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Europe-centric light duty test cycle and differences with respect to the WLTP cycle

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Europe-centric light duty test cycle and differences with respect to the WLTP cycle

Abstract

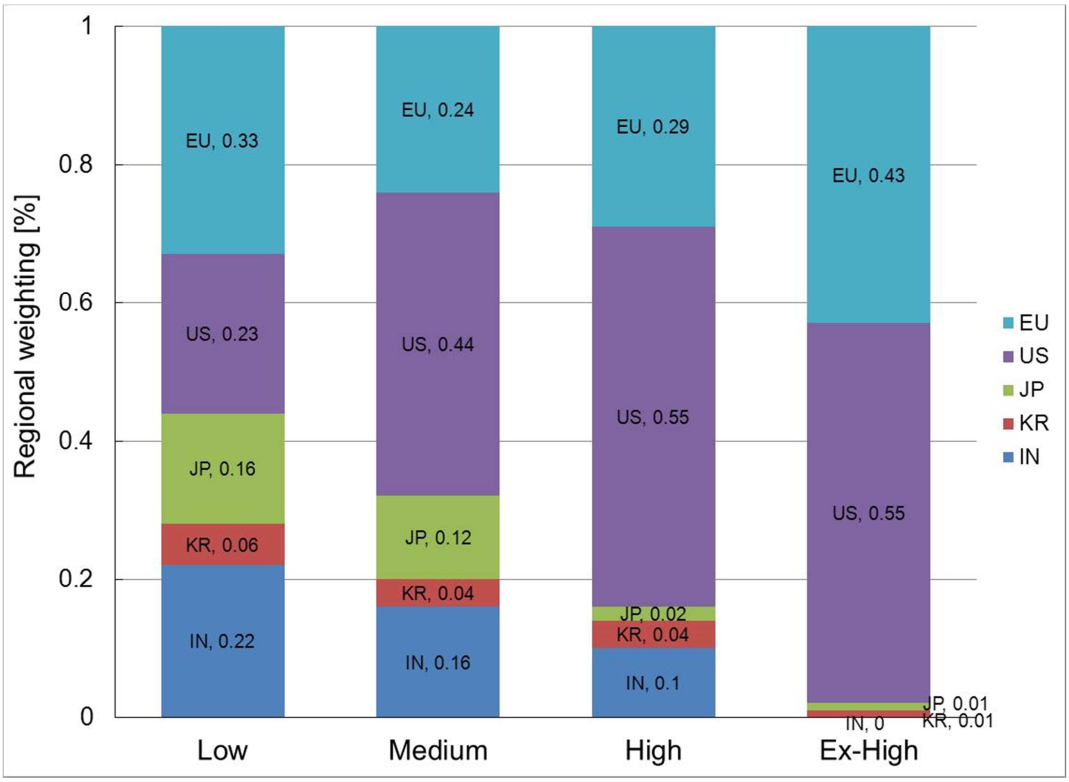
The Worldwide harmonized Light duty Test Cycle (WLTC) has been designed on the basis of the in-use driving databases provided by Europe, India, Japan, Korea and USA. These databases have been merged by applying a weighing factor to each of them, obtaining the "Unified" database. In order to verify the representativeness of the Unified database and the resulting WLTC with respect to the European driving behavior, a comparison between the Unified and the European database has been carried out, which has shown a high level of resemblance for the most important parameters (i.e. speed distribution, acceleration distribution, speed* acceleration, etc.). The drivability tests carried out over the WLTC in several laboratories have shown levels of CO2 emissions similar to those obtained with NEDC. Possible explanations of such results are presented.

The WLTP database and the development of WLTC

The construction of the WLTP database has been based on 4 main contributions: 1) EU + Switzerland; 2) India; 3) Japan + Korea; 4) USA. They are grouped in this way according to their driving characteristics, which in term of decreasing dynamicity can be ordered as:

1. USA database (the most dynamic driving behavior)
2. EU + Ch
3. Japan + Korea
4. India database (the least dynamic driving behavior)

The WLTP database (also called "Unified database" and WWW database) has been obtained by applying a weighing factor to each database, as shown in the following diagram (Figure 1):



Low, Medium, High and Ex-High, refer to the four speed phases in which the WLTP database has been divided. The Low speed phase includes all short trips with a max speed < 60 km/h; the Medium speed phase includes all short trips with max speed > 60 km/h but < 80 km/h; the High speed phase includes short trips with max speed > 80 km/h but < 110 km/h; and the Extra-high speed phase all short trips with max speed exceeding 110 km/h.

The weighing factors are based on traffic volumes (current and foreseen) of each party. To derive such weighing factors the starting point was the national traffic statistics (Table 1).

Region		Total	Urban	Rural	Motorway
World-wide	JP	1.9E+10	1.1E+10	6.5E+09	1.3E+09
	EU	6.8E+10	3.3E+10	3.0E+10	4.7E+09
	US	8.9E+10	4.9E+10	2.0E+10	2.0E+10
	KR	8.4E+09	4.3E+09	1.5E+09	2.6E+09
	IN	2.0E+10	1.4E+10	4.8E+09	1.0E+09
	CN				
	Total	2.0E+11	1.1E+11	6.3E+10	2.9E+10
EU	BE	1.8E+09	5.5E+08	1.0E+09	2.4E+08
	DE	1.1E+10	5.8E+09	4.2E+09	1.1E+09
	ES	8.5E+09	4.5E+09	3.7E+09	2.8E+08
	FR	1.2E+10	5.3E+09	5.4E+09	8.6E+08
	IT	6.0E+09	2.2E+09	3.2E+09	6.1E+08
	PL	2.3E+09	8.4E+08	1.5E+09	3.2E+07
	SI	2.2E+08	1.2E+08	7.6E+07	1.9E+07
	UK	1.1E+10	7.1E+09	3.8E+09	5.3E+08
	CH	2.0E+09	7.2E+08	1.0E+09	2.0E+08
	SE				
	Total	5.5E+10	2.7E+10	2.4E+10	3.9E+09

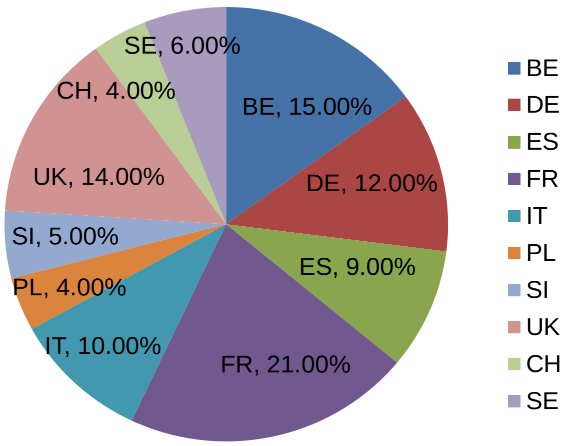
Table 1: Traffic volume (vehicle hours). Sources: JARI; http://unfccc.int/ghg_data/ghg_data_unfccc/items/4146.php; http://www.irfnet.org/statistics.php; for EU also TREMOVE.

During data analysis, the road type (urban, rural, motorway) had to be redefined due to differences in the definitions and in the speed limits on these roads from different regions. It was thus decided to go from the Urban/Rural/Motorway scheme to the Low/Medium/High speed phase approach and, at a later stage, the necessity to split the High speed phase in two (High and Extra-High) emerged as the only possible compromise to continue with a harmonized approach (in fact there was an insurmountable difference in the motorway max allowed speed, around 130 km/h for EU and USA, around 100 km/h for India, Japan and Korea). After subdividing the database of each party into these four speed phases, the time percentage of each of them was multiplied by the total vehicle hour of the party (blue column in the table 1), obtaining the vehicle hour for each speed class and each party (see table 2). For India an exception was applied (total traffic volume increased by 50% in the light of the predicted increase over next years). From this the weighing factors shown in figure 1 were defined.

	Low	Midlle	High	Ex-High	Total
EU	23.338	12.444	15.748	16.380	67.911
US	15.898	22.578	29.541	21.254	89.271
JP	11.126	6.157	1.164	328	18.775
KR	4.053	1.838	2.087	443	8.420
IN	15.629	8.466	5.641	64	29.800
World-wide	70.044	51.484	54.181	38.470	214.178
proportion	**0.327**	**0.240**	**0.253**	**0.18**	**1**

Table 2: Traffic volume (million vehicle hours) per speed class for each contracting party

To build the European database (which included the contribution of 9 EU member states + Switzerland) it was decided to use a slightly different approach. Starting from the observation that the driving behavior did not differ very much among EU countries, it was considered reasonable to give some weight also to the robustness of the single database. Thus, instead of considering only the traffic volume of the country (somewhat representative of the population) a 50% weight was assigned also to the mileage of each country's database). The result of such approach is shown in figure 2:



From the pie-chart it can be seen that, for example, Belgium has a weight of 15%, which is clearly due to the fact that Belgium has provided a very big database of in-use driving data. Different weighing criteria were tested, but they did not bring significant differences in the overall European driving characteristics, confirming that all EU+Ch countries have very similar driving behavior.

Figure 2

The development of the WLTC (Worldwide harmonized Light duty Test Cycle) has of course been based on the WLTP database. The length of the WLTC was set to 1800 seconds, similar to WHDC (Worldwide harmonized Heavy Duty Cycle) and WMTC (Worldwide harmonized Motorcycle Test Cycle). This cycle duration represents an accepted compromise between statistical representativeness on the one hand and test feasibility in the laboratory on the other hand. The relative length of each speed phase (Low, Medium, High and Extra-high speed phase) was determined on the basis of their relative proportion within the world-wide traffic volume, as reported in table 2 (see Annex 1).

The short trips and idling periods within each speed phase of WLTC were selected from the Unified database in order to have the best possible statistical representation of the most important parameters, i.e.:

- Speed distribution
- Idling periods distribution
- Acceleration distribution
- Speed*acceleration (v*a) distribution
- Relative Positive Acceleration (RPA). The relative positive acceleration is a speed-related average acceleration of the vehicle, directly related to the average power. It is calculated according to the following equation:

$$RPA = \frac{\int_0^T \left(v_i * a_i^+\right) dt}{v_i * dt}$$

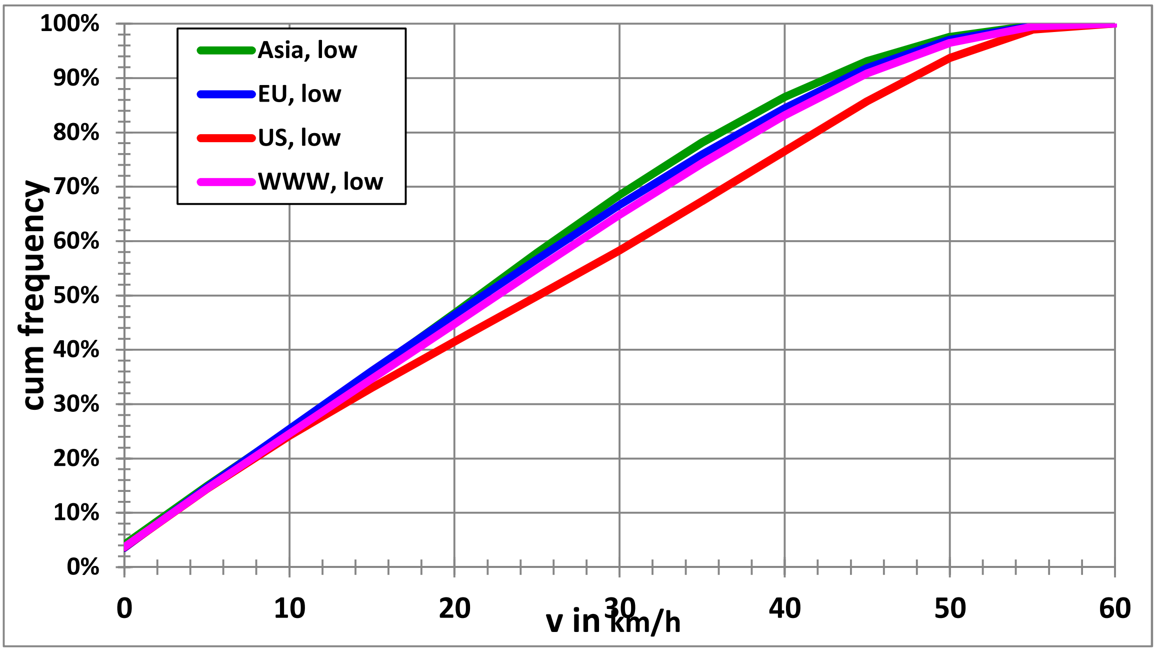
T= total cycle time [s]
v = momentary speed [m/s]
a+ = momentary positive acceleration [m/s2]

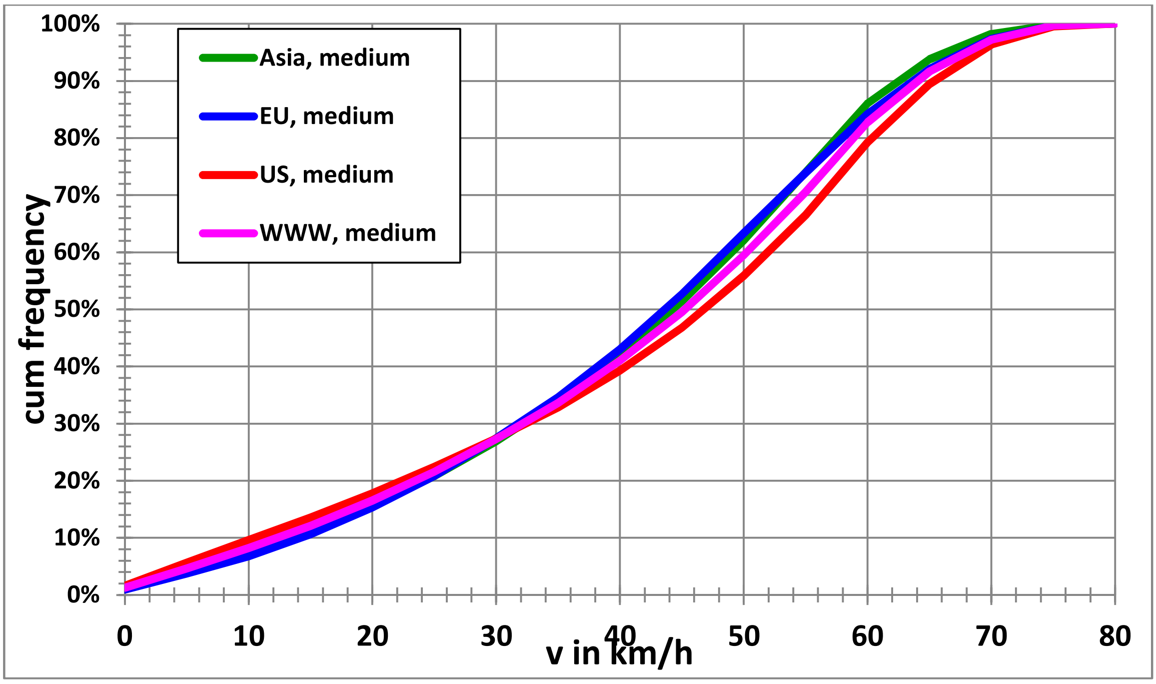
In other words, the WLTC has been designed in order to provide the best statistical representation of those parameters that are known to have the major impact on air pollutant emissions and fuel consumption (see Annex 2).

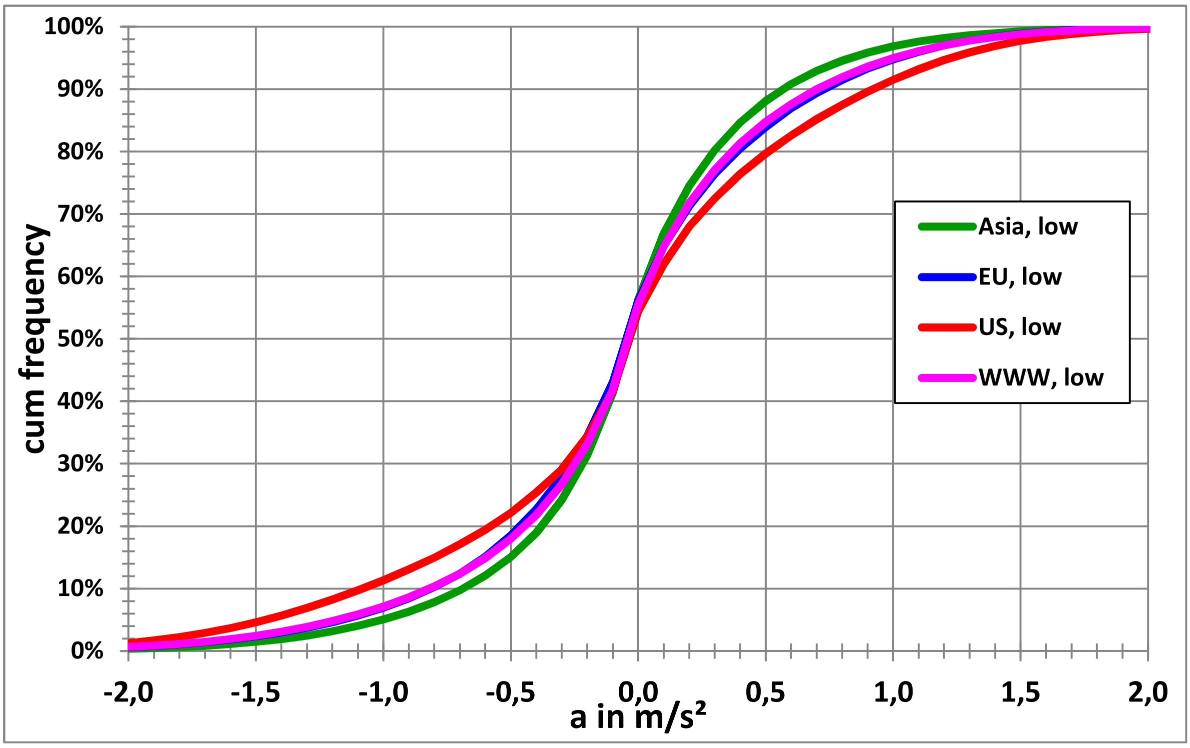
Correlation between Worldwide database and European Database

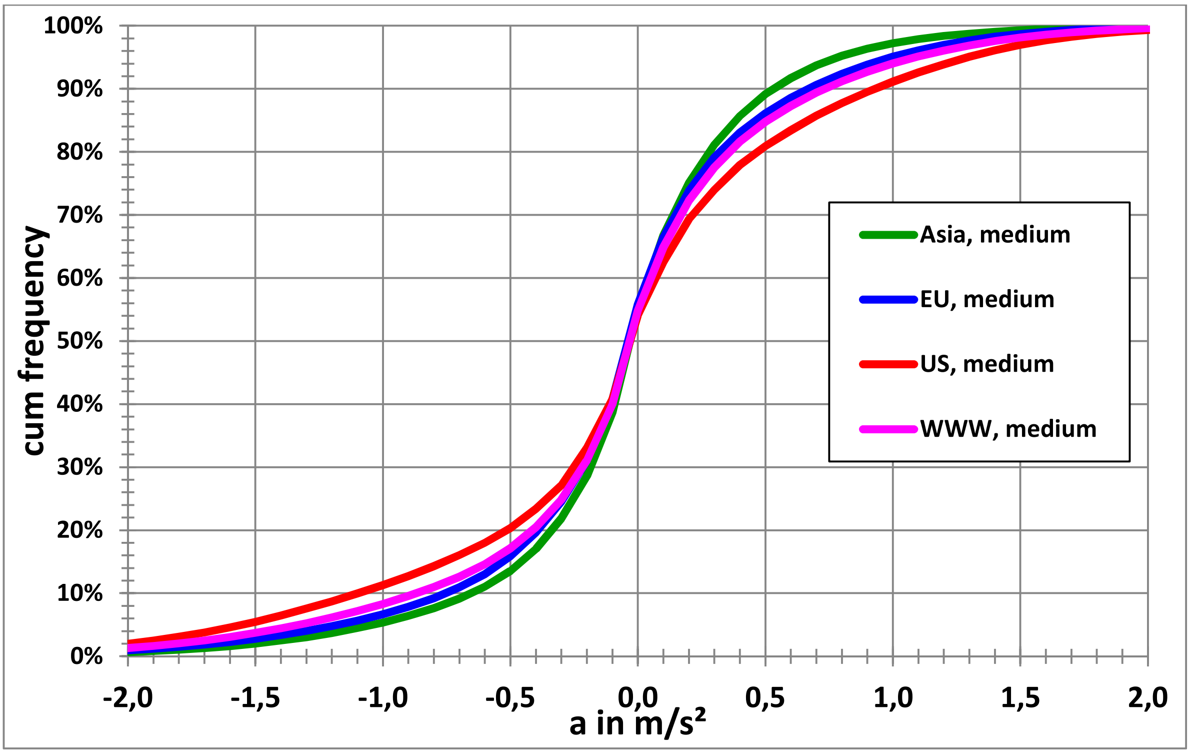
In addition to the development of the WLTC, a comparative study of the representativeness of the Unified database with respect to each party's database was conducted.

From a European perspective the results were very positive, because the two databases (Unified and EU) show similar features for all the above mentioned parameters. The reason of this fortuitous coincidence is due to the European database being midway between the higher-dynamic USA database and the lower-dynamic Asian database (India+Japan+Korea). Thus the Unified database, i.e. the average database, lies very close to the European one. In the following figures some examples of the comparative study are shown, for speed, acceleration and speed*acceleration (v*a) distributions. The figures present only the Low speed phase distributions and the Medium speed phase distributions that show the widest range, while the High and Extra-High speed phases are composed essentially by European and USA data.




Asia, medium
EU, medium
US, medium
WWW, medium
cum frequency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
10
20
30
40
50
60
70
80
v in km/h


Asia, low
EU, low
US, low
WWW, low
cum frequency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-2,0
-1,5
-1,0
-0,5
0,0
0,5
1,0
1,5
2,0
a in m/s²



100%
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-2,0
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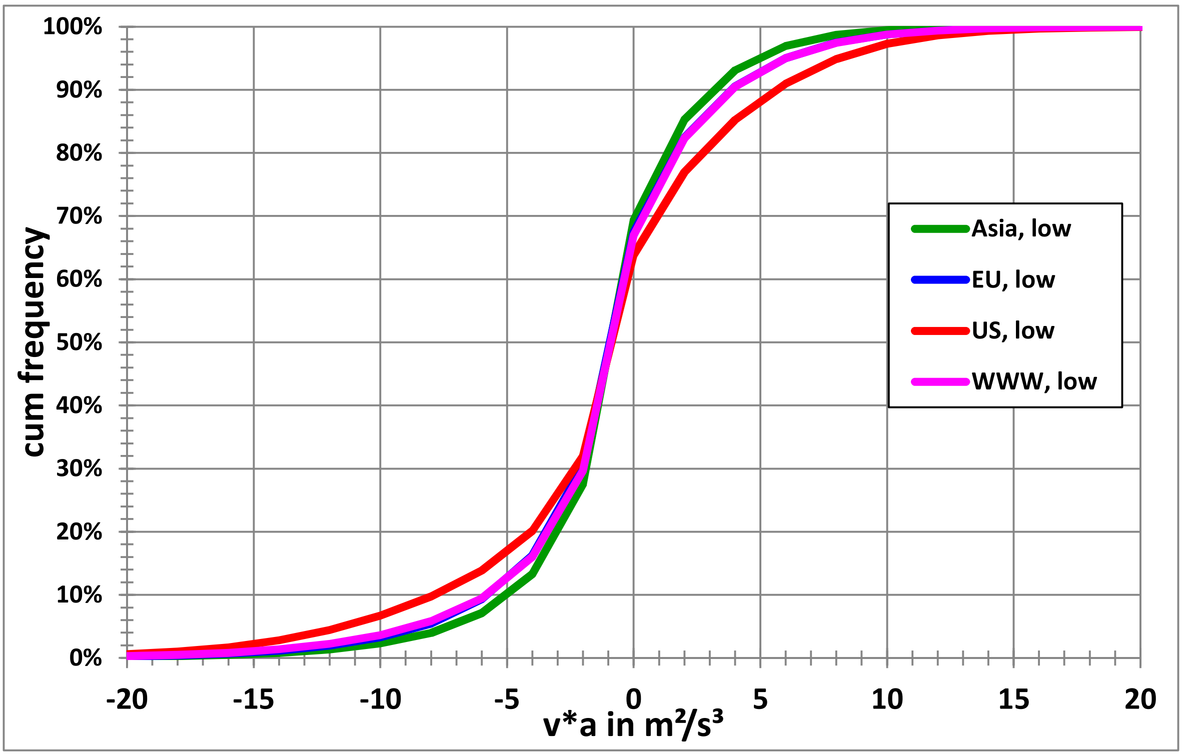
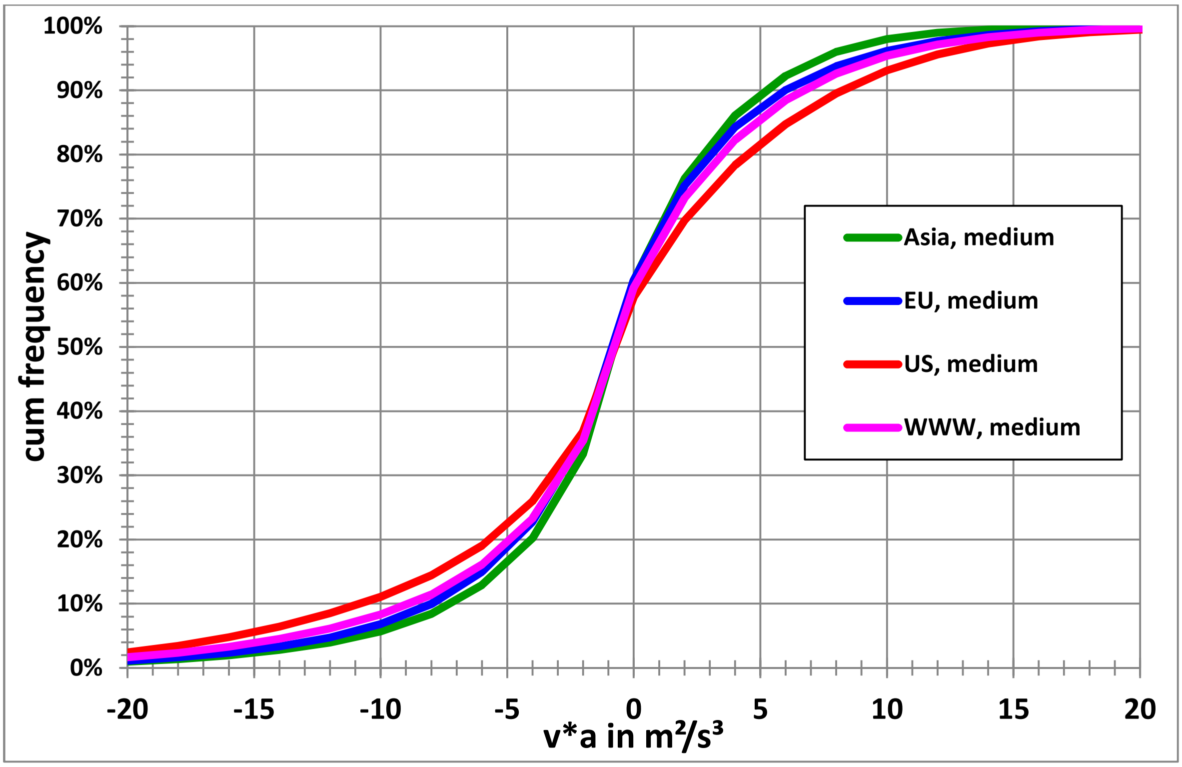
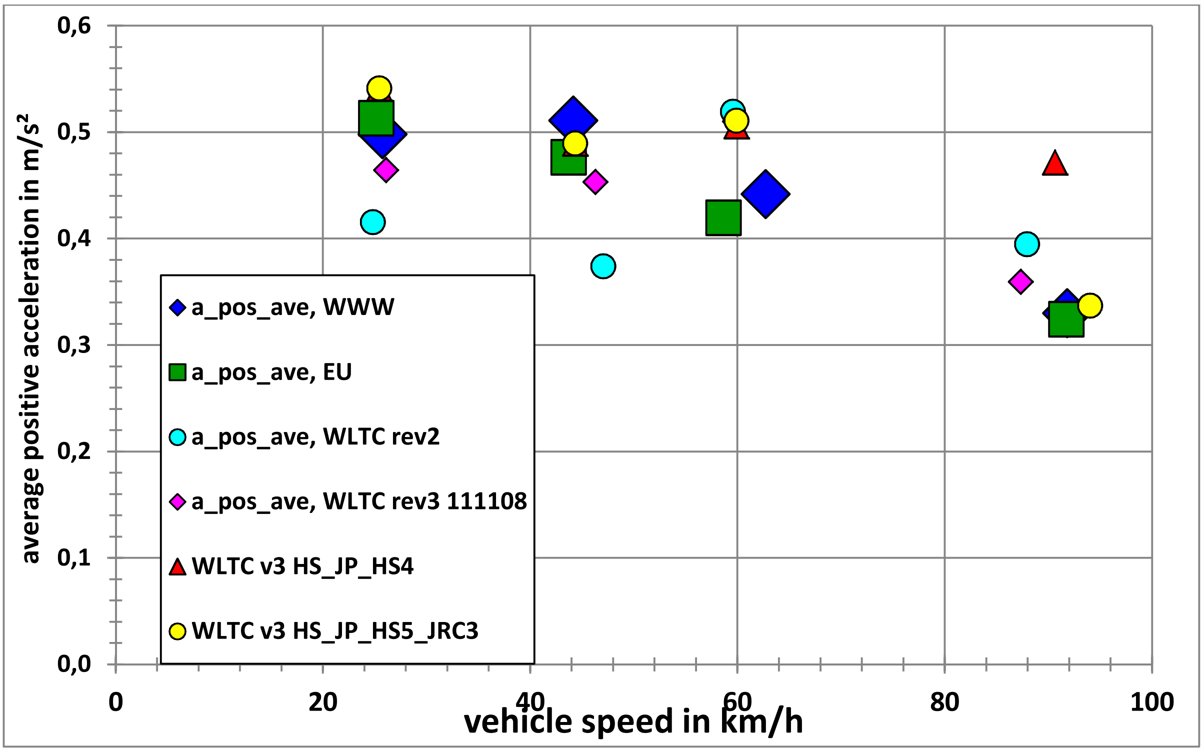
a in m/s²
Asia, medium
EU, medium
US, medium
WWW, medium

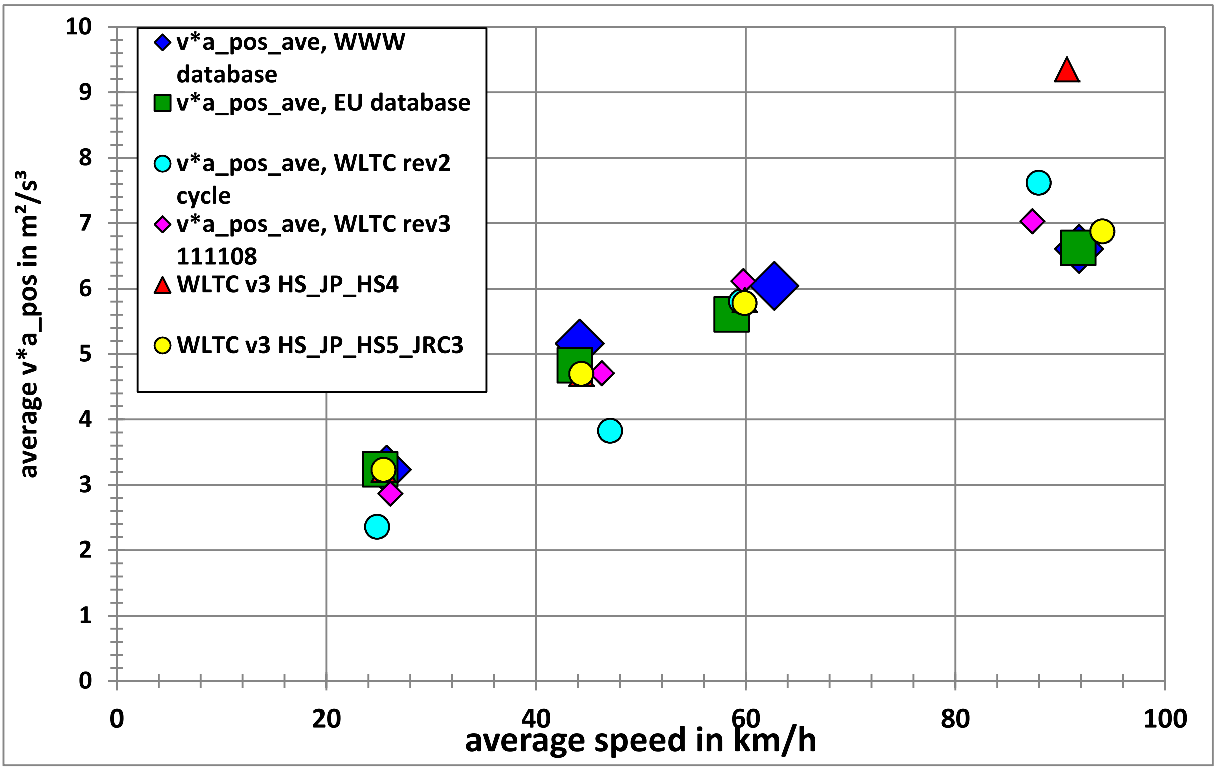


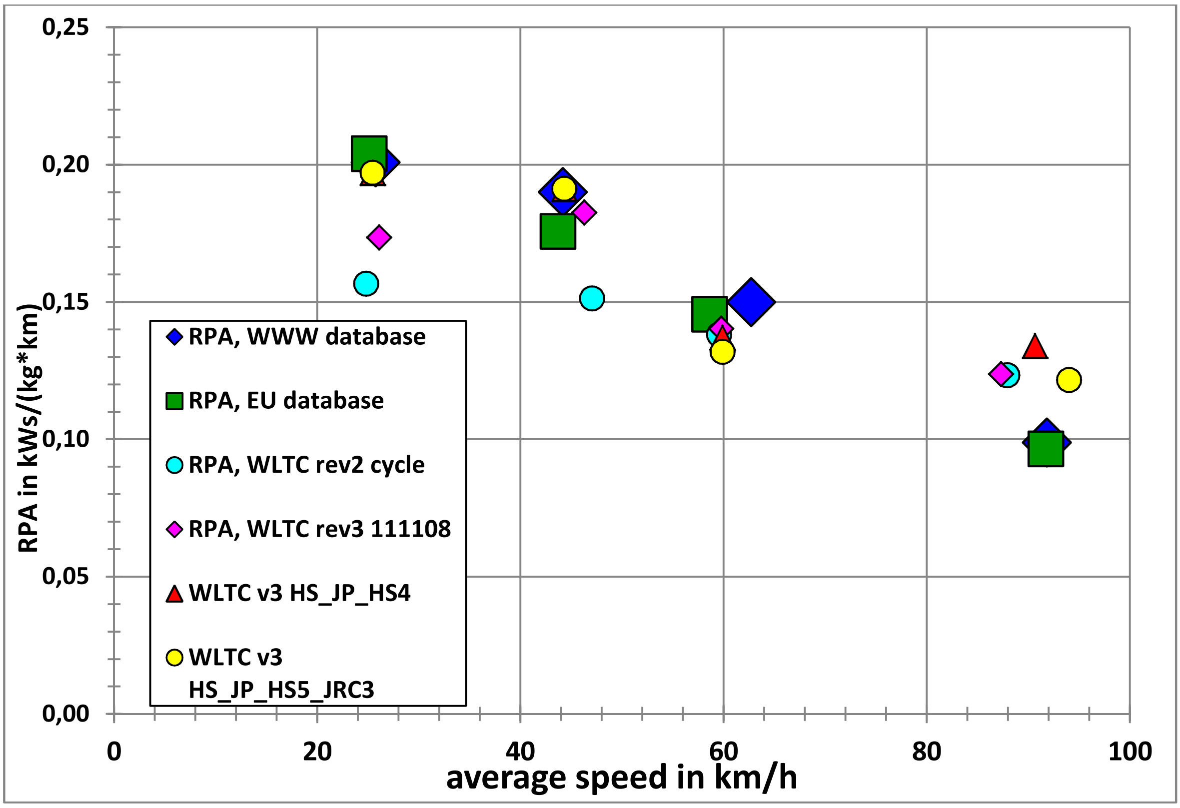
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
cum frequency
-20
-15
-10
-5
0
5
10
15
20
v*a in m²/s³
Asia, low
EU, low
US, low
WWW, low



The World wide database (WWW) contains several hundred thousands of short trips (defined as any trip starting and ending with zero speed) from which a series of short trips were selected to obtain the Worldwide Light-duty Test Cycle (WLTC). While the WLTC is an approximation of the information contained in the WWW, it has been derived so to retain at best the most important characteristics of the complete database.The next series of figures shows a comparative analysis between the Worlwide database, the EU database and the WLTC, but from a different point of view. The results are presented in clusters of points. Each cluster shows the average value of the relevant parameters (ex. average positive acceleration) against the average speed of each WLTC speed phase (Low, Medium, High and Extra-High). The big squares (blue and green) represent the parameter values for the databases (Worldwide and European, respectively); the smaller dots show the results of some candidate WLTCs. The yellow dots refer to the WLTC version 4(tested in the laboratories for drivability and used to simulate CO2 emissions). Previous versions of the WLTC show how the adjustment in the selection of the short trips from the Unified database to build the WLTC brought various parameters closer to the WWW values.


0,6
0,5
0,4
0,3
0,2
0,1
0,0
average positive acceleration in m/s²
a_pos_ave, WWW
a_pos_ave, EU
a_pos_ave, WLTC rev2
a_pos_ave, WLTC rev3 111108
WLTC v3 HS_JP_HS4
WLTC v3 HS_JP_HS5_JRC3
0
20
40
60
80
100
vehicle speed in km/h


10
9
8
7
6
5
4
3
2
1
0
average v*a_pos in m²/s³
v*a_pos_ave, WWW database
v*a_pos_ave, EU database
v*a_pos_ave, WLTC rev2 cycle
v*a_pos_ave, WLTC rev3 111108
WLTC v3 HS_JP_HS4
WLTC v3 HS_JP_HS5_JRC3
0
20
40
60
80
100
average speed in km/h



On the basis of the above evidence, it was decided at EU level (DG ENTR + EU Member States representatives in the EU-WLTP working group) that is was not necessary to pursue the derivation of a European Driving Cycle based only on the European database. Instead it was considered more crucial to start the comparison between the WLTC and NEDC in terms of fuel consumption / CO2 emissions.

Preliminary modeling results of CO2 emissions over WLTC versus NEDC

After the derivation of the first version of the WLTC and its subsequent modifications, made necessary by the results of the drivability tests of the WLTC carried out in several laboratories (including the JRC), the EU-WLTP working group started to carry out a comparison of fuel consumption (FC) / CO2 emissions between WLTC and NEDC.

Such comparison was made both experimentally (measuring CO2 emissions during the drivability tests of the WLTC and driving the same vehicles over the NEDC) and with the help of simulations based on average vehicle fuel consumption data.

The results showed a variety of trends, with the ratio WLTC/NEDC sometimes a little above 1 (i.e. higher FC for the WLTC), some other times slightly below 1, but always very close to 1.

In the following table some simulations carried out by Heinz Steven (ACEA consultant for the WLTP) are presentedThe CO2 emissions calculated as the average emission value of 10 typical diesel and 10 typical gasoline vehicles are first estimated for the Unified database (WWW), the EU database and the WLTC. Then, those emissions are compared with CO2 emissions estimated for the same average vehicles with NEDC.

Comparing the WWW, WLTC and the EU database emission with hot engines, the simulations suggest:

- In the case of emissions without idling periods, there is a difference of about 1-2 g CO2/km for diesel vehicles and for petrol vehicles,, confirming that also from the fuel consumption point of view the dynamicity of the EU driving conditions are well represented by the worldwide cycle.

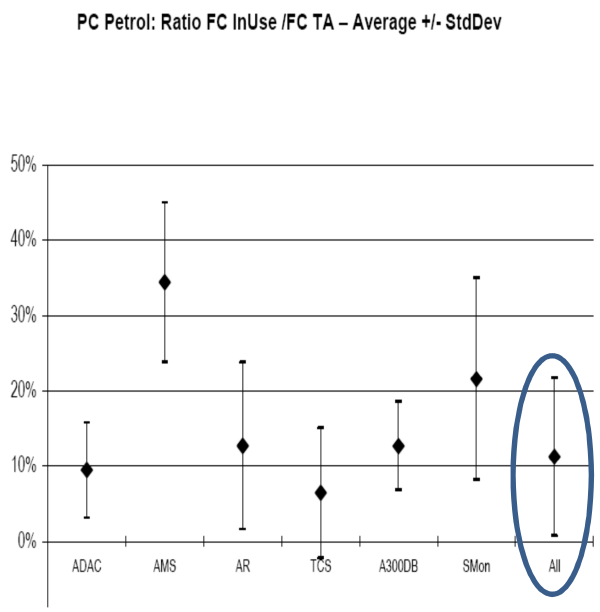
- Considering emissions inclusive of idling periods, a difference of 5 grams is found for petrol vehicles, which indicates a longer idling period in the worldwide database (and in the WLTC) compared to the average EU conditions.

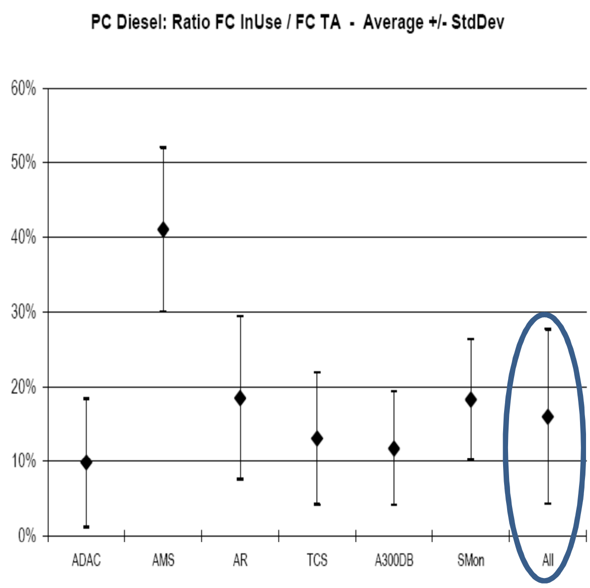
Comparing the WLTC and the NEDC the simulations suggest higher emissions of about 10 g CO2/km for the WLTC if idling is not accounted for, indicating again that the WLTC is a more dynamic cycle than the NEDC. Such difference is however eroded when idling is included, leading to higher emissions in the NEDC with respect to the WLTC for the average petrol vehicle.

			hot emissions, Diesel		hot emissions, Petrol	
region / cycle	**speed part**	**Average speed (km/h)**	CO2 emissions without idling periods (g/km)	CO2 emissions with idling periods (g/km)	CO2 emissions without idling periods (g/km)	CO2 emissions with idling periods (g/km)
WLTP database	low	19.4	159.6	179.3	210.4	242.9
	medium	38.8	134.0	138.9	171.8	179.9
	high	59.0	128.7	130.3	159.2	161.8
	extra high	89.8	143.3	143.6	168.9	169.5
	total	**46.7**	**139.0**	**143.3**	**172.0**	**179.1**
		comparison with NEDC	**7.7%**	**1.9%**	**4.7%**	**-2.3%**
EU regional database	low	20.3	161.3	175.9	213.0	237.0
	medium	39.9	131.9	135.2	167.7	173.3
	high	56.1	125.9	127.1	155.9	157.9
	extra high	90.1	145.6	145.9	171.0	171.4
	total	**55.2**	**140.6**	**142.9**	**171.0**	**174.7**
		comparison with NEDC	**9.0%**	**1.7%**	**4.0%**	**-4.7%**
WLTC	low	18.7	158.0	180.1	205.2	241.7
	medium	39.4	131.8	136.2	170.8	178.0
	high	55.8	125.2	127.1	156.1	159.2
	extra high	92.0	147.0	147.3	173.5	174.1
	total	**46.2**	**138.7**	**143.2**	**171.8**	**179.3**
		comparison with NEDC	**7.5%**	**1.9%**	**4.5%**	**-2.2%**
NECD	**total**		**129.0**	**140.6**	**164.3**	**183.4**

Table 3: Comparison of modeled CO2 emissions from typical diesel and gasoline vehicles.

The experimental results carried out at JRC and the modeling studies, currently underway, show similar trends. This means that driving a vehicle in the laboratory over a WLTC does not seem to make a big difference than driving the same vehicle over the NEDC. That might sound a little surprising and also somewhat disappointing. The "disappointment" is due to the awareness that CO2 emissions measured during type approval (with NEDC) are lower that real driving CO2 emissions. In the following figure a comparison of in-use versus type approval CO2 emissions is shown for gasoline and diesel vehicles (data taken from 6 databases for 5800 vehicles).





ADAC (Allgemeiner Deutscher Automobil-Club)
AMS (Auto Motor und Sport)
SR (Swiss automobile Review)
TCS data come from BAFU (Bundesamt für Umwelt BAFU) but I cannot find the actual meaning for TCS. In any case the data came from swiss BAFU.
A300DB (ARTEMIS 300 Database)
SMon (Spritmonitor.de)

There is an average difference (oval shape above) that can be estimated between 10% and 20%. Given that an average vehicle in the EU emitted 162 g CO2/km in 2005 and 140 g CO2/km in 2010 this translates in about 14 to 28 g CO2/km.

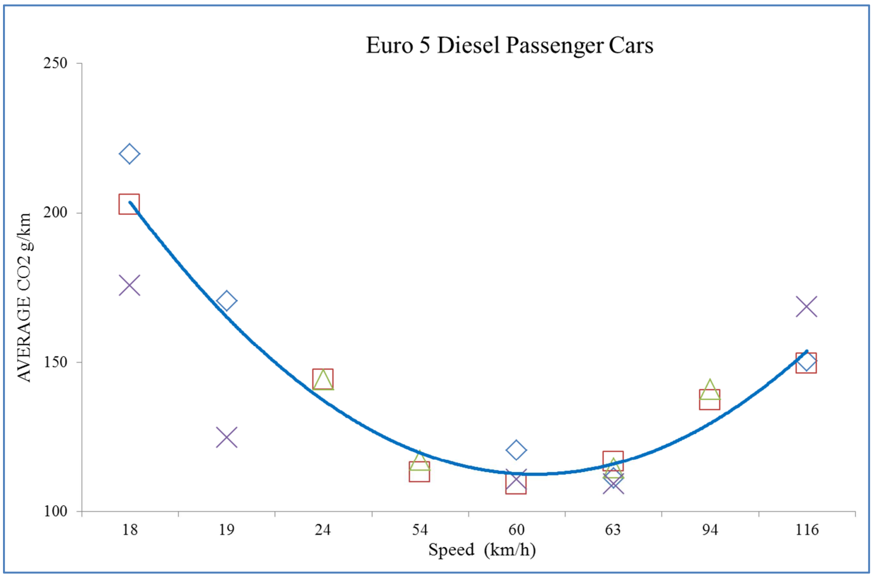
When the WLTP program was started, one of the main objectives was to reduce such gap. By merely comparing WLTC versus NEDC one could think that the objective has been missed. But this is not completely true. Let's examine why.

Taking a driving cycle as a whole, there are several elements that concur to the total amount of CO2 emitted:

- Dynamicity of the cycle
- Average speed
- Percentage of idling periods
- Total mileage and
- Test conditions

Now, having the same test conditions between NEDC and WLTC, the analysis of the differences shall focus on the first 4 elements noted above. Let's analyze them one by one.

1. A higher dynamicity of the cycle (i.e. a wider distribution of accelerations) brings higher CO2 emissions. WLTC is more dynamic than NEDC (see table 3 emissions without idling).
2. The correlation between average speed of the cycle and CO2 emissions is less straightforward. It follows a U-shaped curve with higher values of CO2 emissions at low speed and at high speed and a minimum ranging somewhere between 50 km/h to 80 km/h (see next figure)



The NEDC has an average speed of 33 km/h, while WLTC has an average speed of 47 km/h.

3. Percentage of idling periods. This parameter can have a quite strong impact on CO2 emissions. For example, in Table 3 it can be seen that if the comparison between WLTC and NEDC was made without idling periods, the WLTC would have 7.7% higher CO2 emission than NEDC for diesel vehicles and 4.7% higher for gasoline vehicles. This is due to the fact that during idling the vehicle is emitting CO2 without any distance being driven. An increase in the percentage of idling period is in the direction of higher

CO2 emissions (that are expressed in g/km). The NEDC has a higher idling percentage compared to WLTC(23.2% versus 13.4%).

4. Total mileage of the driving cycle. The impact of the total length of the cycle on CO2 emissions is not unidirectional, however for the driving cycle normally used in emission test cells, it has been demonstrated that the longer the cycle, the lower are CO2 emissions. WLTC is 23.3 km long compared to the 11 km of the NEDC.

From the above description it is evident that 3 out of the 4 elements are in favor of higher CO2 emissions with NEDC compared to WLTC, and dynamicity alone cannot overcome the effects of the other elements.

However, it must be clearly stated that the comparison between WLTC and NEDC is not completely appropriate. As specified at the beginning of the present report, WLTC (the cycle) is not WLTP (the complete procedure) and the correct comparison shall be made between WLTP and NEDC, hence accounting for the differences in the procedure and not the difference in the cycle only presented in this chapter.

When we say "NEDC", we mean NEDC driving cycle and NEDC test procedure (i.e. roller bench setting, vehicle test mass, temperature of the test, etc..), while WLTC covers only the driving cycle part of the WLTP (in fact the experimental tests in the laboratories have been carried out driving the vehicle over the WLTC but using the same test conditions of the NEDC). The new Test Procedure of the WLTP is currently under development and it is expected to be tested between April and December 2012. Most of the changes of the WLTP relative to NEDC are in the direction of more realistic test conditions and are summarized as follow:

Parameter	NEDC setting	WLTP setting	EU position
Road load factors	Based on the lightest version of the vehicle family	Based on the heaviest version of the vehicle family	In line with WLTP
Test mass	Based on the lightest version of the vehicle family	Based on the heaviest version of the vehicle family	In line with WLTP
Ambient temperature	Between 20 °C and 30 °C	25 °C ± 2 °C	EU has accepted WLTP proposal for the sake of harmonization, but it is intentioned to derive a correction factor to the CO2 emissions obtained at 25 °C, to take in account a more realistic average ambient temperature in EU (closer to 15°C – 18 °C)
Gear shift	Based on vehicle speed	Based on normalized engine speed	In line with WLTP
Battery charge	No prescription	Fully charged before testing	In line with WLTP
Auxiliaries	OFF	OFF	The EU has in place a procedure for assessing CO2 emission form eco-innovations. As a result, additional ad-hoc tests may be required (eg. a test with a standard energy equipment switched on to determine its efficiency).
Other topics	-	-	UNECE regulation 101 allows extending the type approval to all vehicles within a 4% interval on their respective CO2 emissions. Such provisions were not discussed in the WLPT process

The above differences between the two procedures should lead to higher CO2 emissions under the WLTP compared to the NEDC. The actual results will be available in December 2012 after the conclusion of the validation phase 2 of the WLTP programme.

With regard to the timetable the WLTP process, the current plan foresees its conclusion in spring 2014, on time for the revision of the EU test procedure called upon in article 13(3) to Regulation (EC) 443/2009 whereby "*From 2012, the Commission shall carry out an impact assessment in order to review by 2014, as provided for in Article 14(3) of Regulation (EC) No 715/2007, the procedures for measuring CO2 emissions as set out under that Regulation*".

Acknowledgements

The authors of this report wish to acknowledge the contribution of Mr Heinz Steven (consultant) to the construction of WLTP database and the development of WLTC. JRC colleagues Giorgos Fontaras, Alexandros Nikolian and Fabio Dalan have also actively collaborated to the report. Special thanks go to the VELA team and in particular to Urbano Manfredi for managing all the experimental tests on WLTC.

ANNEX 1

WLTC - version 4

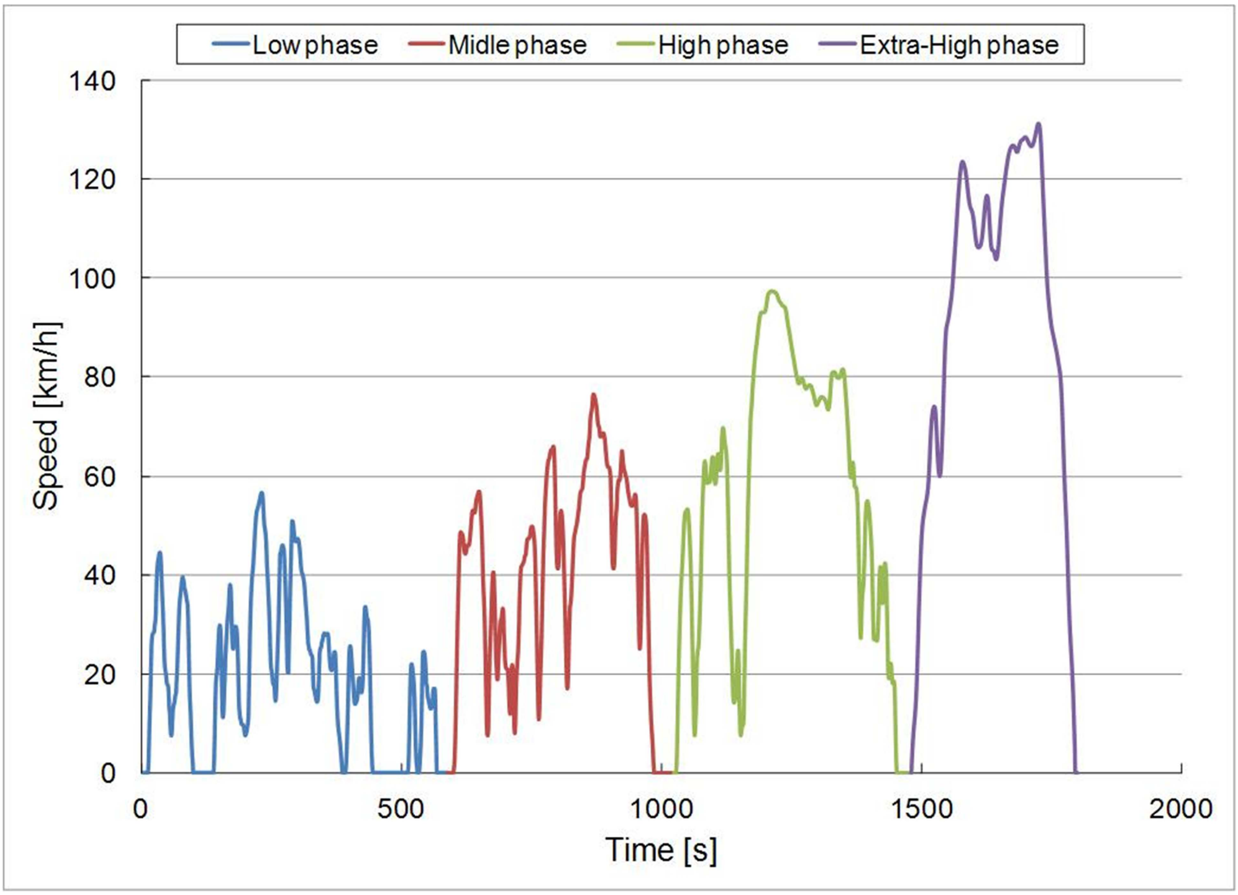


Figure A1.1

ANNEX 2

WLTC Methodology

The methodology to develop the WLTC involved initially filtering and thinning the activity data. Filtering was performed using the T4253H smoothing algorithm. Reducing data frequency from 10Hz to 1Hz was necessary only for a limited amount of data as most of the data was 1Hz data. The resulting smoothed data was converted into idling and short trips portions to create short trips and idles databases for each region and part of the cycle. A series of elimination criteria have been applied to the raw data for determining the short trips and idle periods excluded from the data base for the drive cycle (e.g. idling periods with duration higher than ten minutes, short trips with duration smaller than ten seconds, short trips with the maximum speed less than 3.6 km/h; short trips with accelerations higher than $4 m/s^2$ and smaller than $-4.5 m/^2$). The short trip and idle databases were used to determine: short trip length cumulative frequency distributions, short trip average speed distribution, Idling length distribution which were furthermore used for developing the unified distributions. The duration of the world-wide harmonized light-duty test cycle was set to 1800 seconds similar to WHDC (World Harmonized Heavy Duty Cycle) and WMTC. Firstly, the length of each speed phase (Low, Medium, High and Extra-high speed phase) was determined based on traffic volume ratio between the L/M/H/ExH phases (Low: 589 s, Mid.: 433 s, High: 455 s, Ex-High: 323 s). Then, the number of short trips ($N_{ST,i}$) and idle periods ($N_{I,i}$) using the following equations:

$$N_{ST,i} = \frac{\text{drive cycle duration in each phase } (T_i) - \text{average idling duration}}{\text{average short trip duration} + \text{average idling duration}}$$

$$N_{I,i} = \text{number of short trips } (N_{ST,i}) + 1$$

Table 3 shows, the target cycle duration, average short trip duration, average idle duration, number of short trips and number of idle for each phase.

	Target cycle duration [s]	**Average ST duration [s]**	**Average Idle duration [s]**	**No. of ST [#]**	**No. of Idle [#]**
Low	589	84	22	5	6
Medium	433	238	22	1	2
High	455	446	23	1	2
Extra-high	323	824	14	1	2

To determine the duration of the short trips in the Low speed phase of the cycle a cumulative frequency graph of the short trip duration had to be generated.

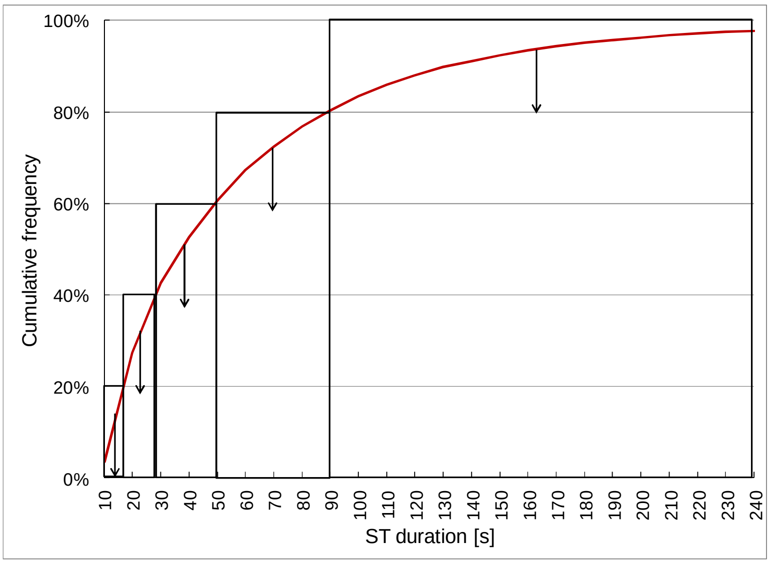


Figure A2.1

The Y axis of the graph was divided into ($N_{ST,i}$) equally spaced parts and by selecting the average duration in each part the duration of the short trips (ST_1, ST_2, ..., ST_N) was decided. Similar procedure was applied for determining the Idle periods duration.

In order to select the actual short trips for each speed phase, it was necessary to reduce the number of combinations by applying several selection criteria: average vehicle speed, acceleration duration ratio, deceleration duration ratio. The combination of the short trips whose distribution of the key parameters (speed, acceleration, v*a, etc.) had the smallest chi-squared value when compared with the same distributions of the Unified database, was selected in Version 1 of the WLTC driving cycle.

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Abstract
The Worldwide harmonized Light duty Test Cycle (WLTC) has been designed on the basis of the inuse driving databases provided by Europe, India, Japan, Korea and USA. These databases have been merged by applying a weighing factor to each of them, obtaining the "Unified" database. In order to verify the representativeness of the Unified database and the resulting WLTC with respect to the European driving behavior, a comparison between the Unified and the European database has been carried out, which has shown a high level of resemblance for the most important parameters (i.e. speed distribution, acceleration distribution, speed* acceleration, etc.). The drivability tests carried out over the WLTC in several laboratories have shown levels of CO2 emissions similar to those obtained with NEDC. Possible explanations of such results are presented.

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