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ORIGINAL ARTICLE

The WLTC vs NEDC: A Case Study on the Impacts of Driving Cycle on Engine Performance and Fuel Consumption

J. Lasocki

Faculty of Automotive and Construction Machinery Engineering, Warsaw University of Technology, Narbutta 84, 02-524 Warsaw, Poland
Phone: +48222348780

ABSTRACT – The World-wide harmonised Light-duty Test Cycle (WLTC) was developed internationally for the determination of pollutant emission and fuel consumption from combustion engines of light-duty vehicles. It replaced the New European Driving Cycle (NEDC) used in the European Union (EU) for type-approval testing purposes. This paper presents an extensive comparison of the WLTC and NEDC. The main specifications of both driving cycles are provided, and their advantages and limitations are analysed. The WLTC, compared to the NEDC, is more dynamic, covers a broader spectrum of engine working states and is more realistic in simulating typical real-world driving conditions. The expected impact of the WLTC on vehicle engine performance characteristics is discussed. It is further illustrated by a case study on two light-duty vehicles tested in the WLTC and NEDC. Findings from the investigation demonstrated that the driving cycle has a strong impact on the performance characteristics of the vehicle combustion engine. For the vehicles tested, the average engine speed, engine torque and fuel flow rate measured over the WLTC are higher than those measured over the NEDC. The opposite trend is observed in terms of fuel economy (expressed in l/100 km); the first vehicle achieved a 9% reduction, while the second – a 3% increase when switching from NEDC to WLTC. Several factors potentially contributing to this discrepancy have been pointed out. The implementation of the WLTC in the EU will force vehicle manufacturers to optimise engine control strategy according to the operating range of the new driving cycle.

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INTRODUCTION

Light-duty vehicles powered by internal combustion engines have been tested for exhaust emissions and fuel consumption since the late 60s. The general idea of most test procedures is based on the principle of simulating actual road driving conditions on a chassis dynamometer in a controlled laboratory environment. In order to accomplish this objective, a vehicle follows a predefined speed profile called 'driving cycle', which determines engine working states by applying the right sequence and magnitude of engine torque and speed [1, 2].

The ideal driving cycle should comply with the following requirements [2, 3]; be practical (easy to execute in a laboratory) and provide full repeatability and reproducibility, and statistically represent diverse real-world driving conditions. Thereupon, various driving cycles for emission certification have been developed around the world. The most commonly used are the New European Driving Cycle (NEDC) in Europe, the JC 08 in Japan and the Federal Test Procedure 75 (FTP-75) in the USA. Yet none of them fulfils all the requirements mentioned earlier. The NEDC is not complicated, easy to drive, as it contains only steady-state modes and therefore ensures good repeatability. However, it has been highly criticised for not representing real-world vehicle operation [4, 5]. The JC 08 is regarded to be closer to the actual driving conditions, mainly due to more dynamic changes of vehicle speed, but it has been designed to reflect urban traffic. In consequence, the Japanese cycle is not suitable for the simulation of other driving conditions [3]. The same problem applies to the FTP-75, which represents mixed, urban and extra-urban traffic. It still has to be accompanied by additional driving cycles, the Highway Fuel Economy Test (HWFET) and the Supplemental Federal Test Procedures (SFTP) US06, corresponding to highway traffic and aggressive driving at high speed respectively. As a result, the imperfections of driving cycles contribute to the growing discrepancy between results of laboratory and on-road testing of emission and fuel consumption of vehicles [6, 7].

In the pursuit to reduce this disconnect and facilitate implementation of global unification of vehicle testing procedures, in 2007 United Nations Economic Commission for Europe (UNECE) launched a program with the aim to develop the World-wide harmonised Light-duty Test Cycle (WLTC) and the World-wide harmonised Light duty Test Procedure (WLTP) [3, 8, 9]. This international initiative was driven by the main automotive markets, i.e. EU, Japan, India, China, Korea, with the support of other countries, including the USA (although the US Environmental Protection Agency decided to withdraw its active participation and sponsorship of the WLTP in 2010). In 2014 Global Technical Regulation No. 15 (GTR15) [10] was published, defining technical specifications of the new test cycle and test procedure. First to apply the WLTC for all new vehicle type approvals (M_1 and N_1-class I vehicles) was the EU, which introduced

***CORRESPONDING AUTHOR** | J. Lasocki | jakub.lasocki@pw.edu.pl

new regulations starting on the 1st September 2017, when step 2 of the Euro 6 standard (Euro 6c) goes into effect [3]. It is without a doubt that the introduction of the new driving cycle and the new test procedure in the EU will affect official certified values of fuel consumption and pollutant emission of vehicles under type-approval.

The aim of this study is to give an overview of the WLTC and evaluate its expected influence on the performance of combustion engines, with particular emphasis on fuel consumption (pollutant emissions are beyond the scope of this paper). The key characteristics of the WLTC are discussed and compared to the previously used NEDC. For quantifying the differences between the old and new approaches, exemplary results of dynamometer testing of two light-duty vehicles, equipped with compression-ignition (CI) and spark-ignition (SI) engines were analysed. In this context, the current paper seeks to address only the effects of the driving cycle itself, i.e. vehicle speed profile, and not the whole test procedure.

CHARACTERISTICS OF THE WLTC AND NEDC

General Information

The original intention of the WLTC developers was to simulate typical driving conditions around the world. Therefore the driving cycle has been combined from 'real-world' data recorded in different regions of the world, including the EU, India, Japan, Korea, and the USA, by applying suitable weighting factors. The resulting WLTC is in fact, a set of driving cycles, with separate speed profiles dedicated for three light-duty vehicle classes, depending on the power to weight ratio (PWR) of a tested vehicle [3]:

i. The WLTC class 3 applies to high-powered vehicles with PWR higher than 34 W/kg. It is further divided into two subclasses: 3.1 for vehicles with a maximum speed lower than 120 km/h and 3.2 for vehicles with a maximum speed higher than 120 km/h.
ii. The WLTC class 2 shall be applied to middle-powered vehicles, having PWR in the range of 22–34 W/kg. It is similar to the class 3 cycle, but its speed profile has been downscaled.
iii. The WLTC class 1 is designed for low-powered vehicles with a maximum PWR of 22 W/kg. It has been derived from the class 3 cycle, but is shorter and has lower accelerations and top speeds.

The WLTC for each vehicle class consists of phases representing driving with speed within a certain range. Class 3 and class 2 include four-speed phases: low, medium, high and extra high, while class 1 only has two: low and medium. Each phase is composed of a sequence of idles and short trips (i.e. driving sequences from start to full stop of a vehicle). The differences between WLTC class 3.1 and class 3.2 occur in medium, high and extra high-speed phases. There are some minor, fixed changes in speed profiles of medium and high-speed phases, aiming at enabling the tested vehicle to reach a certain level of acceleration. The extra high-speed phase is modified individually according to the rated power of the tested vehicle [10]. Speed profiles of the WLTC class 3.2, 2 and 1 are shown in Figure 1.

Until recently, the NEDC has been used in the EU certification procedures for all light-duty vehicle classes. It consists of two parts [11]:

i. Urban Driving Cycle (UDC), representing city traffic;
ii. Extra Urban Driving Cycle (EUDC), representing rural and motorway driving.

The UDC includes four consecutive runs of the ECE-15 (the name corresponds to UNECE Regulation No. 15), which comprises phases of idling, steady accelerations, steady speeds and steady decelerations. The ECE-15 was the first cycle to be legislated in the EU in 1970 for certification of emission from vehicles with spark-ignition engines (fuelled with gasoline) only. In the late 80s, it also covered vehicles with compression ignition engines (supplied with diesel fuel). The EUDC part was introduced in 1989. Its alternative version, with a maximum speed limited to 90 km/h, is dedicated to low-powered vehicles having a maximum engine power lower than 30 kW (30 W/kg for light-duty vans) and a maximum speed lower than 130 km/h [2]. Initially, there was an engine warm-up phase with idling for 40 s executed before the actual cycle began, but it was waived in 2000 with the introduction of the engine cold start requirement. Figure 2 shows the speed profile of the NEDC in its final form (dotted line marks the version for low-powered vehicles).

Although both the NEDC and WLTC are based on data collected empirically, through on-road measurements, they represent different approaches in vehicle driving cycle development. It can be clearly seen comparing speed profiles shown in Figure 1 and 2. The NEDC is a typical 'synthetic' or 'modal' driving cycle, derived mathematically and composed of straight lines, which correspond to constant or zero acceleration phases. On the contrary, driving sequences within the WLTC are characterised by irregularities in speed which are typical of real-world driving. The WLTC was constructed as a compilation of the selected fragments of speed traces obtained from collected data so that the target parameters of the whole cycle are met (average speed, acceleration etc.) [2].

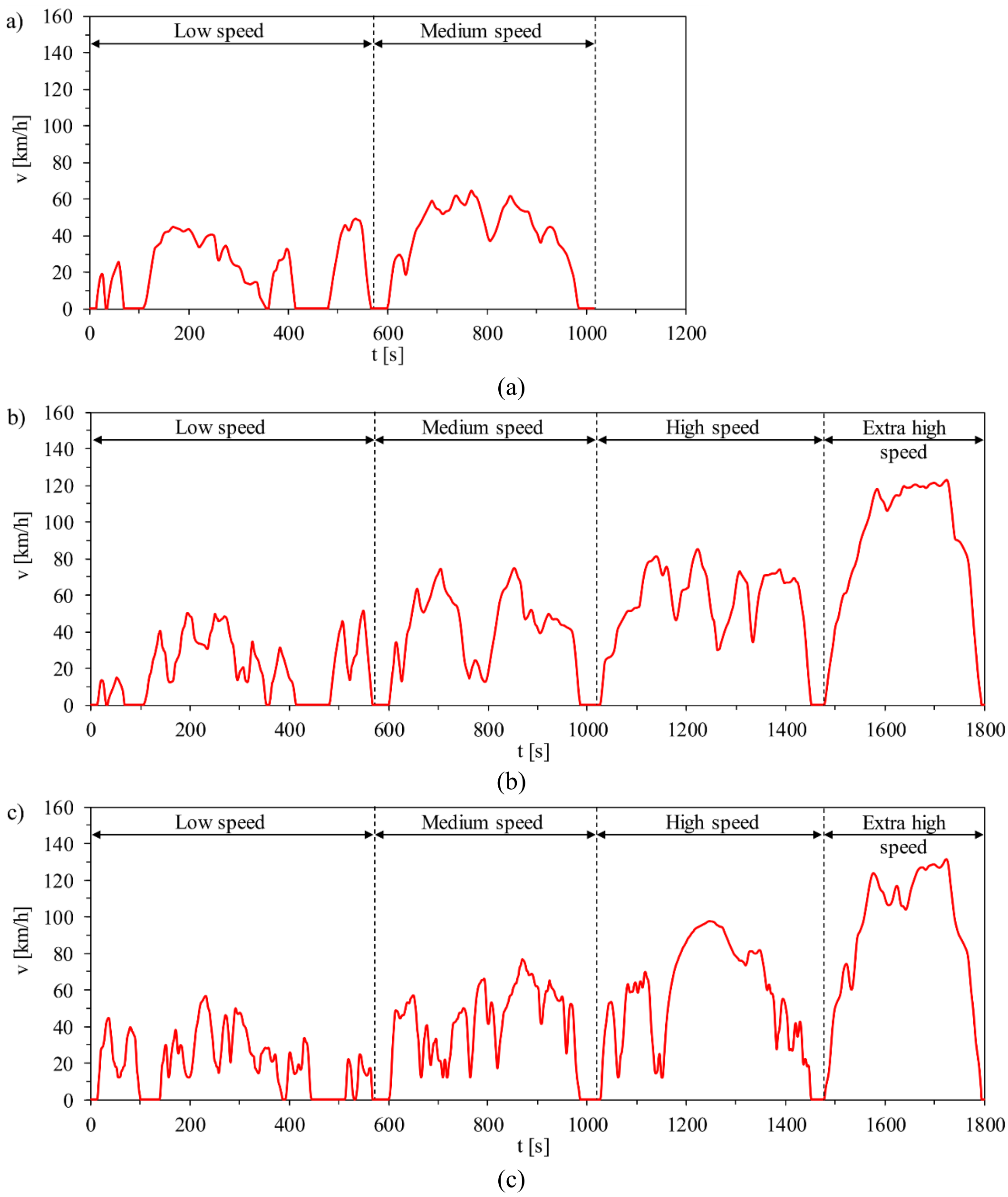

Figure 1. Vehicle speed – v in the WLTC: (a) class 1, (b) class 2, and (c) class 3.2.

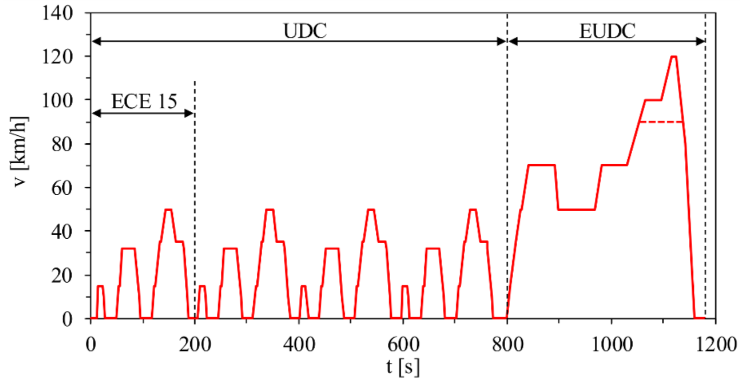

Figure 2. Vehicle speed – v in the NEDC.

Driving Characteristics

Further differences between the cycles concern their driving characteristics. Table 1 lists the most important parameters of the NEDC and the WLTC class 1, class 2, class 3.1, and class 3.2. Presented values were calculated on the basis of data taken from UNECE regulations [10, 11].

Table 1. Selected parameters of the NEDC and WLTC (class 1, 2, 3.1, and 3.2).

Parameter	NEDC	WLTC 3.2	WLTC 3.1	WLTC 2	WLTC 1
Duration (s)	1180	1800	1800	1800	1022
Distance (km)	11.02	23.27	23.19	22.65	8.10
Average speed (with stops) (km/h)	33.62	46.51	46.36[a]	45.27	28.50
Average speed (without stops) (km/h)	44.08	53.49	53.32[a]	52.23	35.38
Maximum speed (km/h)	120.00	131.30	131.30[a]	123.10	64.40
Average positive acceleration (m/s^2)	0.59	0.41	0.39	0.28	0.21
Maximum positive acceleration (m/s^2)	1.04	1.67	1.67	0.97	0.81
Average negative acceleration (m/s^2)	-0.80	-0.45	-0.45	-0.34	-0.22
Minimum negative acceleration (m/s^2)	-1.39	-1.49	-1.49	-1.11	-1.11
Relative positive acceleration (m/s^2)	0.110	0.159	0.154[a]	0.119	0.083
Standing time ratio (%)	23.73	12.56	12.56	12.83	18.79
Positive acceleration time ratio (%)	20.93	43.83	44.78	45.83	39.53
Negative acceleration time ratio (%)	15.76	39.94	38.94	37.39	38.65
Standing time ratio (%)	39.58	3.72	3.78	4.00	3.13

[a]Depending on the downscaling factor applied for vehicle speed profile in extra high speed phase.

Since the WLTC class 3.2 is representative of the vast majority of European vehicles [8], it can be directly compared with the NEDC. The WLTC class 3.2 (referred later to as the WLTC) lasts for 1800 s and has a mileage of 23.27 km, which is more compared to 1180 s and 11.02 km, respectively, in the NEDC. Therefore increased fuel consumption surcharge due to the engine cold start, considered to be almost independent of the driving pattern [12], has a lower impact on the overall fuel consumption figure in the WLTC than in the NEDC. Furthermore, the WLTC is characterised by a more dynamic speed profile: almost 84% of the time, a vehicle is subjected to accelerating or decelerating, less than 13% – standing and less than 4% – driving at a constant speed. In the case of the NEDC, it is almost 40% for driving at a constant speed, less than 37% for accelerating or decelerating and almost 24% for standing (idling). Longer stop duration favours cars with start-stop systems; thus, possible fuel savings coming from the use of these devices will decrease in the WLTC. Different shares of acceleration phases affect Relative Positive Acceleration (RPA) – a good descriptor for the dynamics of a cycle – which for the WLTC equals 0.159 m/s^2, while for the NEDC is much lower – only 0.110 m/s^2. This trend continues in terms of average and maximum values of speed. The average speed in the WLTC is 46.5 km/h (53.5 km/h if not including stops) and reaches maximally 131.3 km/h, whereas in the NEDC, it is 33.6 km/h (44.1 km/h) and 120 km/h, respectively. As for acceleration and deceleration, the extreme values are higher for the WLTC, but on the other hand, the NEDC has higher average values. It is worth emphasising the importance of negative acceleration. The negative acceleration time ratio in the WLTC is more than two times larger than in the NEDC (39.94% vs 15.76%). This may involve at least two effects that are significant for fuel (energy) consumption and, consequently, pollutant emissions. Firstly, it gives the opportunity to recover energy to vehicles that have such an option, for example, hybrid or electric cars. Secondly, in the case of some modern internal combustion engines, when the vehicle is decelerating, fuel injectors deliver less fuel (the effect known as "fuel cut-off"). It can be concluded that the WLTC covers a broader spectrum of engine conditions and is more realistic in simulating real driving conditions.

In addition, the introduction of the WLTP brings some fundamental changes to gearshift prescriptions (necessary for manual transmission vehicles). So far, the gears in the NEDC have been changed explicitly in compliance with the fixed strategy defined in the legislation. The WLTP enables individual shifting points for each vehicle, where the right sequence is calculated according to vehicle technical specifications [13].

MATERIALS AND METHODS

The effects of the transition from the NEDC to the WLTC on the performance of vehicles' combustion engines were investigated, drawing upon raw experimental data generated at the Advanced Powertrain Research Facility (APRF) of Argonne National Laboratory [14]. This study considered two light-duty vehicles, which differ in terms of, i.e. manufacturer, size, weight, body type, engine technology and construction parameters, fuel type (gasoline and diesel fuel), and performance. The idea behind this choice was to uncover some qualitative tendencies, supported by example test results, and not to make specific quantitative claims concerning all the segments of the light-duty vehicle market. The main technical specifications of the selected vehicles are compared in Table 2.

The tests were carried out using a 4-wheel-drive chassis dynamometer with rollers of 1.22 m (48") diameter, providing variable equivalent inertia weight of 136–5443 kg. The apparatus is capable of testing vehicles having a wheelbase up to 4.57 m and maximum power (at one axle) of 186 kW. Test cell includes a thermal chamber that is EPA 5-cycle-capable. Ambient conditions, i.e. temperature, humidity, solar load, were fully controlled. The volumetric flow rate of fuel consumed by the engine was measured with the use of a Re-Sol RS840-060 fuel measurement system mounted in the fuel line between the vehicle tank and the engine fuel rail. The system enables the measurement of flow rates within the range of 0.3–60 l/h with an accuracy of ± 0.5% of the reading. Vehicle instrumentation consisted of a custom fully integrated data acquisition system that merges and time aligns data streams from different digital and analogue sensors [17]. For detailed specifications of testing equipment at Advanced Powertrain Research Facility, see Lohse-Busch et al. [18].

Table 2. Technical specifications of the vehicles tested [15, 16].

Parameter	Chevrolet Cruze	Dodge Ram 1500 HFE
Body type	4-door sedan	Pick-up
Number of seats	5	3
Curb weight (kg)	1587	2074
Test weight (kg)	1727	2245
Drive type	Front-wheel drive	Rear-wheel drive
Engine trade name	GM 2.0L I4 LUZ	3.6L Pentastar V6
Engine type	CI, DOHC, turbocharged	SI, DOHC
Fuel	Diesel fuel	Gasoline
Cylinder configuration	4 in-line	V6 (60 deg)
Engine displacement (cm^3)	1956	3604
Bore/stroke (mm)	83.0/90.4	96.0/83.0
Compression ratio	16.5:1	10.2:1
Engine power (kW @ rpm)	112 @ 4000	227 @ 6400
Engine torque (Nm @ rpm)	358 @ 2600	365 @ 4175
Fuel supply system	Direct injection	Multi-port injection
Cooling system	Liquid-cooled	Liquid-cooled
Transmission	6-speed automatic	8-speed automatic
Additional features	DPF, cooled EGR, urea injection after-treatment	Variable valve timing, start-stop, active grille shutters

In order to eliminate all differences related to the specific type-approval test procedures and isolate the vehicle speed effects, both vehicles were prepared for tests and tested in the same conditions. No specific gearshift points were applied during testing since both vehicles have automatic transmission. The target coefficients for road-load simulation on the chassis dynamometer were determined from the coast down testing of vehicles. The average temperature and relative humidity of the air in the test cell were 296.250 ± 0.005 K and 49.30 ± 0.05% (mean values with the measurement errors), respectively. Vehicles' air conditioning systems were not activated during testing. Both driving cycles were performed with vehicle engines warmed up. Thus, the impact of engine cold start was not investigated.

Out of all 10 Hz signals recorded during testing, the following were used in the present study: time, vehicle speed, engine speed, dynamometer tractive force, mass fuel flow rate, air temperature, and air relative humidity. The signals were further processed with the use of the moving average filter, acting as a low pass filter, to eliminate noise component from the recorded data. Only one implementation of each drive cycle was used for the analysis. To ensure the consistency of the chassis dynamometer test results at APRF, the fuel economy cycle-to-cycle repeatability was determined. Thus, 0.6 per cent was obtained for a hot engine start with a 90 per cent confidence interval [17]. The low test-to-test variability at APRF is achieved, i.e. by employing experienced professional dynamometer drivers. Their accuracy in reproducing the cycle is verified with the use of SAE J2951 drive quality metrics (a set of parameters aimed at quantifying how close the driving speed trace followed the actual drive trace) [19].

RESULTS AND DISCUSSION

In this section, the performance characteristics of two vehicles tested in the WLTC and NEDC are analysed and compared, with a special emphasis on engine speed, engine torque, and fuel consumption. Given large differences in the technical characteristics of the vehicles tested, the results should not be compared in the context of the vehicles, but the driving cycles. The question is whether and what would be the impact of the driving cycle on vehicle performance. Engine speed and non-negative torque measured over both driving cycles are presented in Figure 3 (note that the traces for the NEDC and WLTC do not have common time axes). The dynamic character of the WLTC, manifested by higher vehicle speed and stronger acceleration forces, results in higher engine speed and torque, if compared with the NEDC.

With respect to engine speed, there is on average a 12% and 18% increase for Chevrolet and Dodge, respectively, as a result of the change of driving cycle from the NEDC to WLTC. In general, engine speed followed the pattern determined by vehicle speed in the given driving cycle. This is particularly noticeable over the NEDC (Figure 3 (a) and (c)), where urban and extra-urban phases are clearly distinguishable. In addition, a start-stop system deactivated the Dodge engine when the vehicle stopped. Regarding engine torque, important increases can be observed over the WLTC compared with the NEDC, reaching on average 77% more for Chevrolet and 74% more for Dodge. This phenomenon indicates a possible increase in engine efficiency since the efficiency typically increases with engine load, especially in the case of current advanced engine technologies [12, 20].

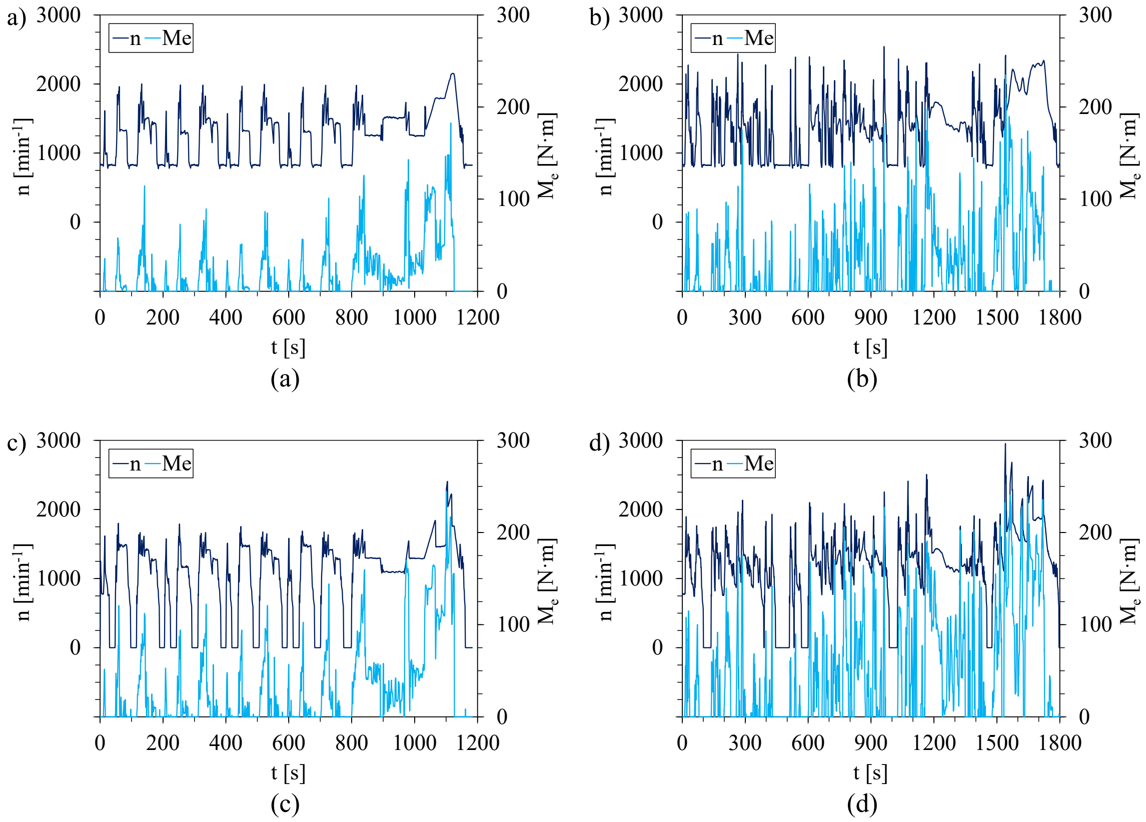

Figure 3. Engine speed – n and non-negative torque – Me measured in driving cycles: Chevrolet in NEDC (a) and WLTC (b), Dodge in NEDC (c) and WLTC (d).

To get more insights into this issue, the distributions of engine speed and non-negative torque were explored. In terms of engine speed, the WLTC shifted the distribution towards higher values, as shown in Figure 4. This change can be explained by a lower share of vehicle stop time in the WLTC and a higher average speed of the vehicle. Moreover, the use of start-stop system in Dodge makes its engine speed distribution more uniform. The situation is similar with regard to the distribution of non-negative engine torque, given in Figure 5. Despite the similar range of torque over both driving cycles, a considerable change was observed. The NEDC favours vehicle stop-and-go driving, distinguished by zero or low engine loads, while the WLTC extends operating conditions towards the higher levels of load.

To further exemplify this issue, Figure 6 shows the engine map coverage, in respect of engine speed and non-negative torque, for both vehicles over the NEDC and WLTC. As can be seen in this figure, the greater part of vehicle operation over the NEDC occurs at fairly low or moderate engine speed and torque levels. On the contrary, engine operating areas over the WLTC are significantly broadened and have more homogeneous character. This can have significant consequences for vehicle powertrain design, which must take into account the optimisation of engine control for wider, more dynamic operating conditions.

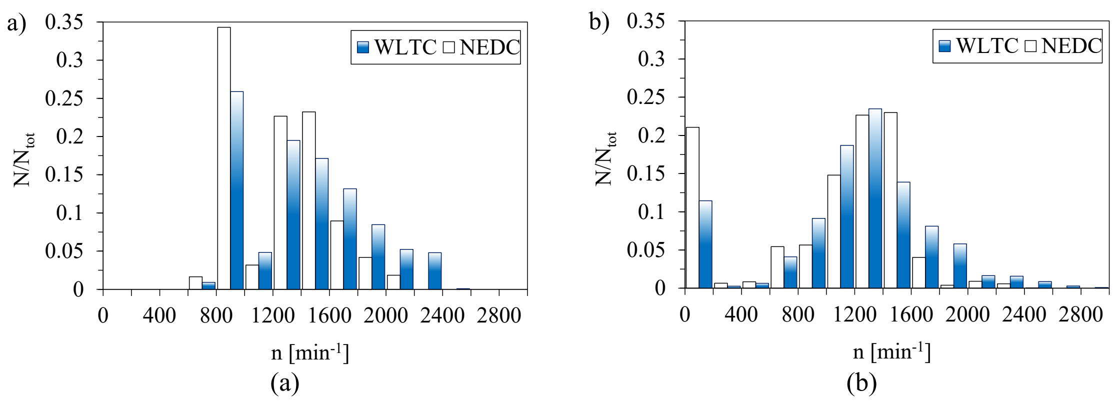

Figure 4. Normalised histograms of engine speed – n over the NEDC and WLTC for (a) Chevrolet and (b) Dodge.

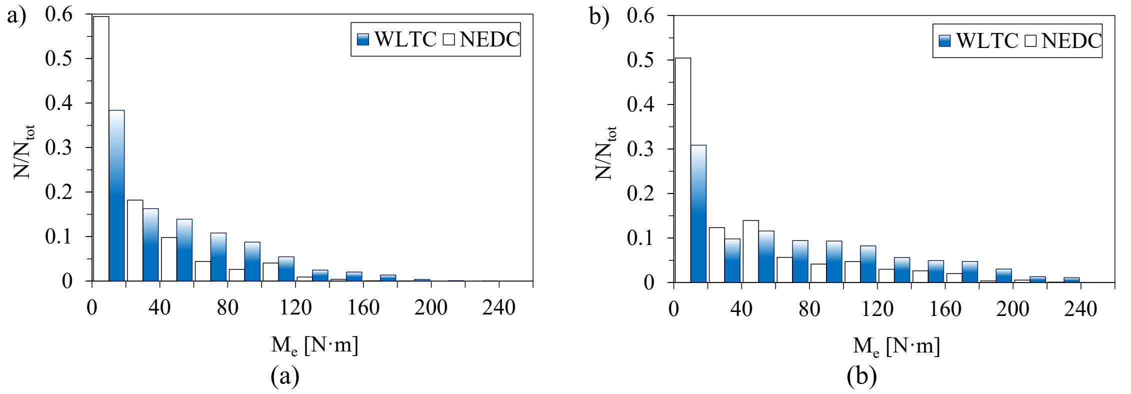

Figure 5. Normalised histograms of non-negative engine torque – Me over the NEDC and WLTC for (a) Chevrolet and (b) Dodge.

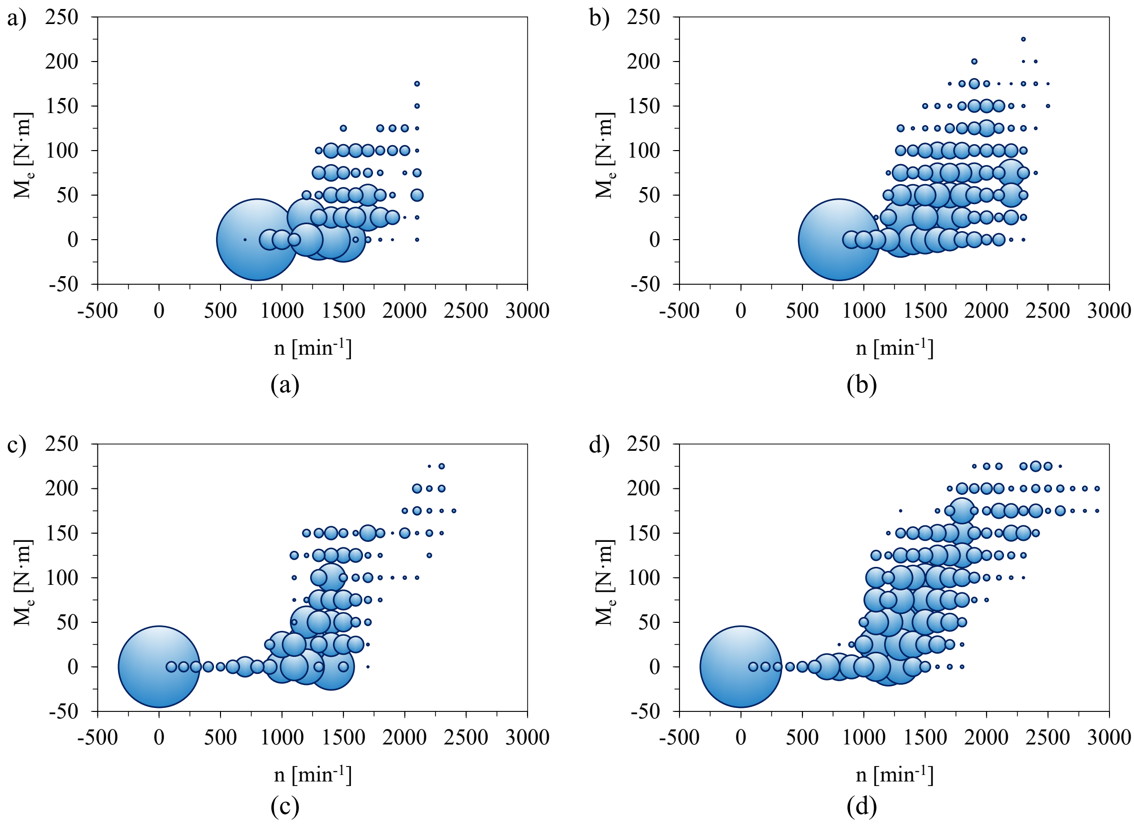

Figure 6. Engine map coverage for Chevrolet in NEDC (a) and WLTC (b), Dodge in NEDC (c) and WLTC (d); the area of an individual point corresponds to the incidence of the given engine operating state in the driving cycle.

The differences between the NEDC and WLTC, regarding the value and the distribution of engine speed and torque, had an inevitable impact on fuel consumption characteristics. Figure 7 shows the fuel flow rate and total mass of fuel consumed over two driving cycles by both vehicles. The profile of fuel flow rate in this figure has a number of similarities with the profile of non-negative engine torque shown in Figure 3. Again, a trend towards a higher average fuel flow rate was observed over the WLTC regardless of the vehicle driven. Specifically, for Chevrolet, it was a 25% increase and for Dodge – 42%.

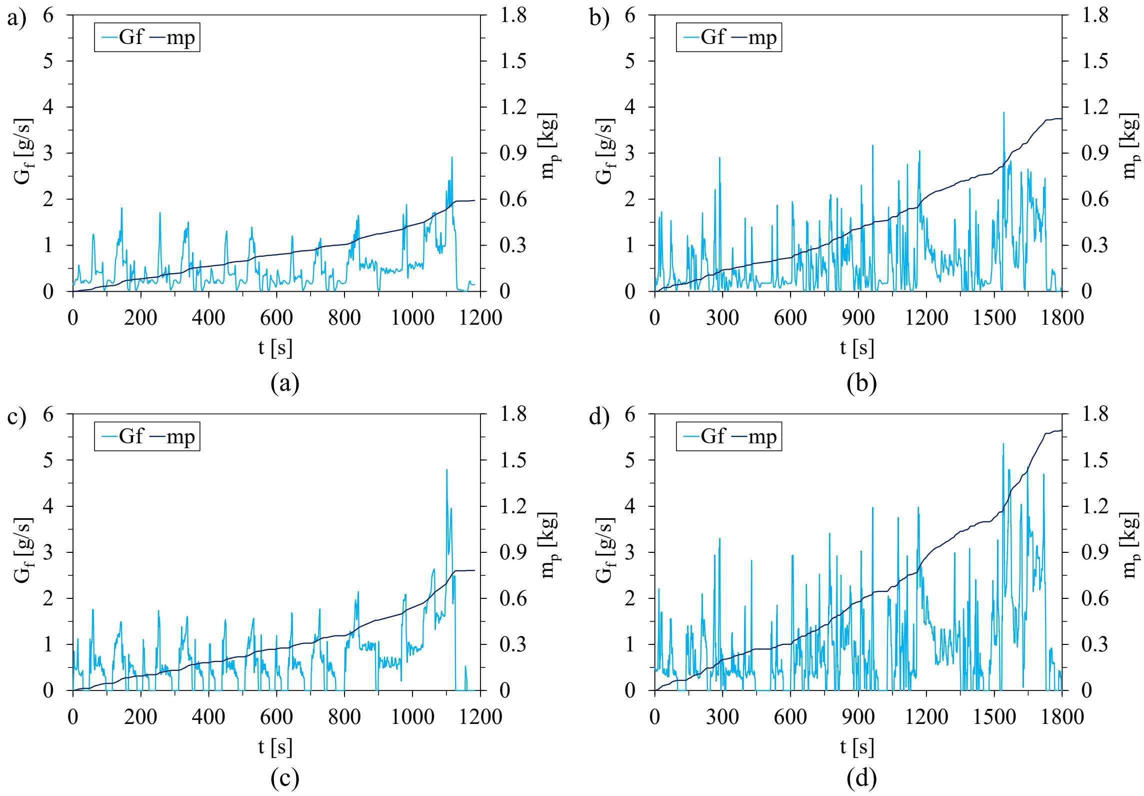

Figure 7. Fuel flow rate – G_f and total mass of fuel consumed – m_f in driving cycles: Chevrolet in NEDC (a) and WLTC (b), Dodge in NEDC (c) and WLTC (d).

While averages are important, of more interest is how the variability of range was impacted under different driving conditions. More detailed information on this issue is shown in Figure 8, comparing normalised histograms of fuel flow rate over analysed driving cycles. The distribution of fuel flow rate behaved in a similar manner to the distribution of non-negative engine torque (Figure 5). However, while maintaining the general trend of increasing the share of higher values, in this case, the difference between driving cycles is not that significant.

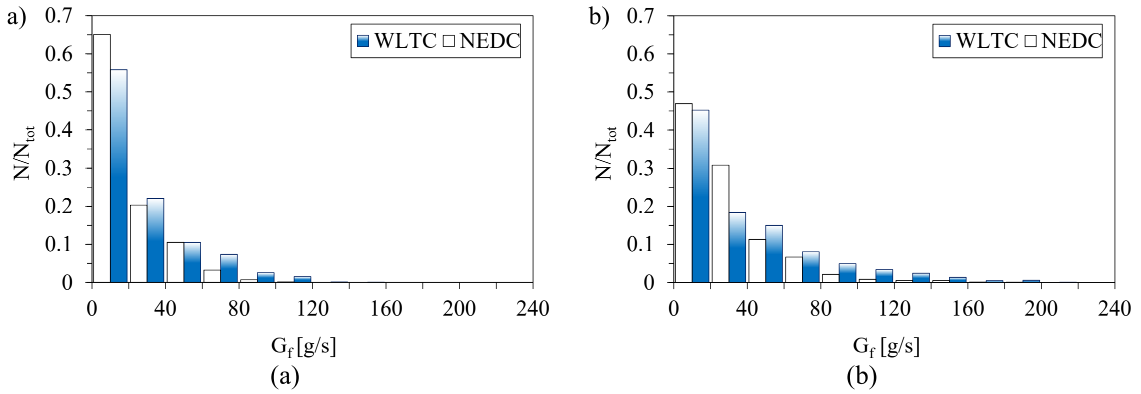

Figure 8. Normalised histograms of fuel flow rate over the NEDC and WLTC for (a) Chevrolet and (b) Dodge.

Perhaps surprisingly, given the earlier information on the increased average fuel flow rate, the results in Figure 9 suggest that the driving cycle in itself appears to have a rather little discernible impact on the overall fuel economy (expressed in l/100 km). These findings are consistent with those observed in earlier studies [12, 21], where similarly small differences in the fuel consumption between the WLTC and the NEDC were reached. The reason for this ostensible lack of influence involves at least two overlapping factors. The WLTC is more transient than the NEDC, having more frequent speed and load changes; hence it promotes higher fuel consumption. On the other hand, higher average vehicle speed and higher engine load level during the WLTC favour better fuel efficiency compared to the NEDC. These factors have opposing effects and, in many cases may even neutralise each other. Besides, negative acceleration and the associated phenomenon of fuel cut-off (as described previously in section 2) should also be included in the analysis. Observing the graphs in Figure 7, it can be seen that for the WLTC, both vehicles present higher peaks of fuel flow rate, but they also achieve 0 g/s frequently, which decreases the average fuel consumption. This is apparently confirmed by the higher fuel flow rates obtained from t = 1000 s when the vehicles start the high-speed fraction of the cycle. For Dodge, the difference in fuel consumption was affected by the start-stop routine. Even more pronounced effects of the fuel cut-off phenomenon during negative acceleration should be noticeable in tests of vehicles with energy recovery systems (e.g. hybrid vehicles). Comparative studies on the performance of this type of vehicle in the NEDC and WLTC could open new perspectives in this area.

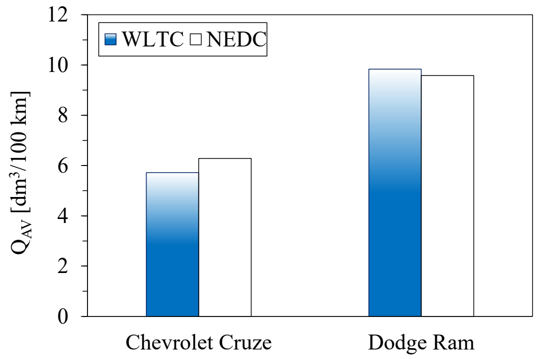

Figure 9. Fuel economy in the NEDC and WLTC for vehicles tested.

Arguably, the most remarkable result to emerge from the analysed data is the fact that the vehicles tested were characterised by the opposite change in the overall fuel economy when switching from the NEDC to WLTC. To be specific, a 9% decrease in fuel economy was observed for Chevrolet, while in the case of Dodge, it was a 3% increase. The non-uniformity of the obtained results, where both increases and decreases are possible, suggest a more complex situation. In fact, there are several aspects that have to be taken into consideration. Firstly, engines with larger displacement volume, like the one used in Dodge, usually benefit more in terms of efficiency at high-load operating conditions, whereas smaller engines may already reach relatively high efficiency even during low-load driving [12]. Secondly, vehicles with conventional combustion engines and no advanced technologies generally tend to get lower fuel consumption over the WLTC than the NEDC, although there are some variations in individual vehicle segments (see also [12, 22] for details). For example, vehicles that make use of a start-stop system, like Dodge, benefit much more over the NEDC, where the share of stop time is higher [23]. Finally, previous studies [12] reported possible discrepancies between diesel and gasoline vehicles. The difference may not be large, but diesel vehicles tend to have slightly higher fuel consumption over the WLTC than gasoline vehicles, with an exemption of the vehicles equipped with high-powered engines, e.g. Dodge.

CONCLUSION

In search for a solution to close the growing gap between pollutant emission and fuel consumption values determined in official laboratory tests and in real-world on-road driving, a big hope has been set towards the WLTC – newly developed international driving cycle for testing vehicles on a chassis dynamometer. This study provided some background information on the WLTC and evaluated its expected impact on vehicle engine performance by means of comparison with the NEDC – type-approval driving cycle previously used in the EU. Summing up the results of the investigation presented in this paper, it is possible to draw the following conclusions:

i. The characteristics of a driving cycle used for testing vehicles have a direct impact on the performance of their combustion engines.
ii. The WLTC, compared to the NEDC, is more dynamic in terms of vehicle speed profile.
iii. The WLTC covers a broader spectrum of engine working states than the NEDC and is more realistic in simulating typical real-world driving conditions.
iv. A large share of the negative acceleration in the WLTC allows the engine to work under fuel cut-off, which reduces fuel consumption and gives the opportunity to recover energy in hybrid and electric vehicles.
v. For the vehicles tested, the average engine speed, engine torque and fuel flow rate measured over the WLTC are higher than those measured over the NEDC.
vi. In terms of fuel economy, the diesel vehicle achieved a 9% reduction, while the gasoline vehicle – a 3% increase when switching from NEDC to WLTC. The difference between fuel economy obtained in the WLTC and NEDC depends on several factors, including vehicle technology.
vii. The implementation of the WLTC in the EU will force vehicle manufacturers to optimise engine control strategy according to the conditions of the new driving cycle.

While interpreting the results of this study, it is important to keep in mind its limitations. To begin with, it should be pointed out again that the core of the present paper was to compare exemplary results of vehicles tested over the WLTC and NEDC and to identify some qualitative trends regarding combustion engine performance. A more thorough analysis would have to include data over a wider range of tests, with more samples collected (numerous repetitions for statistical reliability) and involve vehicles representing different categories and engine technology. Moreover, the presented comparison between two driving cycles was focused only on vehicle speed profile effects and not differences arising from the whole testing procedure. Since each test performed on a chassis-dynamometer for type approval purposes is carried out according to the specific procedure outlined in the relevant regulatory documents (which define test temperature, vehicle test mass, pre-test vehicle conditioning etc.) [24, 25], it is possible to obtain different results from the ones presented in this paper.

Finally, an issue that was not addressed in this study due to the lack of proper experimental data was the effect of engine cold start. However, it has commonly been assumed that the absolute cold start surcharge in terms of fuel consumption is virtually not affected by the driving pattern. Previous works in this field have revealed that engine cold start contributing to the total fuel consumption in the WLTC is only about half of that in the NEDC because it depends on the distance covered by a vehicle [12]. Notwithstanding the above-mentioned limitations, the study provided some interesting trends in line with other similar studies.

Although it is not possible to design an ideal driving cycle that would precisely replicate all existing real-world driving conditions in a laboratory, it appears that the introduction of the WLTC was a right step towards a compromise between what should be obtained in terms of testing vehicles for exhaust emissions and fuel consumption on a chassis dynamometer and what is possible to achieve with current technical and financial constraints.

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