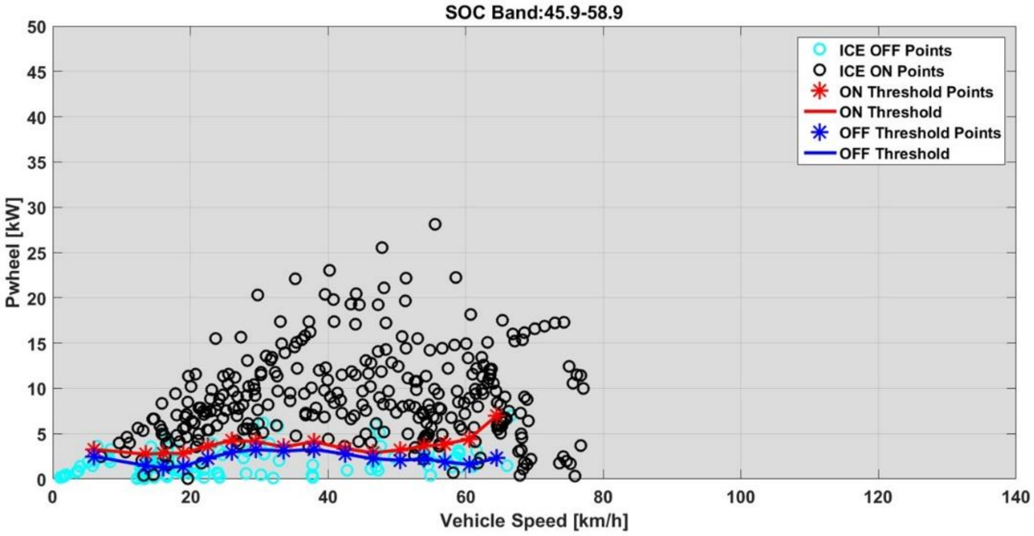

Figure 13: Engine on/off strategy for a HEV as function of battery SOC, vehicle speed and wheel power

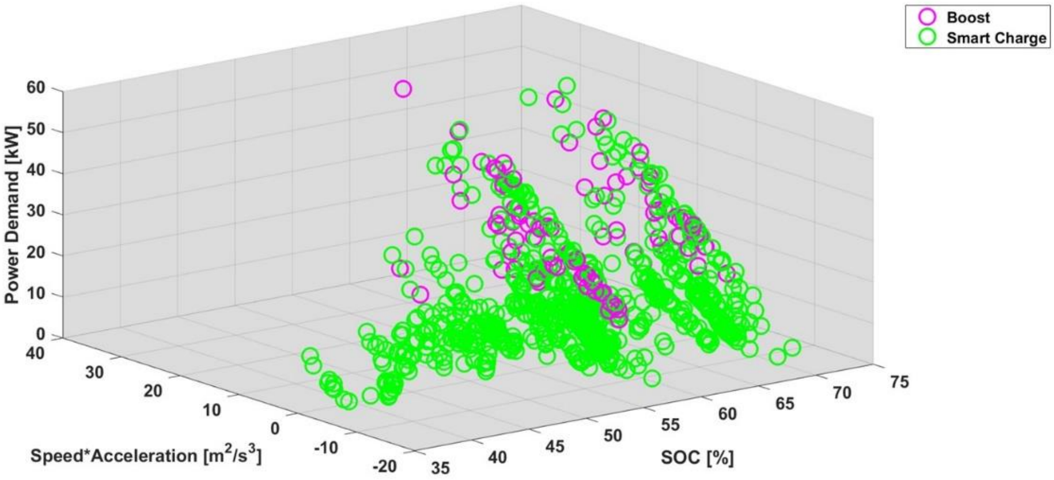

Figure 14: Powertrain operating volume of HEVs when the internal combustion engine is enabled

Similar to the PHEVs, the modelling of the HEVs operation is based on reverse engineering test data of a Euro 6 hybrid vehicle based on an Electric Continuous Variable

Transmission (eCVT) architecture, which uses two electric machine with a rated power of 60 kW and a 1.8 l spark ignition engine. Similar to the PHEV model, the HEV model identifies and predicts the various operating conditions of a hybrid powertrain. For the computation of K-Factor, the model simulates the vehicle considering two different initial SOC values (40% and 65% representative of the discharged and charged condition). The HEV model, as the PHEV one, simulates the engine on/off strategy using curves defined as function of the SOC, vehicle speed and motive power, as reported in Figure 13.

The efficiency of the powertrain during the regenerative braking and the electric drive, as the PHEV case, is assumed to be constant and equal to 0.8. The enabling of the load point moving (or smart charge) or the electric boost is modelled using a statistical approach, based on the experimental data of the reference vehicle used for the model development. The load point moving/electric boost model correlates the battery SOC, the product between vehicle speed per acceleration and the motive power, obtaining the volume reported in Figure 14, where the green points stand for the load point moving while the magenta for the electric boost.

During the simulation of the HEV powertrain along the NEDC and WLTC cycles, as the PHEV case, the model evaluates the weight of the load point moving or electric boost depending on the SOC and vehicle kinematic parameters (speed, acceleration and motive power) at each instant of time, allowing the correct mode enabling.

The power adsorbed or released by the battery during these two modes is modelled through maps, using the same approach as PHEVs. These maps are effective for different size of the battery since the power adsorbed/released are strictly dependent on the maximum charge/discharge current of the cell, which chemistry is supposed to be same for all the virtual prototypes and equal to the NiMH [37], actually used by the main HEV manufacturer (Toyota).

The battery modelling is based on a 0-D circuital approach, similar to the one used for PHEVs (Figure 9). The Open Circuit Voltage (OCV) and Internal Resistance (R0) data representative of a NiMH cell, which are variable as function of the battery SOC, as illustrated in Figure 15. Moreover, the battery cells are supposed to be connected in series.

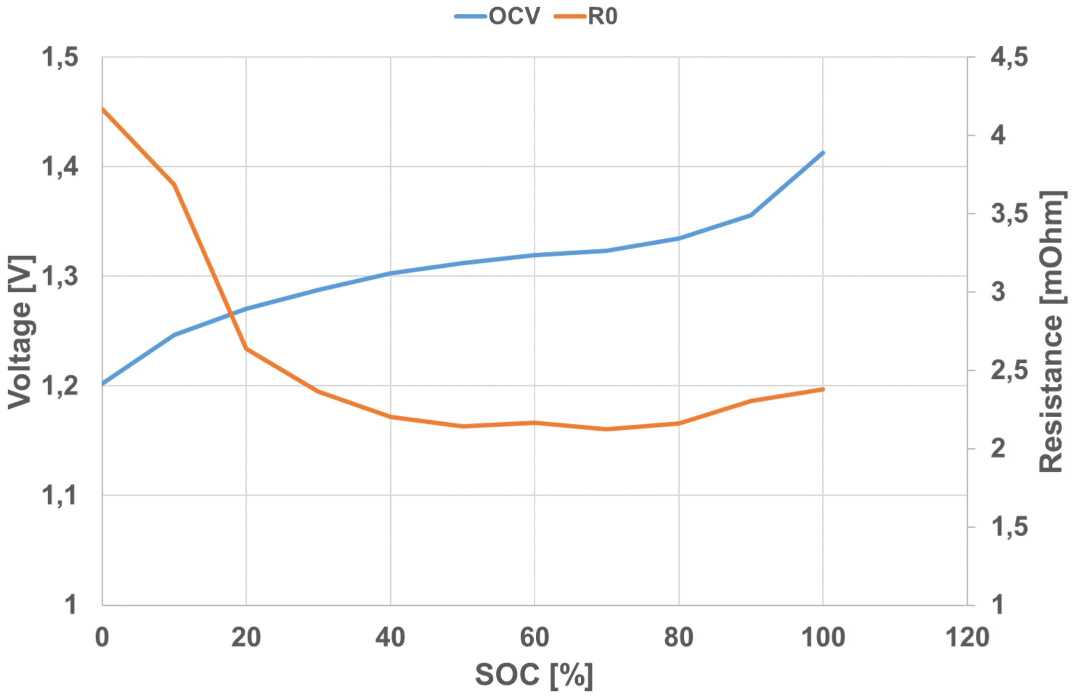

Figure 15: OCV and Internal resistance curves for a NiMH

Finally, the model computes the CO_2 emissions for the two initial SOC levels (40% and 65% of battery SOC) and the integral of battery current, necessary for the computation of K-Factor. The approach for the computation of CO_2 emissions is equivalent to the PHEVs methodology.

The simulation of the considered vehicle portfolio uses a fixed size of the electric machine, equal to 60 kW representatives of the actual HEV portfolio, and variable number of cells connected in series, which is function of the vehicle mass, as reported in Figure 16.

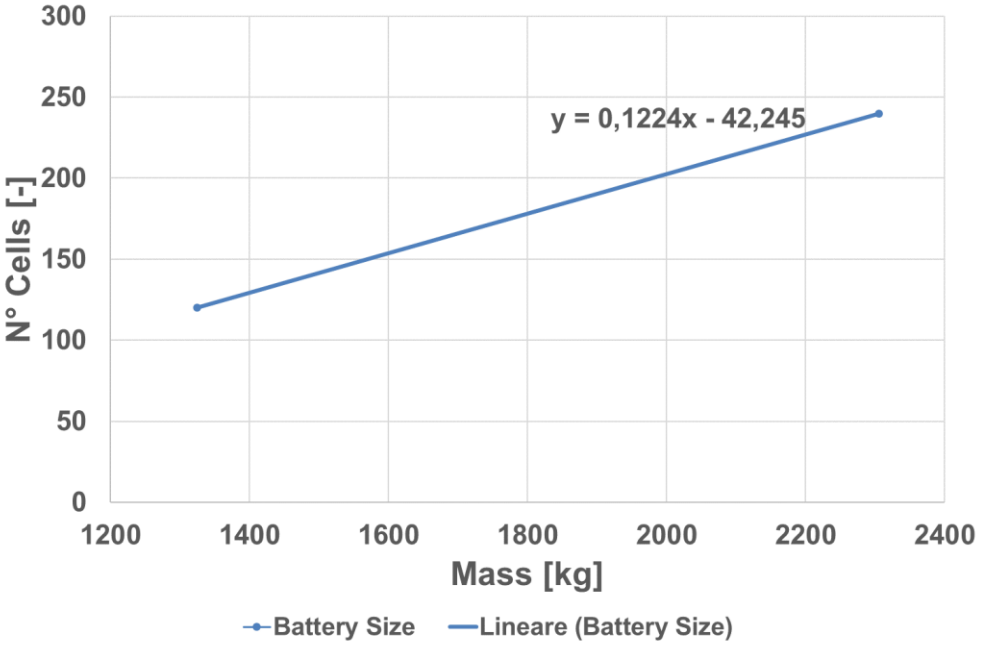

Figure 16: Battery size versus vehicle mass for HEVs

3.3.2 Results

From the application of the modelling approach presented in the previous sections to the fleet of vehicles (in line with what presented for BEVs and FCVs) the WLTP-NEDC CO_2 correlation factors presented in Table 6 have been derived for the different vehicle categories.

Using the factors presented in Table 6 the conversion factors of hybrid light-commercial vehicles have been also calculated. Due to the lack of adequate data, the ratio between conventional and hybrids WLTP to NEDC ratios for diesel and gasoline vehicles calculated for the passenger cars has been applied to calculate the respective values of light-commercial vehicles as defined in the following equation (pivoting approach):

$$R_{hybrid_{lcv}} = R_{conventional_{lcv}} * {R_{hybrid_{passenger}}}\Big/{R_{conventional_{passenger}}} \tag{3}$$

Table 6: WLTP/NEDC CO_2 Ratio for Hybrid Passenger Cars

	WLTP/NEDC CO_2 Ratio
Hybrid gasoline <1.4 l	*1.37*
Hybrid gasoline 1.4 - 2.0 l	*1.32*
Hybrid gasoline >2.0 l	*1.23*
Hybrid diesel <1.4 l	*1.38*
Hybrid diesel 1.4 - 2.0 l	*1.34*
Hybrid diesel >2.0 l	*1.30*

Results of the calculations are reported in Table 7.

Table 7: WLTP/NEDC CO_2 Ratio of for Hybrid Light Commercial Vehicles

Avg. WLTP/NEDC for Hybrid LCVs	
Diesel	1.45
Gasoline	1.38

4 Summary

Conversion factors were calculated between NEDC and WLTP type approval CO_2 values that can be used for the analytical work performed for the impact assessment of future WLTP-based CO_2 emission targets. The analysis was based on the reported 2015 CO_2 emissions from the European CO_2 Emissions Monitoring Database, and a collection of approximately 1,200 vehicles, whose technical characteristics were available. The main findings are the following:

- The fleet-wide, sales weighted average ratio between WLTP and NEDC officially reported CO_2 emissions for conventional passenger cars for year 2015 fleet composition was estimated to be 1.21.
- The WLTP/NEDC ratio decreases as the NEDC CO_2 value increases. This ratio becomes around 1 at values of approximately 250 gCO_2/km in NEDC.
- A slightly higher ratio between WLTP and NEDC is observed for gasoline vehicles as compared to diesel ones, while there is a decreasing trend in the ratio with increasing mass, capacity, or power of the vehicle.
- Results for Light-Commercial Vehicles are expected to follow the same trend as passenger cars. However the WLTP to NEDC ratios resulting from the calculations seem overall higher than those derived for passenger cars (especially for diesel vehicles, which however represent the vast majority of the fleet of light-commercial vehicles)
- Battery electric vehicles, fuel cell vehicles and hybrid vehicles show slightly higher WLTP/NEDC ratios than ICEVs and for BEVs and FCVs the dependency of the ratio from the size of the vehicle is less pronounced and opposite in sign, with bigger vehicles experiencing slightly higher ratios).
- Different considerations hold for plug-in hybrid vehicles instead. Due to the difference in the two procedures (NEDC & WLTP) for calculating the final CO_2 emissions, after several analyses it resulted that the WLTP to NEDC ratio will quickly decrease as the size of the vehicle batteries will increase. Given the uncertainty in the market evolution, in the present report it was considered appropriate to assume that in the coming years the WLTP CO_2 emissions for plug-in hybrid vehicles will be very close to the NEDC ones.

Considering that different sources show an increasing gap between real-world and NEDC fuel consumption as CO_2 emissions decrease, the fact that a similar trend is found also between WLTP and NEDC confirms that the new test procedure should be more representative of real-world emissions. In this light, the recent introduction of WLTP in the EU emission type-approval of light duty vehicles is crucial in order to reduce the gap between real-world and type-approval fuel consumption and CO_2 emissions.

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[32] European Commission. Regulation (EC) No 1230/2012 implementing Regulation (EC) No 661/2009 of the European Parliament and of the Council with regard to type approval requirements for masses and dimensions of motor vehicles and their trailers and amending Directive 2007/46/EC of the European Parliament and of the Council. 2012. n.d.

[33] EEA. Monitoring of CO2 emissions from passenger cars – Regulation 443/2009 2016.

[34] Monitoring of CO2 emissions from vans – Regulation 510/2011. Eur Environ Agency n.d. https://www.eea.europa.eu/data-and-maps/data/vans-8 (accessed October 2, 2017).

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[36] Lithium iron phosphate battery. Wikipedia 2017.

[37] Nickel–metal hydride battery. Wikipedia 2017.

List of abbreviations and definitions

EU	*European Union*
EC	*European Commission*
NEDC	*New European Driving Cycle*
WLTC	*Worldwide Light duty vehicle Test Cycle*
WLTP	*Worldwide Light duty vehicle Test Procedure*
REESS	*Rechargeable Electric Energy Storage System*
CO$_2$MPAS	*CO$_2$ Model for PAssenger and commercial vehicles Simulation*
PyCSIS	*Passenger Car fleet emissions Simulator*
ICE	*Internal Combustion Engine*
S/S	*Start/Stop System*
2WD	*2 Wheel Drive*
4WD	*4 Wheel Drive*
P_{dtr}	*Drivetrain Power (kW)*
F_0, F_1, F_2	*Road Load Coefficients (N, N/(km/h), N/(km/h)^2)*
m	*Vehicle Mass (kg)*
v	*Vehicle Velocity (km/h)*
a	*Vehicle Acceleration (m/s^2)*
φ	*Road Gradient (radians)*
g	*Acceleration of Gravity (m/s^2)*
η_{trn}	*Transmission Efficiency (%)*
P_{eng}	*Engine Power (kW)*
P_{elc}	*Vehicle Electrical System Power (kW)*
P_{mec}	*Vehicle Auxiliaries Mechanical Power (kW)*
t	*Time (s)*
FMEP	*Fuel Mean Effective Pressure (bar)*
BMEP	*Brake Mean Effective Pressure (bar)*
Cm	*Engine Mean Piston Speed (m/s)*
a, b, c, a2	*Willans Lines Model Thermodynamic Efficiency Parameters (-)*
l, l2	*Willans Lines Model Engine Losses Parameters (-)*
k	*Exponential Parameter (-)*
T	*Engine Temperature (^{o}C)*
T_{trg}	*Engine Target Operating Temperature (^{o}C)*
T_{thres}	*Engine Thermostat Temperature (^{o}C)*
T_{max}	*Engine Max Allowed Temperature (^{o}C)*
N	*Engine Speed (RPM)*
s	*Engine Stroke (mm)*
CC	*Engine Displacement (cc)*

FC	*Engine Fuel Consumption (g/s)*
$FLHV$	*Fuel Lower Heating Value (kJ/kg)*
ΔT	*Delta Temperature (^{o}C)*
ΔQ	*Delta Heat (J)*
eng_{m*cp}	*Engine Heat Capacity (J/K)*
cc	*Cooling Constant (-)*
$cool_{m*cp}$	*Coolant Heat Capacity (J/K)*
$cool_{flow}$	*Coolant Flow (g/s)*
EEA	*European Environmental Agency*
AP	Affinity Propagation
$CO2_{fleet}$	Fleet Sales Weighted CO_2 Emissions (g/km)
$CO2_{model}$	Individual Model CO_2 Emissions (g/km)
r_{model}	Individual Model Registrations (-)
m_{fleet}	Fleet Sales Weighted Mass (kg)
m_{model}	Individual Model Mass (kg)
TA	Type-Approval

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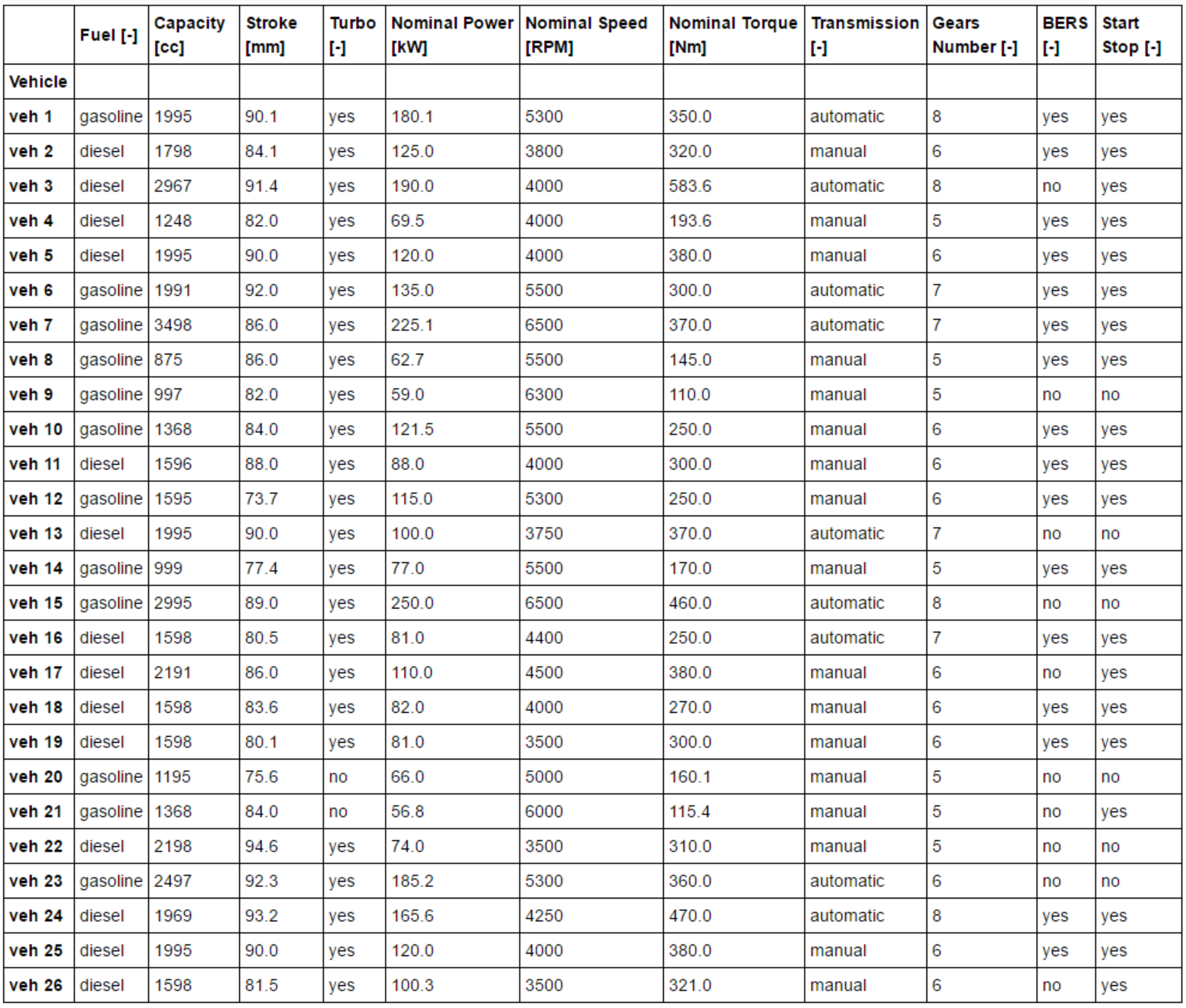
Annex 1. Database of measured cars

Table A.1: Measured cars



	Fuel [-]	Capacity [cc]	Stroke [mm]	Turbo [-]	Nominal Power [kW]	Nominal Speed [RPM]	Nominal Torque [Nm]	Transmission [-]	Gears Number [-]	BERS [-]	Start Stop [-]
Vehicle											
veh 1	gasoline	1995	90.1	yes	180.1	5300	350.0	automatic	8	yes	yes
veh 2	diesel	1798	84.1	yes	125.0	3800	320.0	manual	6	yes	yes
veh 3	diesel	2967	91.4	yes	190.0	4000	583.6	automatic	8	no	yes
veh 4	diesel	1248	82.0	yes	69.5	4000	193.6	manual	5	yes	yes
veh 5	diesel	1995	90.0	yes	120.0	4000	380.0	manual	6	yes	yes
veh 6	gasoline	1991	92.0	yes	135.0	5500	300.0	automatic	7	yes	yes
veh 7	gasoline	3498	86.0	yes	225.1	6500	370.0	automatic	7	yes	yes
veh 8	gasoline	875	86.0	yes	62.7	5500	145.0	manual	5	yes	yes
veh 9	gasoline	997	82.0	yes	59.0	6300	110.0	manual	5	no	no
veh 10	gasoline	1368	84.0	yes	121.5	5500	250.0	manual	6	yes	yes
veh 11	diesel	1596	88.0	yes	88.0	4000	300.0	manual	6	yes	yes
veh 12	gasoline	1595	73.7	yes	115.0	5300	250.0	manual	6	yes	yes
veh 13	diesel	1995	90.0	yes	100.0	3750	370.0	automatic	7	no	no
veh 14	gasoline	999	77.4	yes	77.0	5500	170.0	manual	5	yes	yes
veh 15	gasoline	2995	89.0	yes	250.0	6500	460.0	automatic	8	no	no
veh 16	diesel	1598	80.5	yes	81.0	4400	250.0	automatic	7	yes	yes
veh 17	diesel	2191	86.0	yes	110.0	4500	380.0	manual	6	no	yes
veh 18	diesel	1598	83.6	yes	82.0	4000	270.0	manual	6	yes	yes
veh 19	diesel	1598	80.1	yes	81.0	3500	300.0	manual	6	yes	yes
veh 20	gasoline	1195	75.6	no	66.0	5000	160.1	manual	5	no	no
veh 21	gasoline	1368	84.0	no	56.8	6000	115.4	manual	5	no	yes
veh 22	diesel	2198	94.6	yes	74.0	3500	310.0	manual	5	no	no
veh 23	gasoline	2497	92.3	yes	185.2	5300	360.0	automatic	6	no	no
veh 24	diesel	1969	93.2	yes	165.6	4250	470.0	automatic	8	yes	yes
veh 25	diesel	1995	90.0	yes	120.0	4000	380.0	manual	6	yes	yes
veh 26	diesel	1598	81.5	yes	100.3	3500	321.0	manual	6	no	yes

Annex 2. Fields of public datasets

Table A.2: Fields in the passenger cars fleet dataset

Name	**Field Definition**	**Data type**
ID	ID	integer
MS	Member state	varchar(2)
MP	Manufacturer pooling	varchar(120)
Mh	Manufacturer harmonised	varchar(120)
MAN	Manufacturer name OEM declaration	varchar(120)
MMS	Manufacturer name as in MS registry	varchar(120)
T	Type	varchar(120)
TAN	Type approval number	varchar(255)
Va	Variant	varchar(120)
Ve	Version	varchar(120)
Mk	Make	varchar(120)
Cn	Commercial name	varchar(120)
Ct	Category of the vehicle type approved	varchar(2)
r	Total new registrations	integer
m (kg)	Mass	integer
e (g/km)	Specific CO_2 Emissions	Integer
w (mm)	Wheel Base	Integer
at1 (mm)	Axle width steering axle	Integer
at2 (mm)	Axle width other axle	Integer
Ft	Fuel type	varchar(120)
Fm	Fuel mode	varchar(1)
ec (cm3)	Engine capacity	Integer
z (Wh/km)	Electric energy consumption	Integer
IT	Innovative technology or group of innovative technologies	varchar(255)
Er (g/km)	Emissions reduction through innovative technologies	Integer
ep (KW)	Engine power	Integer

Table A.3: Fields in the vehicle dataset

Field name	Field Definition	Data type
Model	Vehicle Model [-]	string
fuel_type	Fuel [-]	string
engine_capacity	Engine Capacity [cc]	integer
engine_max_power	Engine Nominal Power [kW]	integer
engine_max_speed_at_max_power	Engine Nominal Speed [RPM]	integer
final_drive_ratio	Final Drive Ratio [-]	float
gear_box_type	Gear Box Type [-]	string
gear_box_ratios	Gear Box Ratios [-]	dict
has_start_stop	Start Stop [-]	boolean
running_order_mass	Mass in Running Order [kg]	float
vehicle_mass_N	NEDC Inertia Mass [kg]	integer
target_co2	"Declared"/"Official" CO_2 Emissions Value [CO_2 gr/100 km]	float
nedc_parametric_co2	Simulated NEDC CO_2 Emissions Value [CO_2 gr/100 km]	float
wltp_parametric_co2	Simulated WLTP CO_2 Emissions Value [CO_2 gr/100 km]	float

Table A.4: Fields in the light-commercial fleet dataset

Name	**Field Definition**	**Data type**
ID	ID	Integer
MS	Member state	varchar(2)
MP	Manufacturer pooling	varchar(120)
Mh	Manufacturer harmonised	varchar(120)
MAN	Manufacturer name OEM declaration	varchar(120)
MMS	Manufacturer name as in MS registry	varchar(120)
T	Type	varchar(120)
Va	Variant	varchar(120)
Ve	Version	varchar(120)
Mk	Make	varchar(120)
Cn	Commercial name	varchar(120)
Ct	Category of the vehicle type approved	varchar(2)
Cr	Category of the vehicle registered	varchar(120)
r	Total new registrations	Integer
m (kg)	Mass	Integer
mb (kg)		Integer
TPMLM (kg)	Technically permissible maximum laden mass	Integer
Dam (kg)		Integer
mf (kg)		Decimal
e (g/km)	Specific CO_2 Emissions	Integer
w (mm)	Wheel Base	Integer
at1 (mm)	Axle width steering axle	Integer
at2 (mm)	Axle width other axle	Integer
Ft	Fuel type	varchar(120)
Fm	Fuel mode	varchar(1)
ec (cm3)	Engine capacity	Integer
z (Wh/km)	Electric energy consumption	Integer
IT	Innovative technology or group of innovative technologies	varchar(255)
Er (g/km)	Emissions reduction through innovative technologies	Integer
TAN	Type approval number	varchar(255)
ep (KW)	Engine power	Integer

Annex 3. Road Loads Calculation Model

Definition of Masses

A list of the required vehicle masses for the calculation of the Road Loads is provided bellow:

- Mass in Running Order (*MRO*) is defined as in Article 2(4)(a) of Commission Regulation (EU) No 1230/2012.
- Reference Mass (*RM*) is defined as $RM = MRO + 25\ [kg]$
- Max Permissible Mass (*MM*), when not available is defined as $MM = RM + 500\ [kg]$
- Unladen Mass Min (*UMMin*) is defined as $UMMin = RM - 100\ [kg]$
- Unladen Mass Max (*UMMax*) is defined as $UMMax = RM + DUM\ [kg]$, where *DUM* is defined from the following empirical relationship for passenger cars:

  $$DUM = 0.00009 * UMMin^2 - 0.0364 * UMMin\ [kg]$$

  While for light-commercial vehicles the following functions are used:

  $$cla = 0.00009 * UMMin^2 - 0.0364 * UMMin\ [kg]$$

  $$clb = 0.0777 * UMmin + 67.744\ [kg]$$

  $$DUM_{class\ I\ lcv} = cla; DUM_{class\ II\ lcv} = {(cla + clb)}/_{2}\ ; DUM_{class\ III\ lcv} = clb$$

- Laden Mass Max (*LM*) is defined as equal to *MM*, $LM = MM\ [kg]$
- Test Mass High (*TMH*) is calculated as:

  $$TMH = UMMax\ +\ 100\ +\ 0.15\ *\ (LM\ -\ UMMax\ -\ 100)\ [kg]$$

- Test Mass Low (*TML*) is calculated as:

  $TML = UMMin\ +\ 100\ +\ 0.15\ *\ (LM\ -\ UMMax\ -\ 100)\ [kg]$.

Definition of Aerodynamic Drag

The Aerodynamic Drag (*Drag*) is defined as $Drag = FA * Cw\ [-]$, where *FA* and *Cw* are defined as presented in the following paragraphs.

The Delta Drag (*DCDA*) which captures the effect in the drag of the difference between the "best case" and the "worst case" cars within the same category, is defined as $DCDA = 2 * 0.04\ [-]$ for passenger cars and class I light-commercial vehicles, $DCDA = 0.1\ [-]$ for class II light-commercial vehicles, and $DCDA = 0.12\ [-]$ for class III light-commercial vehicles.

Frontal Area

The Frontal Area (*FA*) of the vehicle is defined as $FA = W * H * 0.84\ [m^2]$, where *W* represents the vehicle's width, in meters, and *H* the vehicle's height, in meters.

The factor 0.84 is an empirical factor used for the correction of the "dead" areas of the product of width and height, e.g. area between ground and vehicle's bottom side in-between the wheels, side areas between vehicle's sides and tips of mirrors, etc. For class II and class III light-commercial vehicles, this factor is considered equal to 0.91 and 0.98 respectively.

Aerodynamic Coefficient

The Aerodynamic Coefficient (*Cw*) of the vehicle is provided by the following table, based on the vehicles carbody type.

These values are taken from the BOSCH Automotive Handbook [28] and amended in order to capture the effect of advanced aerodynamic design of modern cars - when it was judged that the minimum value does not well define modern cars another value has been picked from the defined range. For class II and class III light-commercial vehicles, the aerodynamic coefficient is increased by 12.5% and 25% respectively.

Carbody	Cw
Cabriolet	0.28
Sedan	0.27
Hatchback	0.3
Stationwagon	0.28
SUV/Crossover	0.35
MPV	0.3
Coupe	0.27
Pick-up	0.4

Definition of Wheel Rolling Resistance

Regulation (EC) No 1222/2009 of the European Parliament and of the Council defines the energy classes of the various tyres based on their rolling resistances. For the purposes of the present exercise C1 tyres of Energy Efficiency Class A are considered representative and thus the Wheel Rolling Resistance (*WRR*) is defined as equal to $WRR = 0.0065\,[-]$, for both passenger cars and class I light-commercial vehicles. For class III light-commercial vehicles C2 tyres of Energy Efficiency Class B are considered, $WRR = 0.006\,[-]$, while for class II an average $WRR = 0.00625\,[-]$ is used.

The Delta Wheel Rolling Resistance (*DRR*) which captures the effect of the different tyres / in the rolling resistance of the difference between the "best case" and the "worst case" cars within the same "category", is defined as $DRR = 0.0105\ -\ 0.008\,[-]$.

Definition of Procedural Differences affecting Road Loads

Pre-conditioning effect

In preparing the chassis-dynamometer for the execution of a type-approval test, the vehicle is pre-conditioned in order to reach similar conditions to those used in the coast-down test. The pre-conditioning procedure used in the WLTP test differs from that used for the purpose of NEDC so that, with equal road loads, the vehicle is considered subject to higher forces under the WLTP. That difference, defined as Pre-conditioning Effect (*PCE*) shall be set at 6 Newtons, such as $PCE = 6\,[N]$.

Tyre pressure

According to the WLTP, the lowest tyre pressure for the vehicle test mass shall be used, while this is not specified in the NEDC. For the purpose of determining the tyre pressure to be taken into account for the purpose of calculating the NEDC road load, the tyre pressure shall, taking into account the different tyre pressure per vehicle axle, be the average between the two axles of the average between the minimum and the maximum tyre pressure permitted for the selected tyres on each axle for the NEDC reference mass of the vehicle. The calculation shall be carried out for both the "best case" vehicle / vehicle L and the "worst case" vehicle / vehicle H.

For the purpose of the present exercise the followings are defined:

$P_{max} = 3\,[bar]$, is the average of the maximum tyre pressures of the selected tyres for the two axles; considered constant for both vehicles L and H

$P_{min} = 2\ [bar]$, is the average of the minimum tyre pressures of the selected tyres for the two axles; considered constant for both vehicles L and H,

$P_{avg} = {}^{(P_{max} + P_{min})}/_{2}\ [bar]$, the average between the previous two.

The corresponding effect in terms of resistance applied to the vehicle, defined as *TP*, shall be calculated using the following formulae: $TP = \left({}^{P_{avg}}/_{P_{min}} \right)^{-0.4}\ [-]$.

Tyre Tread Depth

A minimum tyre tread depth of 80% is to be considered for the WLTP test, while the minimum allowed tyre tread depth for the purpose of the NEDC test is to be considered as equal to 50% of the nominal value. This results in an average difference of 2mm in tread depth between the two procedures. The corresponding effect in terms of the resistance applied to the vehicle, defined as *TTD*, shall be determined for the purpose of the NEDC road load calculation in accordance with the following formulae: $TTD = 2 * 0.1 * RM * {}^{9.81}/_{1000}\ [-]$.

Inertia of Rotating Parts

During the WLTP test four rotating wheels are to be considered, while for the purpose of the NEDC tests only two rotating wheels are to be considered. The effect this has on the forces applied to the vehicle, defined as *RI*, shall be taken into account in accordance with the formulae: $RI = {}^{1.015}/_{1.03}\ [-]$.

Results / Road Loads Definitions

Definition of "physical" F0, F1, & F2

The three functions bellow define the "physical" road loads which are later used for the calculation of the regulated road load coefficients.

$$F0 = RM * WRR * 9.81\ [N]$$

$$F2 = {}^{0.5 * 1.2 * Drag}/_{3.6^2}\ [N/(km/h)^2]$$

$$F1 = {}^{(-71.735 * F2 + 2.7609)}/_{2}\ [N/(km/h)]$$

The last function, *F1*, is an empirical function derived from known road load coefficients of measured cars. For class II and class III light-commercial vehicles *F1* is calculated by the following empirical functions:

$$F1_{class\ II\ lcvs} = {}^{(-44.5 * F2 + 2.6)}/_{2}\ [N/(km/h)]$$

$$F1_{class\ III\ lcvs} = {}^{(-18.31 * F2 + 2.4439)}/_{2}\ [N/(km/h)]$$

Definition of NEDC Road Loads

Starting from the physical coefficients *F0*, *F1*, *F2*, and taking into account the respective procedural differences the road load coefficients for NEDC are calculated, along with the respective reference mass, as follows:

$$F0N = (F0 - TTD) * TP * RI\ [N]$$

$$F2N = F2\ [N/(km/h)^2]$$

$$F1N = {}^{F1}/_{2}\ [N/(km/h)]$$

$$RMN = RM\ [kg]$$

Definition of WLTP H Road Loads

Starting from the NEDC coefficients *F0N*, *F1N*, *F2N*, and performing all correction in order to take into account the respective procedural differences the road load coefficients for WLTP High are calculated, along with the respective reference mass, as follows:

$$F0H = (F0N + PCE + TTD) * {}^{1}/_{RI} * {}^{1}/_{TP} * {}^{TMH}/_{RM} + (DRR * TMH * 9.81)\ [N]$$

$$F2H = {}^{F2N}/_{RI} + \left({}^{1.189}/_{2} * {}^{DCDA}/_{3.6^2}\right)\ [N/(km/h)^2]$$

$$F1H = {}^{F1N}/_{RI}\ [N/(km/h)]$$

$$RMH = TMH\ [kg]$$

Definition of WLTP L Road Loads

Starting from the NEDC coefficients *F0N*, *F1N*, *F2N*, and performing all correction in order to take into account the respective procedural differences the road load coefficients for WLTP Low are calculated, along with the respective reference mass, as follows:

$$F0L = (F0N + PCE + TTD) * {}^{1}/_{RI} * {}^{1}/_{TP} * {}^{TML}/_{RM}\ [N]$$

$$F2L = {}^{F2N}/_{RI}\ [N/(km/h)^2]$$

$$F1L = {}^{F1N}/_{RI}\ [N/(km/h)]$$

$$RML = TML\ [kg]$$

Annex 4. Procedural differences between the WLTP and the NEDC for the CO_2 emissions of PHEVs

Driving cycles

A comparison of the two driving cycles (NEDC and WLTC) is provided in Table A.5, which can be helpful for a better understanding of the difference between the two testing conditions.

Table A.5: Key parameters of the driving cycles NEDC and WLTC

Parameters	**NEDC**	**WLTC**
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

Test-procedures

A summary of the main procedural differences identified between NEDC and WLTP procedures that will have either direct or resulting impact on CO_2 emissions and Fuel Consumption can be mainly summarized in the following three points:

1. Higher WLTP road load (RL) due to stricter road load and mass determination procedure;
2. Changes in the test protocol and the laboratory test conditions;
3. Procedures introduced for post-processing of the data.

However, for PHEVs there are additional differences to consider related to laboratory procedures and post-processing of the data that need to be considered and that significantly affect the final CO_2 and FC numbers. These procedural differences are discussed in the following sections.

Charge-Depleting Test

In the NEDC if the electric range of a vehicle is longer than 1 NEDC cycle (~11km), the manufacturer (OEM) had the possibility to request CD mode test to be carried out in a pure electric mode. Given that most PHEVs present in the market already have range higher than 11km, CD mode CO_2 emissions resulting from NEDC testing are equal 0 g/km.

These favourable testing assumptions for CD NEDC testing will be eliminated with the introduction of WLTP, where WLTP CD test can bring a non-negligible increase in the CD CO_2 emissions and FC. In the WLTP, CD CO_2 emissions and FC of each phase of WLTP test (low, medium, high, and extra-high) have a different weighting in the final CD CO_2 emissions in line with the formula:

$$\mathrm{M}_{\mathrm{CO2,CD}}^{WLTP} = \frac{\sum_{\mathrm{j=1}}^{\mathrm{k}}(\mathrm{UF_j} \times \mathrm{M_{CO2,CD,j}})}{\sum_{\mathrm{j=1}}^{\mathrm{k}} \mathrm{UF_j}}$$

Where $M_{CO2,CD}^{WLTP}$ is the WLTP's utility factor-weighted CD CO_2 emission in g/km, UF_j is the utility factor of WLTP's CD phase j, and $M_{CO2,CD,j}$ is the CO_2 mass emission of CD phase j in g/km.

Method for calculation of specific utility factors for each phase of the WLTP is explained in details in Annex 8 (Appendix 5) of the GTR#15[8]. Utility factors represent the ratio of the distance covered in CD mode to the total distance covered between 2 subsequent charges. The UF curve (Figure 1) is developed based on driving statistics described in SAE J2841[9].

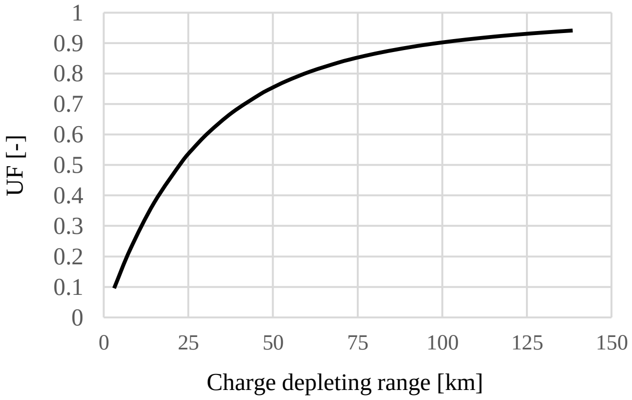


Figure 17: WLTP Utility Factor curve

The UF curve for Europe (according to statistics for Europe) is valid from 0 km to 800 km where at 800 km the UF converges to 1. With increasing electric range CD phase-CO_2 emissions contribute less to $\boldsymbol{M_{CO2,CD}}$ and their phase-UFs decrease with increasing the number of WLTP tests in CD mode.

Charge-Sustaining Test

CS test is performed following procedures for standard Type 1 test under cold start conditions, i.e. the standard European Certification test. Although the WLTP test will inevitably result in higher CS CO_2 emissions and FC compared to the NEDC due to higher WLTP RLs and more energy demanding driving cycle, it is worth to recall that the WLTP introduces an energy balance correction which was not present in the NEDC TA

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[8] http://www.unece.org/fileadmin/DAM/trans/doc/2016/wp29grpe/ECE-TRANS-WP29-GRPE-2016-03e_clean.pdf.

[9] SAE 2841. "Utility factor definitions for plug-in hybrid electric vehicles using travel survey data", September 2010, Hybrid-EV Committee

procedure, and which might result in lower WLTP CS CO_2 emissions and FC compared to the NEDC CS results. Therefore, the increase in the CD CO_2 and FC, as described in the previous section, might be partially compensated by the energy-balance correction foreseen in the WLTP.

Under the WLTP procedure, the OEM has the possibility to correct the CS CO_2 emissions for the difference of the State of Charge (SOC) of the battery between the start and end of the CS test. This was not foreseen under the NEDC and the formula for WLTP CS correction is the following:

$$M_{CO2,CS}^{WLTP} = M_{CO2,CS,nb} - K_{CO2} \times EC_{DC,CS}$$

Where K_{CO2} is the CO_2 correction coefficient (g/km)/(Wh/km)), $EC_{DC,CS}$ is the electric energy consumption of CS test (Wh/km), and $M_{CO2,CS,nb}$ is the non-balanced CO_2 result (g/km) obtained in the CS cycle, which doesn't take into account whether the Rechargeable Electric Energy Storage System (REESS) has been charged or discharged during the test. For the correction of FC K_{fuel} shall be developed in a similar way.

The correction coefficients K_{CO2} and K_{fuel} are determined by the manufacturer from results of at least three CS Type 1 tests and are approved and reviewed by the approval authority. If the electric energy change during the CS test is more than 0.5% and the SOC decreased (that corresponds to battery discharge) correction is mandatory. Correction is optional in situations with SOC increase, but since in these cases applying the correction will result in lower CO_2 and FC it is easy to predict that OEMs will take advantage of it. Therefore, for the vehicles with charging battery strategy during the CS test this correction will reduce the CS CO_2 and FC and since this correction did not apply under the NEDC, this is an important reduction that OEMs can benefit under the WLTP.

Weighted Final CO_2 Emissions

In the NEDC, the final CO_2 emissions, FC, and electric energy consumption (EC) are calculated as weighted values using the following formula:

$$M_{CO_2}^{NEDC} = \frac{D_{OVC} * M_1 + D_{av} * M_2}{D_{OVC} + D_{av}}$$

Where D_{OVC} is the vehicle's off-vehicle charging range in km (OVC); M_1 is the CD CO_2, FC, or EC; D_{av} is equal to 25 km and represents the average distance covered in CS mode prior to the next battery charge; and M_2 is the CS CO_2, FC, or EC.

As we already highlighted, the CD CO_2 and FC may be 0 if the electric range of vehicle is higher than 1 NEDC cycle, which is the case for most PHEVs. Therefore, only CS CO_2 and FC contribute to the final weighed NEDC results.

The formula introduced in the WLTP to calculate the final weighted CO_2 and FC is the following:

$$\mathrm{M}_{\mathrm{i,weighted}}^{WLTP} = \sum_{\mathrm{j=1}}^{\mathrm{k}} (\mathrm{UF_j} \times \mathrm{M_{i,CD,j}}) + (1 - \sum_{\mathrm{j=1}}^{\mathrm{k}} \mathrm{UF_j}) \times \mathrm{M_{i,CS}}$$

In this formula UFs are used to weight CD and CS CO_2 and FC. The longer the electric range is, the lower contribution of CS CO_2 and FC to the total weighted result is expected.

Before performing any test, in order to quantitatively compare and estimate the effects of the two different weighting approaches (NEDC and WLTP) on CS results and total weighted results, simple calculations with different assumed electric ranges of the vehicles were performed by the authors and the results are shown in Table A.6.

Table A.6: Difference in CS weighting factors depending on electric distance in the NEDC and WLTP

Electric range NEDC (km)	Electric range WLTP (km)	NEDC/WLTC electric range	NEDC CS UF	WLTP CS UF	WLTP/NEDC CS UF	WLTP/NEDC CS TOTAL
25	25	1	0.43	0.27	0.62	0.69
50	50	1	0.31	0.17	0.53	0.58
75	75	1	0.25	0.11	0.45	0.50
100	100	1	0.19	0.08	0.43	0.47
150	150	1	0.14	0.05	0.33	0.36
200	200	1	0.11	0.03	0.27	0.30
25	20	1.25	0.43	0.49	1.14	1.25
50	40	1.25	0.31	0.27	0.86	0.95
75	60	1.25	0.25	0.17	0.67	0.74
100	80	1.25	0.19	0.11	0.60	0.66
150	120	1.25	0.14	0.06	0.42	0.47
200	160	1.25	0.11	0.05	0.43	0.47

In the first scenario (first six rows of the table) we assumed the same electric distances driven under the NEDC and WLTP (NEDC/WLTC electric range ratio equal to 1) to see the influence of only different CS weighting formulas present in two regulations. As it can be seen, with the same electric range the contribution of CS emissions is lower in WLTP compared to the NEDC. Increasing the range results in lower WLTP/NEDC CS ratio. For example, the ratio WLTP/NEDC of CS UFs decreased from 0.62 for vehicle with 25 km electric range to the ratio of 0.27 for vehicle with 200 km range.

In the second scenario (last six rows of the table) we assumed electric distance of WLTP to be 25% lower than that of NEDC (NEDC/WLTC electric range ratio equal to 1.25), due to the more energy demanding cycle and the higher road loads resulting from the more strict new procedure. That consequently resulted in higher WLTP/NEDC CS UFs ratios compared to the first case. In the last column, the WLTP/NEDC CS UFs ratio has been further increased by 10%, providing the WLTP/NEDC CS TOTAL ratio, which considers also the overall higher CS CO_2 emissions and FC expected from the WLTP compared to the NEDC testing[10]. The results of the experimental campaign reported in the following sections will show how close to reality these pure theoretical calculations are.

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[10] Pavlovic, J., Marotta, A., Ciuffo, B. "CO2 emissions and energy demands of vehicles tested under the NEDC and the new WLTP type approval test procedure", Applied Energy, 2016, 177, 661-670.

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