

# Development of the World-wide harmonized Light duty Test Cycle (WLTC) and a possible pathway for its introduction in the European legislation



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## ABSTRACT

This paper presents the World-wide harmonized Light duty Test Cycle (WLTC), developed under the Working Party on Pollution and Energy (GRPE) and sponsored by the European Union (with Switzerland) and Japan. India, Korea and USA have also actively contributed. The objective was to design the harmonized driving cycle from “real world” driving data in different regions around the world, combined with suitable weighting factors. To this aim, driving data and traffic statistics of light duty vehicles use were collected and analyzed as basic elements to develop the harmonized cycle. The regional driving data and weighting factors were then combined in order to develop a unified database representing the worldwide light duty vehicle driving behavior. From the unified database, short trips were selected and combined to develop a driving cycle as representative as possible of the unified database. Approximately 765,000 km of data were collected, covering a wide range of vehicle categories, road types and driving conditions. The resulting WLTC is an ensemble of three driving cycles adapted to three vehicle categories with different power-to-mass ratio (PMR). It has been designed as a harmonized cycle for the certification of light duty vehicles around the world and, together with the new harmonized test procedures (WLTP), will serve to check the compliance of vehicle pollutant emissions with respect to the applicable emissions limits and to establish the reference vehicle fuel consumption and CO<sub>2</sub> performance.

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## Introduction

Since the early Nineties, more stringent limits than in the past have been introduced, on NO<sub>x</sub> (nitrogen oxides), CO (carbon monoxide), HC (hydrocarbons) and PM (particulate matter) emissions from vehicles. Over the past two decades, the emissions of these regulated air pollutants have generally decreased and urban air quality has improved, however some problems still remain (European Commission, 2011). For example, the legislation entered into force in Europe in 2011 (Euro

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5b) and starting in 2014 (Euro 6) leaves some issues open (European Commission, 2007, 2008). One of these open issues and key challenge for the European legislator is to ensure that light-duty vehicles emissions at type approval (TA) are in line with real-world driving emissions. In fact, it has been shown that, for example, diesel vehicles, including modern Euro5 cars, in normal driving conditions often exceed legislated  $\text{NO}_x$  emissions limits (Weiss et al., 2011). Also, fuel consumption values measured at TA are generally lower than those encountered in real life (Mock et al., 2013). In Europe, for example, one of the main reasons for the discrepancy between certified and actual emissions comes from the current test cycle (New European Driving Cycle – NEDC) employed for the TA tests for emission certification of light-duty vehicles. It has been shown that NEDC does not represent real driving behavior of a vehicle in actual traffic and thus, does not accurately reflect pollutant emissions and fuel consumption (Joumard et al., 2000; Zacharof et al., forthcoming). Another reason for this discrepancy is the so called “cycle detection”. Some cars may be “programmed” to fulfill the legislative requirements under the well-controlled conditions of the test cycle on the chassis dynamometer in the laboratory but run quite differently when they are on the road.

The European Commission is currently addressing these open issues by introducing a more realistic test-procedure and an additional test carried out by driving the vehicle on the road (Real Driving Emissions or RDE) in the TA process. In particular, for the first point, the European Commission is participating in the development of a new World-wide harmonized Light duty Test Cycle (WLTC) and a new World-wide harmonized Light-duty Test Procedure (WLTP) (UNECE – GRPE – WLTP) and by preparing the ground, including a possible time-frame, for their introduction in the European TA procedure.

The objective of the present paper is to present development of the WLTC from a policy and technical perspective. The possible implications of its introduction in the European legislation are also provided by analyzing its innovative features with respect to the currently adopted cycle (the NEDC).

The paper is organized as follows. In the next section a brief overview of the policy framework that led to the development of the WLTC is provided. The technical aspects of the development are presented in sections ‘Development of a harmonized driving cycle’ and ‘Development of the WLTC’. In section ‘Analysis of the final version of WLTC’ an analysis of WLTC representativeness and its comparison with the NEDC is provided. A concluding section outlines the main outcomes of the study and some policy implications due to the introduction of this cycle in the TA of LDVs.

## The policy framework

A few internationally harmonized engine dynamometer cycles have been developed in the last decade for emission certification of heavy-duty engines (World Harmonized Heavy Duty Cycle – WHDC), and non-road engines (Non-road Transient Cycle – NRTC). A worldwide harmonized test cycle has been developed also for motorcycles emissions (World harmonized Motorcycle Test Cycle – WMTC) (UNECE).

For Light-Duty Vehicles (LDVs), various vehicle dynamometer test cycles are employed in TA tests for emission certification. The most common test cycles are: the European NEDC, the Japanese JC 08 Cycle, and the American Federal Test Procedure (FTP-75) (DieselNet). The NEDC cycle includes four urban driving cycle segments (ECE 15) characterized by low vehicle speed, low engine load, and low exhaust gas temperature, followed by one extra-urban segment to account for more aggressive and higher speed driving. The Japanese JC 08 represents driving in congested city traffic, including idling periods and frequently alternating acceleration and deceleration. In the U.S, currently the FTP-75 is used for emission certification of passenger cars and light duty trucks. The US FTP-75 is a transient cycle produced from real measurements in Los Angeles and represents a specific region in the U.S (Kruse and Huls, 1973). Table I in Supporting Information shows the different characteristics (durations, lengths of the test cycle, average speeds, maximum speeds and number of phases) of the various LDVs test cycles used in Europe, Japan, and USA.

Following different test procedures represents a considerable burden for industry, requiring a vehicle to be optimized in each context in which it enters the market. At the same time different cycles and test procedures will produce very different test results which make it very difficult to understand the real contribution of vehicles to the production of greenhouse gas and pollutant emissions, and therefore for policy makers to design the right measures to take. For this reason it was important to come up with the harmonized procedure presented in this paper.

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

The first roadmap for the development of the new driving cycle and test procedure was presented in 2009. It consisted of three phases to cover all the aspects of the vehicle TA:

- (a) Phase 1 (2009–2014): development of the worldwide harmonized light duty driving cycle and associated test procedure for the common measurement of criteria compounds,  $\text{CO}_2$ , fuel and energy consumption (Type 1 test of EU TA procedure).

- (b) Phase 2 (2014–2018): low temperature/high altitude test procedure, durability, in-service conformity, technical requirements for on-board diagnostics (OBD), mobile air-conditioning (MAC) system energy efficiency, off-cycle/real driving emissions.
- (c) Phase 3 (2018+): emission limit values and OBD threshold limits, definition of reference fuels, comparison with regional requirements.

Since the beginning of the WLTP process the European Union (EU) had a strong political objective set by its own legislation (Regulation (EC) 443/2009 and Regulation (EU) 510/2011) to design and implement a new and more realistic test cycle by 2014, which was a major political driving factor for setting the time frame of the whole WLTP and in particular of phase 1. As a matter of fact the phase 1 of the WLTP development should allow the EU to amend the Type 1 tests in the TA of LDVs in line with the timing foreseen in the above mentioned Regulations. In order to achieve this objective, two main working groups were established with different objectives:

- development of harmonized cycle (DHC): construction of a new Worldwide Light-duty Test Cycle (WLTC);
- development of test procedures (DTP): development of the new test procedures.

In the present paper we focus the attention on the work carried out within the first working group (DHC). However, it is worth mentioning that the two working groups have allowed the drafting and adoption at the UNECE level of a formal Global Technical Regulation (GTR) in April 2014 (UNECE), which includes a complete version of the driving cycle and test procedure (at least for conventional vehicles). The resulting WLTP (cycle and procedure) should be applied for the certification of LDVs around the world and will therefore serve three main purposes:

- check the compliance of vehicle pollutant emissions with respect to the applicable emissions limits;
- establish the reference vehicle fuel consumption and CO<sub>2</sub> performance;
- reduce the gap between TA values and real world emissions.

Some aspects of the procedure, especially for what concerns hybrid and electric vehicles, have not been finalized on time for their inclusion in the GTR. They are currently under discussion (a Phase 1b was introduced for them) and their finalization is expected by the end of 2015.

### Development of a harmonized driving cycle

Ideally a test cycle for TA should have the following characteristics: it should be practical (i.e. not too long or too complicated for its execution in the laboratory); it should be repeatable and reproducible; and, most of all, it should provide results representative of the behavior of the vehicle in real life.

From this point of view each of the driving cycles currently employed in TA tests has advantages and drawbacks. For example, NEDC, which consists of several steady-state test modes, is quite simple to drive and thus repeatable. However, NEDC does not represent real driving behavior of a vehicle in actual traffic (Pelkmans and Debal, 2006). On the other hand, the JC 08 represents real driving behavior but only in congested city traffic situations; it does not cover other driving conditions and road types. The FTP-75 covers a wider range of driving conditions than the JC 08; however it is still not complete enough to cover all possible driving situations. Indeed in the USA, vehicles have to be additionally tested on two Supplemental Federal Test Procedures (SFTP US06) designed to address shortcomings with the FTP-75 (e.g. the SFTP US06 cycle was introduced to test the vehicle at higher speed, up to 130 km/h, and with higher accelerations than the FTP75, and the HWFET (Highway Fuel Economy Test) to test the vehicle in highway driving conditions).

When the WLTC project was started it was aimed to design a new legislative driving cycle more representative of exhaust emissions and fuel consumption under real-world driving conditions. Therefore, one of the primary objectives of the project was to build the WLTC on the basis of real driving conditions around the world.

The world-wide harmonized light duty test cycle presented in this paper was derived from “real world” driving data collected in five different regions: EU + Switzerland, USA, India, Korea and Japan, over different road types (urban, rural, motorway) and driving conditions (peak, off-peak, weekend), covering a wide range of vehicle categories (passenger vehicles of categories M<sub>1</sub> and M<sub>2</sub> with no more than eight seats and a maximum mass of 5 tons as well as vehicles of category N<sub>1</sub> used for the carriage of goods and having a maximum mass not exceeding 3.5 tons), various engine capacities, power-to-mass ratios (PMR) and manufacturers.

In the following sections the methodology used for WLTC development and its driving characteristics are presented.

### Methodology

A schematic representation of the methodology for deriving the WLTC is reported in Fig. 1. First of all, it was necessary to define the main parameters characterizing the driving cycle and the additional inputs to pursue a world-wide harmonization. Driving behavior data (in the form of speed and acceleration profiles) and traffic statistics about light duty vehicle use in the different regions of the world were then collected and analyzed as basic elements to develop the harmonized

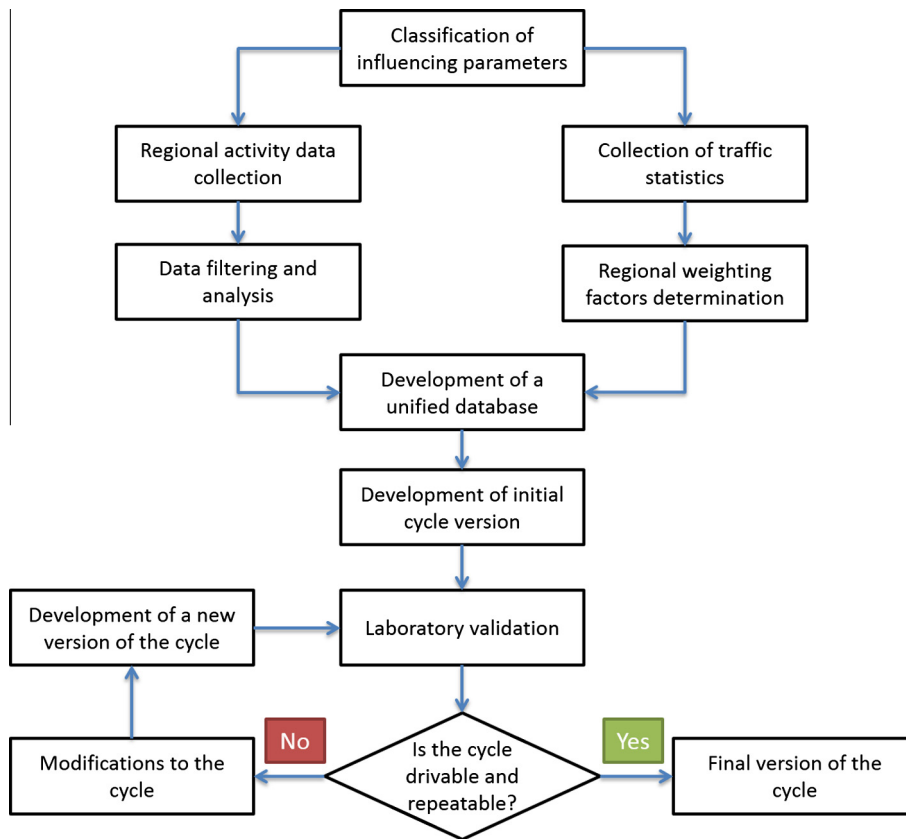


Fig. 1. Flow diagram of WLTC development.

cycle. Driving behavior data were then filtered to remove errors, noise and extreme driving behaviors and analyzed to derive the main elements on which basis new cycle will be developed. In particular, an analysis was undertaken to determine the average short trip durations and idling times which were used to determine the number of short trips that should be included in each drive phase of the cycle. Traffic statistics were instead used to determine the regional weighting factors necessary in order to produce a world-wide representative cycle.

In-use driving behavior data and traffic statistics were then combined in order to develop a reference database representing the worldwide light duty vehicle driving behavior. In particular, in this database, in-use data were weighted and aggregated to produce unified speed–acceleration distributions. From the unified database, short trips were selected and combined to develop the drive cycle. The combination was carried out in order to achieve a driving cycle as representative as possible in statistical terms of the unified database. The chi-squared method applied to the speed–acceleration empirical joint distribution was used for this purpose. In particular, the combination of short trips with the least chi-squared value was selected as the ideal combination. A first draft driving cycle was then produced. The comparison of other relevant parameters such as average speed, relative positive acceleration (RPA), and idling times was conducted to further check the representativeness and where necessary changes were made. A first version of the cycle (vers.1) was produced and presented for the subsequent experimental validation phase. The cycle was tested in several laboratories of all participating regions, on various categories of vehicles ( $M_1$ ,  $M_2$  and  $N_1$ ) with different engine displacements and different power-to-mass ratios (PMR), to understand the drivability and repeatability of the cycle. On the basis of the experience gathered during these tests the cycle was modified until the final version was obtained.

In the next sections, the different phases that led to the development of the final version of the WLTC are described in some more details.

## Development of the WLTC

In the present section, the main steps in the development of the WLTC are described according to the flowchart presented in Fig. 1.

### Classification of influencing parameters

The analysis of the most important parameters for the development of a world-wide harmonized driving cycle led quite naturally to highlight two main elements:

- Regional activity data: It was necessary to have, for each region, activity data that could allow to derive the driving behavior and their distributions in terms of the normally adopted road categories (urban, rural, motorway).
- Regional weighing factors: All the regional activity data databases had to be merged in one single database, according to their specific weighting factor. Such weighting factors were to be determined on the basis of the relative traffic volumes.

#### Regional activity data

**Data collection.** “Real world” traffic data was collected from 441 vehicles equipped with on-board data acquisition systems able to collect the speed and the acceleration of a vehicle as well as the speed of its engine at a frequency of at least 1 Hz.

The activity data used for the development of the WLTC was collected from five regions: Europe, India, Japan, Korea and USA. Within Europe, collection campaigns were organized in Belgium, France, Germany, Italy, Poland, Slovenia, Spain, Sweden, Switzerland and United Kingdom. Table II in Supporting Information summarizes the vehicle type, number of vehicles, total mileage for each region and the methodology used to collect the activity data.

In particular, Japan, Korea and India used “instructed drivers”, EU and Switzerland collected “customer data” (data from vehicles with drivers without any particular instruction to drive their cars). Finally, USA submitted both “customer data” and “instructed drivers” using the “chase car” method (Austin et al., 1993; Ergeneman et al., 1997). The possibility to submit data collected using different approaches was granted for two reasons: (i) in order to complete the project in a reasonable amount of time and with reasonable costs it was allowed to submit data collected also in the framework of other activities (provided that they were compliant with the criteria of accuracy of the signal set for the project); and (ii) it was considered that combining the two approaches would reduce the effect of the most extreme driving behaviors due to the collection method itself. In addition it would be more comprehensive and in the end it would allow to get the advantages of both methods. The main characteristics of the different approaches are reported in the following.

“Instructed drivers” refers to data collected by hired vehicles and drivers who drove on predefined routes at predefined times. The advantage of this approach is the possibility of planning the collection of activity data, in order to be representative for the region where the measurement is performed. The disadvantage of this collection method is that the first trip of the day is determined by the measurement design and might not be representative of the first trip of the day for customers. Furthermore, the instructed driver might not behave as freely as a normal driver.

The “chase car” collection method uses an instrumented vehicle from which the data is recorded (second by second), following a target vehicle in the traffic stream and attempting to mimic its behavior.

The “customer data” method has the advantage of representing real driving behavior, but if the amount of data collected is not sufficiently large, it cannot guarantee the statistical coverage of road/traffic conditions like the instructed drivers method.

For the WLTC the database of customer data has been subject to several comparisons with other publicly available traffic data statistics showing its statistical robustness in terms of representativeness (IRF; Transport and Mobility Leuven; Andre et al., 1999; Annual Report of Vehicle Transportation; Road Traffic Census).

**Data filtering and analysis.** To process the huge amount of recorded data (approximately 765,000 km of data) and for the statistical analysis of the recorded parameters a software developed in-house with the Visual Basic for Application programming language embedded in Microsoft Excel was used. The raw data processing initially involved filtering and thinning the activity data. Filtering was applied to remove noise due to measuring errors (small fluctuations) and was performed using a standard smoothing algorithm (T4253H) as described in the SPSS software (SPSS). Thinning consisted in reducing data frequency from 10 Hz to 1 Hz, (necessary only for a limited amount of data as most of the data was 1 Hz data).

The resulting smoothed data was converted into idling and short trips portions to create short trips and idling databases for each region/country and for each part of the cycle (e.g. urban, rural, motorway phases). The short trip was defined as the distance driven between two idling periods. The speed of the short trip started with a zero, ended with a zero and consisted of different driving modes (acceleration, deceleration, and cruise). The idle was defined as the driving period with a vehicle speed smaller than 5 km/h and acceleration in the range  $[-0.139, +0.139] \text{ m/s}^2$ . Acceleration mode was defined as the part of the short trip where acceleration was greater or equal to  $0.139 \text{ m/s}^2$ . Deceleration mode was defined the part of the short trip where acceleration was smaller or equal to  $-0.139 \text{ m/s}^2$ . Cruise mode was defined as the part of the short trip with vehicle speed greater or equal to 5 km/h and acceleration in the range  $[-0.139, +0.139] \text{ m/s}^2$ . A series of elimination criteria was applied to the short trip and idling databases for determining the short trips and idling periods to be excluded from the subsequent analysis. These were:

- idling periods with duration longer than ten minutes,
- short trips with duration shorter than ten seconds,
- short trips with the maximum speed lower than 3.6 km/h,
- short trips with accelerations higher than  $4 \text{ m/s}^2$  and smaller than  $-4.5 \text{ m/s}^2$ .

The reasons for these eliminations are linked on one hand to considerations of statistical representativeness, and on the other hand to the practicability/feasibility of the test in a laboratory. As a result of this step, data for 654,000 km of driving were retained for the subsequent analysis, with a 15% reduction of the initial data. The short trip and idling databases obtained in this way were used to determine the distributions of short trip duration, average speed, and idling duration.

#### *Regional weighing factors*

*Existing traffic statistics.* The driving cycle was developed from recorded in-use data (“real world” data) from different regions of the world (EU, India, Japan, Korea, USA) combined with suitable weighting factors. Regional weighting factors were necessary to represent each region driving characteristics when developing the unified distributions and harmonized cycle. The weighting factors were based on traffic volumes (current and foreseen) of each party. To derive such weighing factors the starting point was each country’s national traffic statistics (EU: [TREMOVE, 2005](#); INDIA: [World Road Statistics, 2009](#); JAPAN: [Traffic Census Data, 2005](#); USA: [EPA](#)).

*Regional weighting factors determination.* The statistical analysis started on the basis of the road type category (urban, rural, motorway) as defined in each region (Table III in Supplemental Information). However, to achieve the desired harmonization it became necessary to develop the WLTC on speed classes rather than on road categories and the concept of low (L), medium (M), high (H) and extra-high (Ex-H) speed phases replaced the urban, rural and motorway classification. The move from road category to speed phases is described in the next section.

The regional databases (European, American, Japanese, Indian and Korean) expressed in terms of low, medium, high and extra-high speed phases could be merged to obtain the unified database.

However, as the available traffic volume data was not expressed in terms of L/M/H/Ex-H speed classes but in the usual format based on road categories “urban”, “rural” and “motorway”, it was necessary to transform the weighting factors based on road categories into their equivalent values for the L/M/H/Ex-H speed classes. The details of the derivation of the weighting factors from road categories to speed classes are presented in Supporting Information (section ‘Regional weighing factors’).

#### *Development of a unified database*

The statistical analysis of the short trips and idling databases started on the basis of the road type categories (urban, rural, motorway) as defined in each region. [Fig. 2](#) shows the vehicle speed cumulative frequency distribution of various countries based on urban, rural and motorway road types.

While for the urban road type ([Fig. 2a](#)) the vehicle speed cumulative frequency distributions show a certain degree of similarity, for the rural road ([Fig. 2b](#)) there is a lower degree of similarity and for the motorway ([Fig. 2c](#)) category there is a clear difference between Europe on the one hand and Japan and Korea on the other hand. [Fig. 2b](#) shows that the 100% speed cumulative frequency distribution for Japan and Korea is reached at vehicle speed of 80 km/h, while for all European countries the 100% speed cumulative frequency distribution is reached at vehicle speed higher than 100 km/h. On motorways ([Fig. 2c](#)) this difference is even higher. Korea and Japan have motorway top speed of 100 km/h while in Europe the top speed is between 120 and 140 km/h. This discrepancy was further confirmed when the Indian and USA activity data were added to the worldwide database. As already anticipated in section ‘Regional weighting factors determination’, based on this initial data analysis, it became evident that the road category (urban, rural, motorway) could not be used for developing a harmonized cycle due to differences in their definitions and speed limits from different regions (given in Table III in Supporting Information). Therefore, it became necessary to develop the WLTC cycle on speed classes rather than on road categories and the concepts of low (L), medium (M) and high (H) speed phases replaced the urban, rural and motorway classification. Furthermore, it was necessary to split the high speed phase into two segments: one high speed phase with top speed representative of Asian driving and one extra-high (Ex-H) speed phase with a top speed more characteristic of the European and American driving. By applying the same threshold speed values to all regional databases, the short trips were homogeneously reorganized no matter in which road category (urban, rural, motorway) they had been recorded. For example a short trip with maximum speed below 60 km/h was included in the low speed phase even if it had been recorded on a motorway. When all the regional databases were reorganized in this way, the driving characteristics of the different regions showed a much higher degree of similarity among them.

The threshold vehicle speeds between the L/M/H/Ex-H phases were chosen after performing a comparative study of different candidate thresholds (see Table IV in Supporting Information). [Fig. 3](#) presents the speed–acceleration distributions of each speed phase (L/M/H/Ex-H) in each region for the finally selected threshold speed values 60/80/110 (low speed lower than 60 km/h, medium speed lower than 80 km/h, high speed lower than 110 km/h, extra-high speed higher than 110 km/h) among the phases. This combination of the threshold speed values (60/80/110) was the best compromise in terms of similarity of speed–acceleration distribution among the different regions.

Following the methodology described in section ‘Methodology’ and in Supporting Information (Figs. I and II), the regional databases (European, American, Japanese, Indian and Korean) expressed in terms of low, medium, high and extra-high speed phases were then merged to obtain the unified database.

From the unified database, it was possible to derive driving characteristics in terms of relevant parameter (e.g. speed) distributions and average values. [Fig. III](#) in Supporting Information shows the average speed, the Relative Positive Acceleration

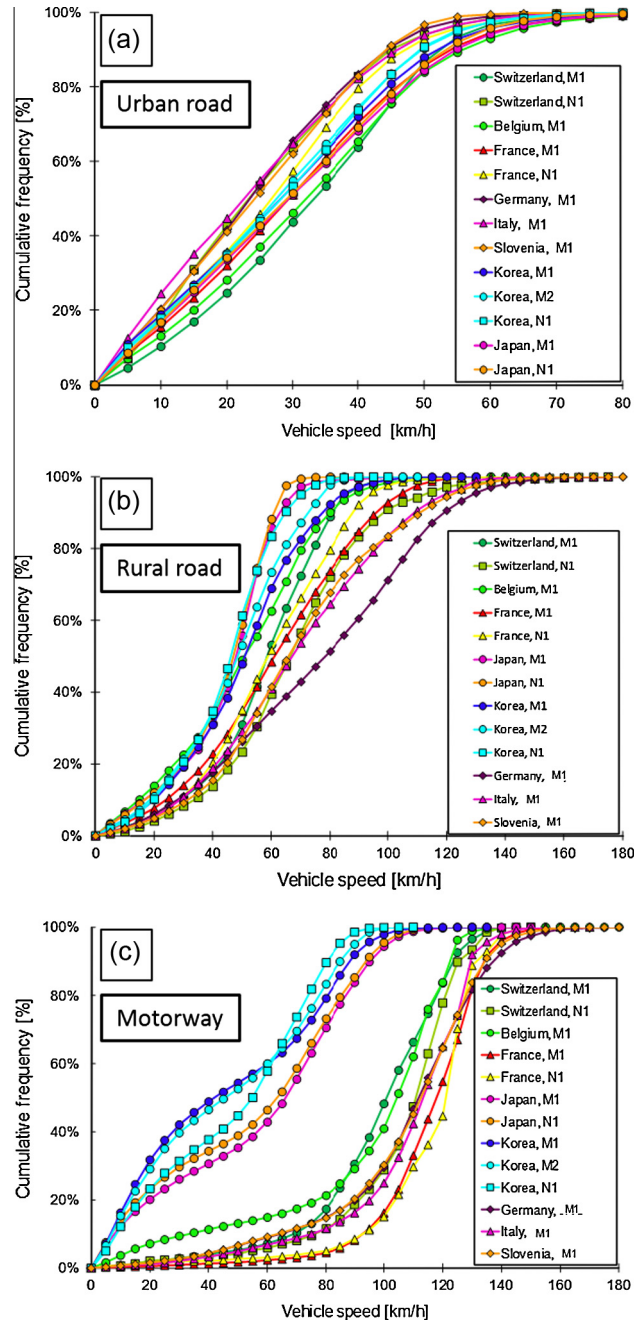


Fig. 2. Vehicle speed cumulative frequency distribution of various countries on urban (a), rural (b) and motorway (c) roads.

(RPA), the average short trips duration and the average idling duration for each region and for the world-wide (unified) database.

RPA is an important parameter used to characterize vehicle trips and compare the dynamicity of each speed phase among the different regions. It is a speed-related average of acceleration of the vehicle (power of a vehicle) calculated as reported in Eq. (1).

$$RPA = \frac{1}{X} \int_0^T v(t) \cdot a^+(t) \cdot dt \quad (1)$$

with  $a^+(t)$  being the instantaneous acceleration ( $m/s^2$ ) at time  $t$  (only positive accelerations are considered),  $v(t)$  the instantaneous vehicle speed at the same time  $t$  ( $m/s$ ) and  $X$  the total trip distance ( $m$ ) (Van de Weijer, 1997).

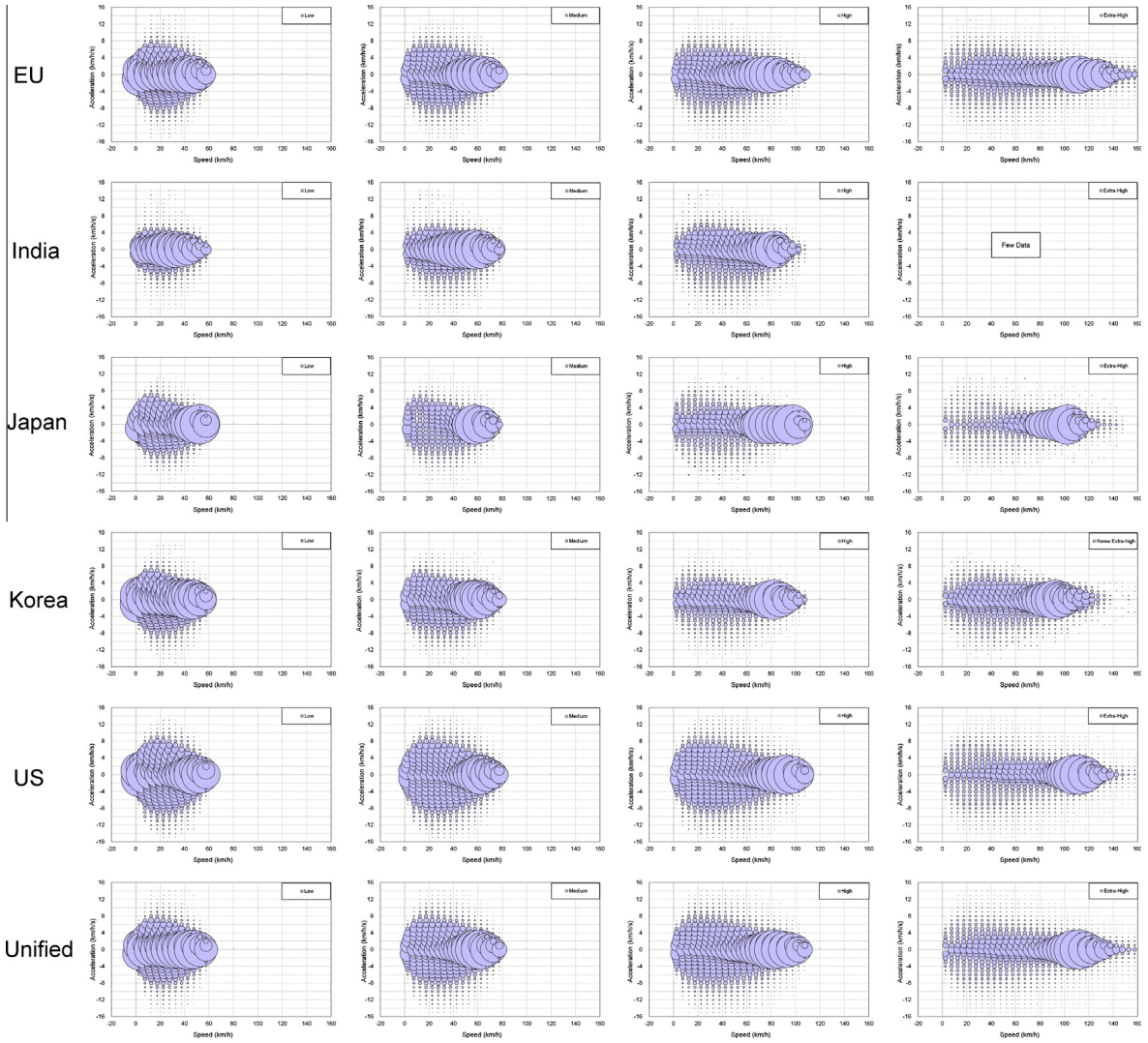


Fig. 3. Speed-acceleration distribution in L/M/H/Ex-H.

### The development of the initial WLTC version

The maximum length of the worldwide harmonized test cycle was set to 1800 s, similar to WHDC and WMTC. 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 length of each speed phase was determined based on the traffic volume ratio among the phases, as shown in the Supporting Information (Fig. 1). The number of short trips ( $N_{ST,i}$ ) in each speed phase was calculated according to Eq. (2) and the resulting number was rounded to the closest integer number  $\geq 1$ .

$$N_{ST,i} = \frac{P_i - \bar{I}_i}{\bar{ST}_i + \bar{I}_i} \quad (2)$$

where  $P_i$  is the phase duration,  $\bar{ST}_i$  is the average short trip duration, and  $\bar{I}_i$  is the average idling duration.

The number of idling periods ( $N_{I,i}$ ) in each speed phase was calculated as:  $N_{I,i} = N_{ST,i} + 1$ .

Table 1 shows, for each speed phase (L/M/H/Ex-H), the total duration, average short trip duration, average idling duration, number of short trips and number of idle periods.

For the low and medium speed phases the number of short trips calculated according to Eq. (1) is higher than 1, while for the high and extra-high speed phases this number is smaller than 1 (approximated to 1). Applying Eq. (1), in order to calculate the number of short trips, was possible only for the low and medium speed phases while for the high and

**Table 1**

Determination of number of short trips and idle periods for the L/M/H/ExH phases.

	Total phase duration (s)	Average short trip duration (s)	Average idling duration (s)	No. of short trips (#)	No. of idling (#)
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

extra-high speed phases the number of short trips had to be approximated to 1 because their average short trip duration (as obtained from the unified database and shown in Table 1) was longer than the total duration of the their phases.

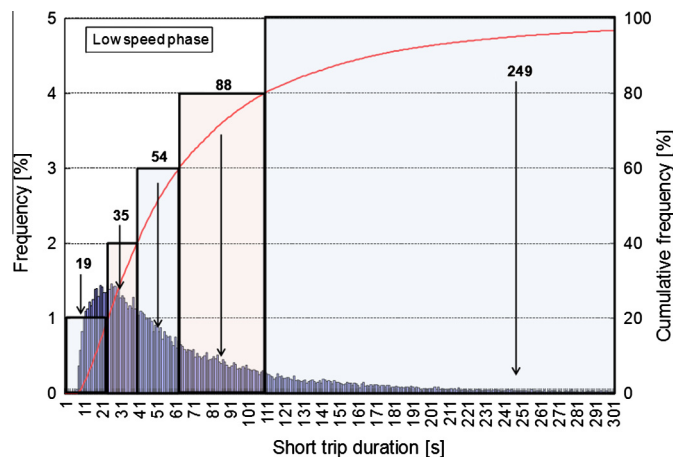
To determine the duration of the five short trips in the low speed phase, a cumulative frequency graph of the short trip duration was generated (Fig. 4). The Y axis was divided into five equal parts and by selecting the average value in each part, the duration of the short trips ( $ST_1 = 19$  s,  $ST_2 = 35$  s,  $ST_3 = 54$  s,  $ST_4 = 88$  s,  $ST_5 = 249$  s) was decided. A similar procedure was applied for determining the durations of the periods of idling. Table 2 shows the short trips and idling durations determined for each speed phase of the WLTC driving cycle.

The actual short trips for the WLTC were selected from the unified database. The selection criteria were based on the concept that the candidate short trip combination must provide similar distributions of speed, acceleration, etc. to those of the unified database. This was accomplished by performing a  $\chi^2$  analysis. The  $\chi^2$  method provides a measure of the level of discrepancy between two samples (the interested reader can refer to Corder and Foreman (2009) for additional information on the  $\chi^2$  analysis). In the present case, it provided a measure of the discrepancy between the unified distributions and the selected short trips combinations. Using an algorithm developed in-house (implemented in Microsoft Excel (Microsoft Office)), we applied this analysis to any combination of short trips. Given the large number of possible combinations (in the order of  $10^{13}$ ), several pre-selection criteria, based on average speed, average acceleration, acceleration and deceleration ratio, were applied. Thus, short trips with extreme characteristics were excluded. In this way, the number of combinations was reduced to  $10^7$  and their consequent  $\chi^2$  analysis to a reasonable computational time (24 h). The combination of the short trips with the smallest  $\chi^2$  value was selected for the WLTC vers.1 driving cycle.

Based on the methodology described above, the initial version (WLTC vers.1) of the world-wide harmonized duty test cycle was developed. The cycle consisted of four phases (low, medium, high and extra-high) covering 22.7 km over 1800 s. Fig. IV in Supporting Information shows the speed profile of the WLTC vers.1. The first short trip  $ST_4$  (88 s) and the first idle period (11 s) of the driving cycle were selected as the most representative of the first short trip and the first idle of the day as determined in a separate statistical analysis. The order of the other short trips in the low speed phase was set randomly. Also, the short trips with lowest speed were connected with the idle periods of the longest duration to reflect traffic jam condition (“start-stop traffic”). The characteristics of the WLTC vers.1 driving cycle are summarized in Table 3.

#### Validation and modifications to the WLTC vers.1

The WLTC vers.1 was tested in several laboratories of all participating regions on various categories of vehicle ( $M_1$ ,  $M_2$  and  $N_1$ ) with different engine displacements and different PMR, to understand the drivability and repeatability of the cycle. On the basis of the experience gathered during these tests the cycle has been modified in different ways:

**Fig. 4.** Cumulative frequency distributions of short trip duration in the low speed phase.

**Table 2**

Number of short trips and idlings and their duration for each phase of the WLTC vers.1.

Phase speed	No. of short trips (#)	Short trip duration (s)	No. of idle periods (#)	Idling duration (s)	Total duration (s)
Low	5	19/35/54/88/249	6	2/5/11/22/38/66	589
Medium	1	385	2	11/37	433
High	1	428	2	4/23	455
Extra-high	1	317	2	1/5	323

**Table 3**

The characteristics of the World-wide Light duty Test Cycle (WLTC) vers.1.

	Cycle duration (s)	Driving distance (km)	Average speed (km/h)	Idling ratio (%)	Max speed (km/h)	RPA (m/s <sup>2</sup> )	$\chi^2$ -value
<i>Characteristics World-wide Unified</i>							
Low	–	–	19.8	24.5	60.0	0.192	–
Medium	–	–	38.4	12.2	80.0	0.188	–
High	–	–	58.0	6.0	110.0	0.156	–
Ex-High	–	–	86.8	2.0	194.7	0.108	–
Total	–	–	45.9	12.8	194.7	0.167	–
<i>WLTC 1st</i>							
Low	589	2.98	18.2	26.3	50.9	0.165	0.244
Medium	433	5.01	41.6	11.1	72.5	0.155	0.629
High	455	7.01	55.5	7.0	97.4	0.144	0.962
Ex-High	323	7.72	86.0	1.5	132.0	0.127	5.312
Total	1800	22.72	45.4	13.3	132.0	0.144	0.738

- Acceleration points were reviewed based on the comments from the participant laboratories. The maximum acceleration parts were limited to the 95th percentiles of cumulative frequency distribution in each speed phase.
- Maximum deceleration points were set to – 5.31 km/h/s, considered appropriate value for avoiding wheel lock and/or shortage of brake power.
- The minimum speed of the cycle was set at 12 km/h due to repeatability problems at lower speed.
- “Micro-transients” (small fluctuations of the speed profile) were smoothed in order to improve the drivability of the cycle.
- Extra-high speed phase: The selection of the Ex-H speed phase as one single short trip extracted from the unified database proved to be not drivable and not representative enough of the characteristics of the extra-high speed phase of the unified database. Because its duration of 317 s (as determined by applying the methodology described earlier) was too small compared to the real world short trips from the unified database, the Ex-H speed phase was thus redesigned with a modified methodology based on combining different segments extracted from real short trips. The combination of the segments forming the Ex-H trip that best fitted the characteristics (maximum speed, average speed, RPA, average positive acceleration, average speed times positive acceleration) of the extra-high speed phase from the unified database and with the smallest chi-squared value, was selected as Ex-H speed phase in the final WLTC driving cycle.

### Final version of the cycle

During the validation phase of the test cycle, it was also observed that for some vehicle categories, it was impossible to follow the cycle. Therefore, it was necessary to adapt the test cycle to three vehicle classes (class 1, class 2 and class 3) of different PMR categories. The initial WLTC was assigned to the highest PMR category (class 3) and two additional test cycles were introduced for the two vehicle categories (class 2 and class 1) with lower PMR.

These two additional test cycles were obtained from the first one, by applying a downscaling factor to the speed profile and to the acceleration profile, which had to be compatible with the actual PMR of class 1 and class 2 vehicles. Such compatibility was tested in the same way as for the initial version of the WLTC, with an iteration of validation phases and modifications of the speed profile until a satisfactory solution was found.

Within WLTC class 3 (PMR > 34 kW/ton) there are two versions of the WLTC cycle. Version 3.1 for vehicles with a maximum speed less than 120 km/h and version 3.2 applicable to vehicles with a maximum speed higher than 120 km/h.

WLTC class 2 (22 kW/ton < PMR ≤ 34 kW/ton) is designed for lower powered vehicles. It has four speed phases like WLTC class 3 but with lower accelerations and top speeds in each phase.

WLTC class 1 (PMR ≤ 22 kW/ton) shall be applied to vehicles with the lowest PMR and is designed to have only the low and medium speed phases.

Selected driving characteristics and vehicle speed and acceleration profiles of the WLTC class 3, class 2 and class 1 are shown in Table 4 and Fig. 5, respectively.

**Table 4**

Driving characteristics of the WLTC class 1, class 2 and class 3.

WLTC	Phase	Duration (s)	Stop duration (s)	Distance (km)	Idling ratio (%)	Maximum speed (km/h)	Average speed (without stop) (km/h)	Average speed (with stop) (km/h)	RPA $\left[\frac{\text{kWs}}{\text{kg km}}\right]$
Class 3	Low	589	156	3.09	24.8	56.5	25.7	18.9	0.2046
	Medium	433	48	4.76(4.72 <sup>a</sup> )	10.6	76.6	44.5(44.1 <sup>a</sup> )	39.2	0.1904
	High	455	31	7.16(7.12 <sup>a</sup> )	6.4	97.4	60.8(60.5 <sup>a</sup> )	56.7(56.4 <sup>a</sup> )	0.1223
	Ex-High	323	7	8.25	1.5	131.3	94.0	92.0	0.1249
	WLTC	1800	242	23.27(23.19 <sup>a</sup> )	12.6				
Class 2	Low	589	155	3.10	24.6	51.4	25.7	19.0	0.1605
	Medium	433	48	4.73	10.6	74.7	44.3	39.4	0.1236
	High	455	30	6.79	6.2	85.2	57.5	53.7	0.1218
	Ex-High	323	7	8.01	1.5	123.1	91.4	89.4	0.0913
	WLTC	1800	240	22.64	12.4				
Class 1	Low	589	154	3.33	24.4	49.1	27.6	20.4	0.0908
	Medium	433	48	4.76	10.6	64.4	44.6	39.6	0.0743
	WLTC	1022	202	8.09	18.4				

<sup>a</sup> Indicates the value for version 3.2, while the other for version 3.1 of the WLTC.

### Analysis of the final version of WLTC

In the present section the results of the analyses carried out on the WLTC concerning its representativeness of both the unified and the regional databases and concerning its comparison with respect to the NEDC are provided.

#### Comparison of the WLTC with the regional and the unified databases

To understand the representativeness of the WLTC (class 3.2) with respect to the regional (EU, ASIA, USA) and the unified (WWW) databases, a comparison analysis was conducted. The comparison took into consideration a series of parameters such as: average positive acceleration, average speed times positive acceleration ( $v \cdot a$ ), RPA and distributions of speed, acceleration and  $v \cdot a$  and the results are shown in Figs. V–VIII in Supporting Information.

It is worth reminding that the WLTC had to fulfill two somewhat opposing requirements: on one side the statistical representativeness of the unified database; on the other side it had to cope with the test constraints (duration, driveability, repeatability). From this point of view the WLTC proved to be the best possible compromise, as any further modification of its speed profile showed some deterioration of one or both aspects. In Figs. V–VIII it can be seen that the WLTP is almost always quite close to the unified database and its parameters are between the corresponding parameters of the unified and the regional databases. The regional databases are the elements that have been weighted and averaged to get the unified database. Therefore, they are to be found on either side of the unified database at a distance that is proportional to their respective difference with the unified database. The characteristics of the regional databases have shown that in terms of decreasing dynamicity they can be ordered as:

- USA (the most dynamic driving behavior)
- Europe
- Asia (the least dynamic driving behavior)

As the European database lies midway between the higher-dynamic USA database and the lower-dynamic Asian database (India, Japan and Korea), it is closer to the unified database and thus to the WLTC. The USA and the Asian databases are a bit more distant from the WLTC. However such compromise was inevitable to reach the primary objective of the WLTC project that consisted in the design of a worldwide harmonized driving cycle.

#### Comparison of the WLTC and NEDC

The WLTC class 3.2, representative for the majority of the existing vehicles, is a more dynamic driving cycle than standard cycles such as NEDC. It covers a wider range of engine conditions and is more representative of real driving conditions. It has higher speeds (maximum speed and average speed with stops are 131.3 km/h and 46.5 km/h, respectively), steeper accelerations- and decelerations and less idling time (12.6%) compared to the NEDC which has the maximum speed and average speed including stops of 120 km/h and 33.6 km/h respectively, constant accelerations and decelerations, and higher idling duration (23.73%). Fig. 6a shows the acceleration profile as a function of speed of the NEDC and WLTC cycles.

Fig. 6b shows a comparison of the engine map coverage in terms of normalized engine speed (rpm-normalized, %) and engine power (power-normalized, %) for a small gasoline vehicle under the WLTC and NEDC cycles. It is clear that the engine operating area is significantly more widely covered under the WLTC compared to the NEDC.

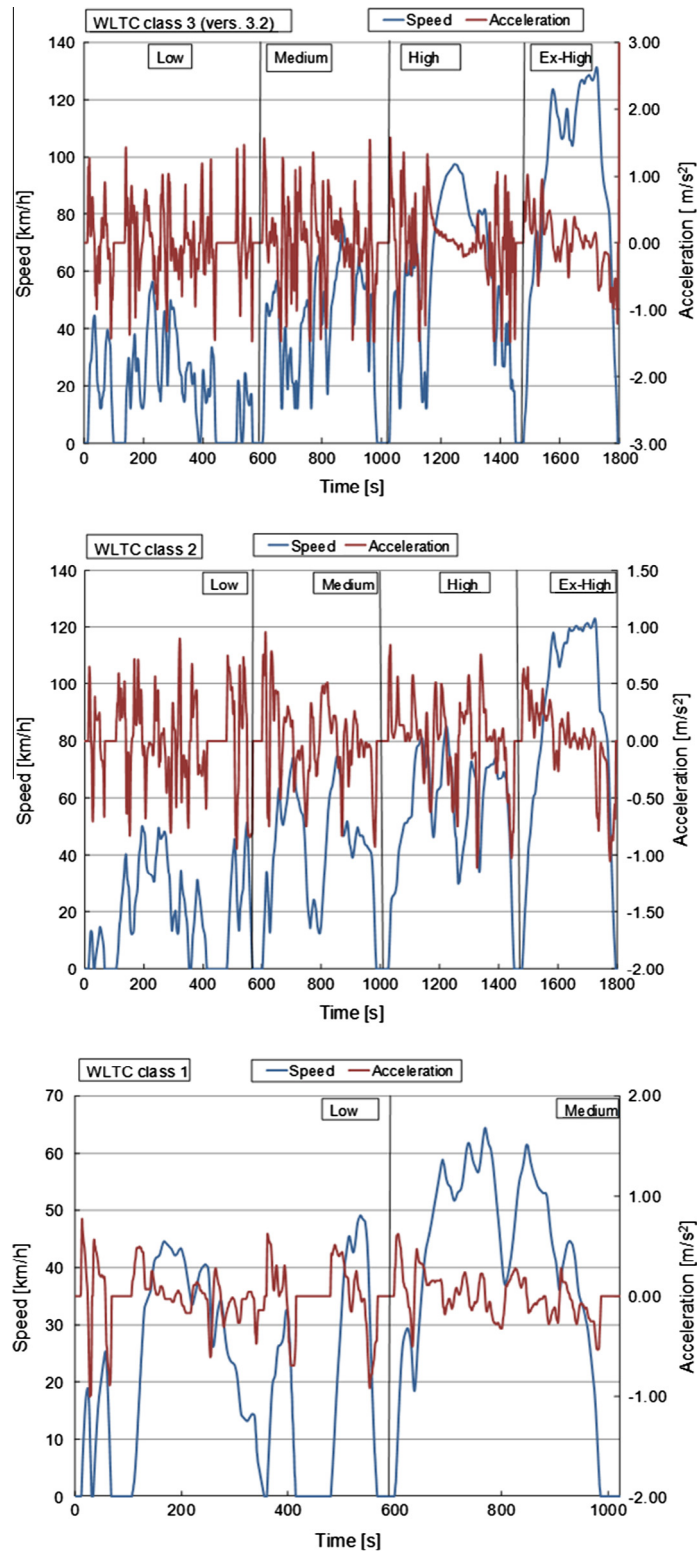
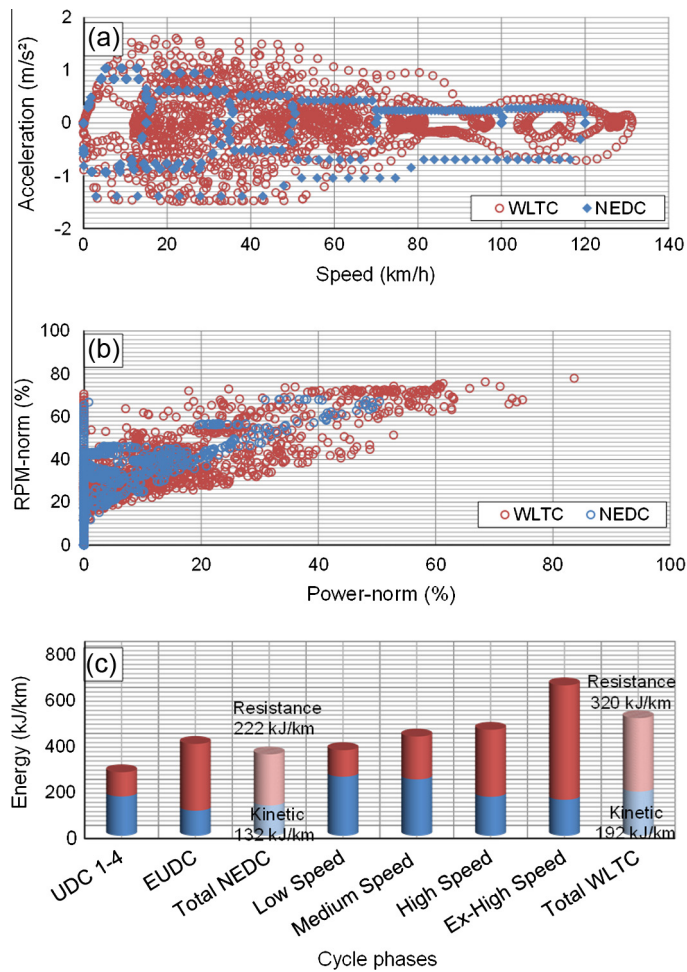


Fig. 5. Speed and acceleration profiles of WLTC class 3 (top), class 2 (middle) and class 1 (bottom).

In addition, more realistic and demanding conditions of the WLTC compared to the NEDC resulted in increase in total energy demand when tested on a chassis dynamometer in accordance with the new WLTP requirements (new test mass,



**Fig. 6.** Acceleration as a function of speed (a); engine map coverage (b); and energy demand (c) of the NEDC and WLTC class 3 – vers.3.2.

road load calculations, gearshift strategy, etc.). Both kinetic energy and active resistance (rolling resistance + air drag) are significantly higher over the WLTC compared to the NEDC as illustrated in Fig. 6c for the same gasoline vehicle.

## Conclusions and policy implications

The development of a World-wide harmonized Light duty Test Cycle (WLTC) based on “real-life” traffic data from different regions of the world (Europe, India, Japan, Korea and USA) was presented. Suitable weighting factors were applied to the world-wide (unified) database in the attempt to provide a balanced representation of real driving conditions of each region. Approximately 765,000 km of data were collected, covering a wide range of vehicle categories ( $M_1$ ,  $N_1$  and  $M_2$  vehicles, various engine capacities, PMR, manufacturers, etc.), over different road types (urban, rural, motorway) and driving conditions (peak, off-peak, weekend). During the validation phase of the first version of the WLTC it was observed that for some vehicle categories it was impossible to follow the speed trace. Therefore, the test cycle was adapted to three vehicle categories (class 1, class 2 and class 3) with different power-to-mass ratio (PMR). The WLTC assigned to the highest PMR category (class 3) has an overall distance of 23,266 m, maximum speed of 131.3 km/h, average speed with and without stops of 46.5 km/h and 53.7 km/h respectively. Idling duration is 12.6% of the total cycle time. The duration of each speed phase L/M/H/ExH is: 589, 433, 455 and 323 s respectively. Within this class there are two versions of the cycle. Version 3.1 for vehicles with a maximum speed less than 120 km/h and version 3.2 applicable to vehicles with a maximum speed higher than 120 km/h.

WLTC for class 2 ( $34 \geq \text{PMR} > 22 \text{ W/kg}$ ) is designed for lower powered vehicles. It has four speed phases like WLTC class 3 but with lower accelerations and top speeds in each phase.

WLTC class 1 ( $\text{PMR} \leq 22 \text{ W/kg}$ ) shall be applied to vehicles with the lowest PMR and is designed to have only the low and medium speed phases.

To conclude, the results presented in this study have direct implications for future environmental policy. WLTC, together with the new test procedure (WLTP) has been designed to substantially improve the monitoring of the reduction of pollutant emissions and fuel consumption from new light-duty vehicles and should therefore contribute to the improvement of urban air quality and greenhouse gas emissions.

As stated in section ‘The policy framework’, the time frame for the development of new test cycle and test procedure was agreed between the two sponsors of the UNECE WLTP project (Europe and Japan) in order to allow its earliest possible introduction. In particular, the plan of the European Commission is to be able to introduce the new test procedure together with the step 2 of the Euro 6 standards (Euro 6c). This means that starting on the 1st September 2017 all new types of M<sub>1</sub> and N<sub>1</sub>-class I vehicles should be tested according to the new procedure, while on the 1st September 2018 all M<sub>1</sub> and N<sub>1</sub>-class I vehicles should be tested on the WLTP. For the N<sub>1</sub>-class II and III vehicles the same applies with a delay of 1 year.

Introducing the WLTP in the TA of LDVs means that emission limits will be evaluated on the new test-cycle. Considering that the same time frame is envisaged also for the introduction of the Real Driving Emission (RDE) test in the European legislation, Europe will be at the forefront in terms of environmental protection and vehicle emission control technology.

Finally, the introduction of WLTP in the TA for LDVs means that also for the CO<sub>2</sub> Regulations (443/2009 and 510/2011), vehicle manufacturers shall demonstrate to be in line with their targets on the basis of CO<sub>2</sub> emissions evaluated with the new test procedure. However, while the introduction of WLTP will not affect the regulated pollutant emission limits, the CO<sub>2</sub> targets will need to be adapted, as foreseen in the Article 13 of the above mentioned regulations. Adapting CO<sub>2</sub> targets is the objective of the WLTP/NEDC correlation project carried out by the European Commission with the support of a Technical Working Group composed by Member States, vehicle manufacturers, technical experts and academia. The results of this project are expected for the end of 2014.

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## Appendix A. Supplementary material

Information on characteristics of various LDVs test cycles, the fleet used for collecting the activity data, definitions of road categories in four world-regions, matrix of different criteria for choosing the threshold vehicle speed between the L/M/H/Ex-H, determination of weighting factors, driving characteristics of the regional and the unified database, the speed profile of the WLTC vers.1, comparison between the characteristics of the WLTC and the regional and the unified databases and abbreviations are given in supporting information. Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.trd.2015.07.011>.

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