Carbon dioxide emissions and fuel consumption from passenger cars tested over the NEDC and WLTC – an overview and experimental results from market-representative vehicles

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Abstract. EU legislation specifies that the New European Driving Cycle (NEDC) be used for type approval testing of existing (not new) types of passenger cars, a test which generates official values for CO₂ emissions and fuel consumption (which is calculated from CO₂ emissions based on a carbon balance). A significant body of evidence shows that the type approval values obtained by manufacturers of light duty vehicles are lower than those which occur during real usage on the road. Longstanding objections that the current test cycle is unrepresentative and delivers unrealistic results has led to the development of a worldwide harmonized light-duty test cycle (WLTC), as part of wider changes in the overall test procedure (the worldwide harmonized light-duty test procedure – WLTP). This paper discusses both driving cycles and their characteristics with the aim of making the topic accessible to the non-specialist; later in the paper CO₂ and fuel consumption results obtained by testing several European passenger cars over both cycles in an emissions testing laboratory are reported. The test vehicles were a good representation of passenger cars in use in EU countries such as Poland – they featured both spark ignition and compression ignition engines, met the Euro 5 standard and had appreciable accumulated mileages.

1. Introduction

Concern over the impact of emissions from light-duty vehicles (principally passenger cars) on the atmosphere remains high. Such concerns can be divided into two main categories: those concerning harmful exhaust emissions which affect air quality and human health; and those concerning emissions which have a climate forcing effect – although these groups are not mutually exclusive in all cases. Regarding emissions which have a climate forcing effect, by far the most relevant in the context of emissions from passenger cars is carbon dioxide (CO₂). The sheer numbers of vehicles in use makes this an important topic. Indeed, ownership of a vehicle and daily commuting distance is a strong predictor of an individual’s CO₂ footprint [1]. Legislation has existed for a number of years to force manufacturers to meet limits for fleet average emissions (or fuel consumption, or fuel economy) from the vehicles they produce. In the European Union (EU), these limits are expressed in terms of CO₂ emissions in units of grams per kilometer. In the USA, similar measures have been taken, but with limits imposed in terms of fuel economy. Despite not being subject to legal limits, fuel consumption data are widely used in the EU for a range of purposes, from advertising the fuel consumption of a particular vehicle or engine...
option to scientific modeling studies, taxation and cost projections. However, in terms of legislative automotive testing, fuel consumption is not measured directly, but rather calculated from a carbon balance, and thus fuel consumption values depend directly (and very strongly) on CO₂ emissions (see [2] for a discussion of this relationship in the context of automotive engines). In order to quantify CO₂ emissions, a vehicle is tested under laboratory conditions according to a well-known, well defined and widely used test procedure ([3] in the EU; other jurisdictions have their own procedures). Over the last 40 years this EU procedure has been amended a number of times, but in terms of changes which affect the way that CO₂ emissions are measured, the procedure has not changed since the year 2000. A 2012 EU document [4] called for more representative test procedures to be employed to aid efforts to reduce CO₂ emissions from light duty vehicles, an ethos which has finally resulted in the implementation a new test procedure: the World harmonized light duty test procedure (WLTP) in EU legislation.

Usage of a vehicle for its intended purpose occurs on public roads, not in a laboratory, and this fact raises the question of the comparability of legislative (type approval) CO₂ emissions and real emissions from on-road usage. This paper will term the CO₂ emissions measured during type approval testing ‘TA CO₂’ and CO₂ emissions resulting from usage of the vehicle on the road ‘R CO₂’. Any discrepancy in these two values would have a number of implications: firstly, since the aim of imposing fleet average CO₂ emissions limits is to reduce the quantity of CO₂ emitted into the atmosphere, the effectiveness of this measure is somewhat dependent on good agreement between TA CO₂ and R CO₂. Secondly, since many countries use TA CO₂ as the basis of vehicle taxation banding, if TA CO₂ is lower than R CO₂ this represents a source of revenue loss [5]; reliable data are required for efficient taxation [4]. Thirdly, and perhaps most controversially, if R CO₂ is appreciably higher than TA CO₂, the same will apply to TA FC and R FC and in turn this will translate into substantial ‘additional’ running costs for the vehicle owner over a timescale on the order of the lifetime of the vehicle. Some studies have focused on fuel consumption, rather than CO₂ emissions themselves; consumers invariably speak of fuel consumption/economy, since CO₂ emissions are impossible to quantify without specialist equipment, but fuel consumption/economy is easy to calculate. The link between CO₂ and fuel consumption is strong and direct [2,6] and so, for the required degree of accuracy, these metrics can be used interchangeably in this context of this area of investigation.

While harmful exhaust emissions are normally of relatively little direct consequence to a vehicle’s owner/operator, CO₂ emissions are inherently linked to fuel consumption, which is usually of considerable importance to the owner. The majority of modern European cars can display both instantaneous and accrued fuel consumption values upon request and the ubiquity of the internet has facilitated the sharing of this information at an international level. A number of organizations gather data on real world fuel consumption as submitted by vehicle owner/operators. While such data are generally of relatively low scientific quality, the large number of datapoints available offsets this concern to an extent – i.e. the impact of outliers calculation errors or any deliberate manipulation is negated by the sheer quantity of datapoints. Making use of such sources, recent reviews and assessments of various comparisons of TA CO₂ and R CO₂ have indicated a substantial difference, which for the year 2011 stood at around 25% (i.e. R CO₂ ≈ 1.25 TA CO₂) [5]. Another recent study came to the conclusion that the mean fuel consumption discrepancies for recent European gasoline- and Diesel-fueled cars were 11% and 16%, respectively [6]. Indeed, some evidence appears to show that the magnitude of the discrepancy has dramatically increased during the past decade [5,6]. Previous work over the past few years [7-9] has generally found the same tendency, as well as research focusing on other markets (e.g. China – [10]). See also [11] for a recent discussion of the topic and brief literature review. These technical studies and reports have added to some other, less formal indications that consumers and the organisations which represent them are increasingly dissatisfied with the difference in fuel consumption which causes the difference between TA CO₂ and R CO₂ (e.g. [12,13]).

There are a multitude of reasons why TA CO₂ values are likely to be lower than R CO₂ values. Such a discussion is not a focus of this paper, but suffice to say that ambient temperature, trip distance, additional payload, driving cycle aggressiveness, altitude, topography and road surface quality, the use of accessories (chiefly air conditioning, but also lights, navigation systems, etc.), tire type/pressure [14]
and the general mechanical condition of the vehicle could potentially all contribute somewhat to the observed discrepancies. Mock et al. [5] identify certain contributing parameters and note that the NEDC was not originally designed to measure TA CO₂ (or indeed TA FC). A discussion of various parameters and engine/driver behaviors regarding the NEDC and ‘real world’ driving scenarios is presented in [15]. Regardless of the condition of the vehicle or attempts at “eco driving” by the driver, realistic European ambient temperatures are for the most part lower than those in the laboratory, causing a noticeable impact on fuel consumption, particularly during and following start-up (see [16], [17] and [18] for discussions). Even when an engine and all powertrain components are fully warmed up, fuel consumption can still be noticeably greater at low ambient temperatures than at standard laboratory temperatures [18]. Prescribed laboratory temperatures in the range 20-30°C can be considered a carry-over from the southern Californian origins of automotive emissions testing, temperatures which are something of an anomaly for many European countries during most of the year. A further factor is that many vehicles are used daily for early morning commutes, having stood idle for some ~12 hours during the night (the coldest part of the diurnal thermal cycle).

In the laboratory, emissions are measured and the fuel consumption is calculated accordingly. During normal vehicle operation on the road, the driver has no direct way of telling what the CO₂ emissions are – in modern vehicles onboard displays show fuel consumption figures, where unavailable vehicle users may calculate fuel consumption figures by dividing the volume of fuel added by the distance covered (or the inverse, for a fuel economy calculation). Thus, any discussion of user-reported R CO₂ is dependent on back calculating the CO₂ from the reported fuel consumption figures. In performing such a calculation, fuel quality/characteristics have a negligible impact – the only important distinction is fuel type: gasoline/Diesel/LPG/CNG. The fuels used for homologation are of identical energy content to those which are commercially available.

In terms of laboratory testing, the most obvious and impactful parameters which can be changed to better reflect real world driving are the ambient temperature, the driving cycle and the road simulation parameters used on the chassis dynamometer. The impact of ambient temperature on CO₂ emissions and fuel consumption is well documented (at least in laboratory contexts – see, [16-18]) and this variable is not the subject of the experimental work described in this paper. Current EU legislation specifies an ambient temperature range of 20°C-30°C, whereas the draft WLTP procedure specifies that a temperature of 23°C ±2°C be maintained for the duration of the test. Therefore, an ambient temperature of 23°C can be used for testing according to both procedures, in order to eliminate any differences resulting from this factor. The road load coefficients set on the chassis dynamometer to replicate the resistive forces experienced on the road are also an important factor, which can significantly change CO₂ emissions results (see [19] and [20] for detailed discussions and test results). The remaining variable is the driving cycle itself, which is the main subject of the experimental work described in this paper. The next section presents the current driving cycle (the NEDC) and the WTLP driving cycle (the WLTC).

The possibility of altered test procedures raises the question of fleet average emissions/consumption limits set under the current regime, but scheduled to come into force in the future. The EU has recognized this, noting that limits must be “strictly correlated to the emissions measured under [the new] test procedure” [4].

This paper discusses the procedures and test cycles and presents some experimental results, which are used to illustrate and expand upon the theoretical considerations and discussions in the paper.

2. Qualitative and quantitative comparisons of the NEDC and WLTC
Following a long period of incubation and development (2008-2013), the WLTP has now been formalized in Global Technical Regulation No. 15 (known by the shorthand ‘GTR 15’), and formally adopted in EU legislation. During development, the driving cycle underwent many modifications and stabilized at a version known as WLTC 5.3. (See, for example [21] and [22] for further information). Version 5.3 was employed in both the theoretical comparisons (this section) and the experimental work (following sections) that are presented in this paper.
Figures 1 and 2 show cycle speed plotted as a function of test time for the NEDC and WLTC cycles. The most obvious differences in the cycles are the duration (1180 seconds versus 1800 seconds) and the overall macroscopic nature of the cycles – the NEDC is a ramped modal cycle with a speed trace made up of straight lines, which represent constant speed or (de)acceleration at a constant rate; the WLTC features an ‘organic’, fluctuating speed trace with perfectly straight lines in the speed trace occurring only at idle. The reason for this is that the WLTC has been developed using real world data on vehicle speed traces and the dynamic nature of the cycle is designed to reflect real driving practices and traffic flow conditions. The total absence of extended periods of constant velocity at non-zero values (so-called ‘cruise’) in the WLTC strongly differentiates it – both qualitatively and quantitatively – from the NEDC. For a fully warmed up vehicle on flat ground, demand for engine power is by definition constant at constant speed (and a given gear). All other factors being equal, travelling at constant speed is the most fuel efficient means to cover distance on a flat surface (or a chassis dynamometer). The maximum speed reached over the two cycles is broadly similar, yet the WLTC only maintains its maximum speed momentarily, while the NEDC’s final cruise mode requires the vehicle to hold a speed of 120 km/h for 11 seconds. Resistance to motion increases rapidly as vehicle speeds begin to take high values (in this paper, speeds ≥100 km/h (≈28 m/s) shall arbitrarily be termed ‘high’ – reasonable, given that virtually all roads except multilane motorways have speed limits ≤100 km/h). An analysis of the proportion of the cycle spend at high speeds reveals that while the WLTC’s maximum speed is only some 9% greater than that of the NEDC, the proportion of the cycle spent at high speed is twice as long for the WLTC (5% versus 10%).

Figure 1. The New European Driving Cycle (NEDC).
Figure 2. The Worldwide Harmonized Light-duty Test Cycle (WLTC), version 5.3, for class 3 vehicles (≥34 kW/tonne).

A variety of metrics have been employed to define and quantify test cycle ‘aggressiveness’. Two noteworthy metrics are relative positive acceleration [23] and vehicle specific power (VSP) [24], although attempts may also be made to quantify the total energy demand for a given driving cycle [25]. The results of such analyses yield subjectively low energy requirements in view of the energy density of petrol and Diesel – the massive disparity between energy required at the wheel and fuel taken from the tank is a result of the low thermal efficiency of a combustion engine powertrain. If the prevailing engine operating conditions during a driving cycle allow the engine to function in a more thermodynamically efficient manner, then a driving cycle with higher energy demands might be executed using the same amount of fuel as a less demanding driving cycle. The speed trace may also be analyzed in terms of orders of motion; a ramped cycle such as the NEDC consists only of first and second order motion (‘straight lines’ – i.e. constant speed and acceleration at a constant rate, respectively), while the WLTC features motion of higher orders (acceleration at variable rates, ‘pulse’ type microacceleration events requiring a brief surge in engine power). A selection of the values of certain key parameters relating to the two cycles is presented in Table 1.

A detailed technical analysis [26] identified the following parameters as the most important: cycle dynamicity, average cycle speed, proportion of idling time and total cycle distance. That analysis found that three of those four factors would suggest emissions to be higher from the NEDC in comparison to the WLTC. However, as that study pointed out, the more useful comparison is in terms of the entire test procedures, not just the test cycles. The exhaust gas sampling and analysis methods of the two test procedures do not differ significantly – in any case, the analysis and calculation method is not the focus of this paper and will not be examined here. In terms of chassis dynamometer testing, the test cycle is the most obvious parameter differing in the two test procedures, but the chassis dynamometer settings and the road load correction data they rely on are also important [27].
Table 1. Key cycle parameters for the NEDC and the WLTC.

| Parameter                                      | Unit | NEDC value | WLTC value | Value ratio (WLTC/NEDC) |
|------------------------------------------------|------|------------|------------|-------------------------|
| Total distance                                 | km   | 10.982     | 23.266     | 2.12                    |
| Duration                                       | s    | 1180       | 1800       | 1.53                    |
| Number of pull away events                     | -    | 13         | 8          | 0.62                    |
| Number of pull away events per km              | km\(^{-1}\) | 1.18 | 0.34         | 0.29                    |
| Number of gear changes (for a manual transmission) | -    | 22         | Varies, typically >>22 | >>1                  |
| Idle time (before initially pulling away)     | s    | 10         | 11         | 1.1                     |
| Total idle time                                | s    | 280        | 234        | 0.84                    |
| Idle time (proportion)                         | %    | 23.73      | 13         | 0.55                    |
| Maximum speed (for manual transmission)        | km/h | 120        | 131.3      | 1.09                    |
| Average speed (all phases, including idling)   | km/h | 33.51      | 46.50      | 1.39                    |
| Time at which the average speed of the entire cycle is first reached | s    | 133        | 217        | 1.63                    |
| Maximum positive acceleration                  | m/s\(^2\) | 1.04 | 1.67      | 1.61                    |
| Maximum value of v·a                           | m\(^2\)/s\(^3\), W/kg | 9.13 | 20.57      | 2.25                    |
| Proportion of cycle for which v≥100 km/h       | %    | 5.76       | 10.11      | 1.76                    |

Vehicle speed is related to engine speed via drivetrain parameters, namely: wheel+tyre dimensions, axle drive ratio and the ratio of the gear in use. For a given vehicle, the only true variable in the aforementioned parameters is the gear chosen for driving at a given speed. For many driving speeds, two or three different gears may be used; the choice of gear for drivability, smoothness/low noise and minimized fuel consumption do not always coincide. There is, however, an overarching limitation: once top gear has been selected, the only way to further increase vehicle speed is to increase engine speed. Of course, engine speed is not the only important parameter – load is of great importance in determining fuel flow rates, thermodynamic efficiency and ultimately exhaust emissions. Figure 3 compares one phase of the NEDC and one phase of the WLTC in terms of CO\(_2\) emissions for the operating points experienced by a given vehicle with a manual transmission.
Figure 3. Engine speed-load coordinates for the extra-urban phase of the NEDC (EUDC) and the WLTC’s first extra-urban phase (High), with the colour zones showing the concentration of CO\(_2\) in the exhaust gas of a small passenger car diesel engine. The insert (right) shows the general tendency regarding engine operating points for various driving cycles (US06=the US Environmental Protection Agency’s supplemental US06 test cycle; RDE=real driving emissions [scenarios]).

As shown in Figure 3, while the maximum speed of the EUDC is greater than that of WLTC High, the range of engine speeds encountered is roughly similar; engine load on the other hand, varies considerably, with WLTC High causing a much wider range of load values, with significantly higher maximum values at a range of engine speeds.

Here, some further parameters and brief considerations are presented; Table 2 shows some theoretical considerations of the aforementioned factors – both in terms of the test cycle and the broader test procedure – and attempts to estimate their likely relative impacts.

With the exception of periods of deceleration, propelling a vehicle at any speed requires in input of energy (fuel). Accurate energy requirements for a given vehicle with a given powertrain over a given driving cycle require complex computation [25], yet certain simplifications and first-order approximations can be made. Driving cycle energy requirements for a given vehicle are discussed in detail in [25]. The vehicle-specific power (VSP) concept developed by Jimenez-Palacios [24], has been employed in various emissions studies (see [33] for a recent example). The calculated VSP values and the total positive VSP per unit distance for most (if not all) vehicles are greater for the WLTC than for the NEDC, implying increased energy demand, even when dividing by the distance covered by the cycle.

However, approach mentioned in the previous paragraph neglects three important factors: periods of idling (where VSP is zero, distance covered is zero, but fuel is still consumed – unless an idle stop system is employed); variable usage of the gearbox; and the non-negligible thermal effects which occur during a cold start driving cycle. Such thermal effects can be of considerable importance. While unequal, engine/powertrain warm up time is not radically different over the NEDC and WLTC (say 400 seconds to obtain a temperature reasonably close to the fully warmed up condition), the proportion of the cycle during which the engine is (close to) warmed up is approximately \(\frac{2}{3}\) for the NEDC, but \(\frac{3}{4}\) for the WLTC.
**Table 2.** Theoretical considerations of various cycle characteristics for the NEDC and the WLTC and their likely impacts on exhaust emissions of CO₂, ordered according to estimated relative impact.

| Aspect                                      | Comparison | Resulting likely impact on CO₂ emissions per unit distance (WLTC compared to NEDC) | Estimated likely relative importance of impact |
|---------------------------------------------|------------|---------------------------------------------------------------------------------|-----------------------------------------------|
| Aggressiveness, dynamicity                  | NEDC<WLTC  | Overall possible increase; greater demand for engine power, higher, non-linear acceleration and lack of constant speed create conditions where fuel consumption is higher [28]. Vehicle inertia has no impact at constant speed, but a large impact when accelerating. On the other hand, a more aggressive initial phase with less idling and more rapid accelerations will achieve engine/transmission/tire warm-up more rapidly. | High                                          |
| Cycle type                                  | NEDC<WLTC  | Increase; use of continuous (‘stepless’) chassis dyno inertia simulation will increase CO₂ emissions in most cases [27][30]. | High                                          |
| Chassis dynamometer settings                | NEDC<WLTC  | Decrease; the WLTC’s ‘customised’ gearshifts should better reflect the power output capabilities of the engine; rational usage of 6th gear (where present); usage of higher gears (i.e. 3rd, 4th) much earlier in the WLTC than in the NEDC. In the EU, over 50% of new cars sold now have 6 or more gears [29], all of which can be used rationally in the customized gearshift approach. (However, around 20% feature automatic gearboxes [29].) | Low to mid (for cars with manual gearboxes)    |
| Gear shift strategy                         | NEDC<WLTC  | Decrease; a greater proportion of the cycle is performed with the engine in a warmed-up condition and total emissions are divided by a larger number of kilometers (larger denominator); emissions resulting from the cold start event are ‘diluted’ to a greater extent. | Low to mid                                     |
| Cycle length (distance)                     | NEDC<WLTC  | Decrease; a greater proportion of the cycle is performed with the engine in a warmed-up condition. This could be particularly important for gasoline-fueled vehicles, where the first few hundred seconds of engine operation use enriched mixtures. | Mid to high                                    |
| Cycle length (time)                         | NEDC<WLTC  | Increase; rate of increase of resistive force is high and non-linear at high speed. Once top gear is engaged, engine speed is forced to increase in order to achieve higher vehicle speeds. However, the difference in maximum speed is a relatively modest 9%, but speeds of this magnitude are maintained for twice as long over the WLTC as over the NEDC. | Low to mid                                     |
| Maximum speed                               | NEDC<WLTC  | Potentially variable; CO₂ emissions per unit time are low at idle, but no distance at all is covered (i.e. \( \infty \) gCO₂/km). Where present, idle stop systems have a lower impact where total idling time is shorter. When at idle, the engine warms up (slowly), but the gearbox, bearings, tires, etc do not gain any thermal energy which would reduce their frictional resistance. | Low to mid                                     |
| Proportion of idling                        | NEDC<WLTC  | Possible decrease; the load acceptance event at pull away is relatively demanding for the engine (see [31] for a discussion). Useful work (engine torque output) is wasted as heat in the clutch mechanism as power is progressively transferred to the wheels; following that, getting back up to speed forces usage of low gears and multiple gear changes. | Low to mid                                     |
| Number of pull away events                  | NEDC<WLTC  | Increase; the WLTC had not been fully defined at the time of the test vehicles’ manufacture – all test vehicles were calibrated to the NEDC, which is the only legislative cycle used in Europe. | Low                                           |
| Novelty of the test cycle                   | NEDC<WLTC  | Variable; an experienced driver can execute the WLTC well within the tolerances, which are in fact the same for both cycles. Vehicles with power to weight ratios well above the 34 kW/tonne cut-off point can execute the cycle easily. | Very low to negligible                          |
| Speed trace drivability, test duration and subjective effects on the test driver | NEDC>WLTC  | Potential small increase; somewhat shorter time at the start of the cycle during which the TWC is unable to convert HC and CO to CO₂ effectively. However, the quantities of CO₂ involved are very small. | Very low to negligible                          |
| Time taken for the aftertreatment system (TWC/DOC) to reach HC and CO light-off | NEDC>WLTC  |                                                                                   |                                               |
Aspec
t Resulting likely impact on CO₂ emissions per unit distance (WLTC compared to NEDC)

| Aspect                                | Comparison | Resulting likely impact on CO₂ emissions per unit distance (WLTC compared to NEDC)                                                                 | Estimated likely relative importance of impact |
|----------------------------------------|------------|------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|
| Proscribed laboratory test temperature | NEDC≠WLTC  | The midpoint of the NEDC range is close to the setpoint for the WLTC. However, all work described in this paper was performed at the same temperature (23°C) | Very low to zero; zero in this study           |
| Average cycle engine speed and load    | NEDC≠WLTC  | Variable; different gearshift strategies mean that for a given vehicle the relationship between vehicle speed and engine speed and load are not the same for the two cycles. (See [32] for a brief discussion.) Thermal effects and the frequency and timing of periods of idling complicate the situation. | Unclear; potentially mid or even high         |

The WLTC can even be conceptualized as being two tests in one: a cold test followed by a hot test. In fact, the dynamicity and lower proportion of idling of the first phase of the WLTC compared to the NEDC should ensure more rapid warm-up not only of the engine and its fluids, but also of the transmission, wheel bearings and tires (which are of course not warmed up at all during idling). While the term ‘warmup’ is usually used in automotive contexts to talk about the process by which the engine reaches its operating temperature, many other components – including those mentioned above – also warm up during driving and thereby gradually reduce the friction they contribute. These factors, together with the incomparable approaches regarding usage of the gearbox for vehicles with manual transmissions, complicate the situation regarding the likely fuel consumption and resulting CO₂ emissions over the two driving cycles. The results obtained from the experimental work described in this paper are discussed in the context of an investigation into these effects.

3. Experimental work

3.1. Experimental approach and test facility

A series of laboratory tests were carried out in the climate-controlled exhaust emissions laboratory (Figures 4-5) at BOSMAL Automotive R&D Institute in Bielsko-Biala, Poland as part of a broader research program investigating regulated emissions, CO₂ emissions and fuel consumption over various driving cycles. The test facility in which the experimental work described in this paper was conducted has been described in detail elsewhere [34,35].

![Figure 4. Internal view of the climatic chamber within the test laboratory used in this study, showing a test vehicle on the chassis dynamometer, with its tailpipe connected to the CVS.](image)
In general, all testing was performed in accordance with the EU’s current legislative exhaust emissions test procedure [3], which involves collecting a sample of diluted exhaust gas in sample bags for accurate chemical analysis, achieved by means of a temperature-controlled constant volume sampler (CVS). Setting aside the test cycle, the general approach specified for the WLTP in GTR 15 [36] is very similar to [3], with the main exception of the chassis dyno inertia setting. The current legislative procedure [3] specifies an ambient temperature range of 20°C-30°C, whereas GTR 15 specifies that a temperature of 23°C ±2K be maintained for the duration of the test. Self-evidently, the latter lies within the range of the former, so an ambient temperature of 23°C was used for all testing, in accordance with the demands of both procedures. The climate chamber is capable of maintaining the set temperature to within ±1.2K during emissions testing [34].

3.2. Chassis dynamometer loading coefficients and vehicle inertia
Chassis dynamometer load settings are of great importance in determining both emissions and fuel consumption. The approach to be applied for the WLTP differs somewhat from the procedure mandated in [3]. In order to compare the test cycles, the same settings were used for each vehicle for over both of the test cycles. The inertia setting was the value specified in current EU legislation based on the mass of the vehicle (divided into categories). The road load coefficients used were the default values for the inertia classes specified in [3].

3.3. Test vehicles and fuel
A total of four test vehicles were used in this study, all of which were unmodified passenger cars meeting the EU’s Euro 5 emissions standard. All vehicles had mileages greater than 10,000 km, but lower than 60,000 km and were in sound mechanical condition. Tire pressure and the specification of the lubricating oil were all in accordance with the vehicle manufacturers’ instructions. Vehicle 1 featured a downsized compression ignition (CI) engine (with a Diesel particulate filter - DPF); vehicle 2 was a bi-fuel (gasoline/CNG) vehicle with a naturally aspirated spark ignition (SI) engine, which was tested on both fuel types; vehicle 3 featured a somewhat larger turbocharged direct injection gasoline engine; vehicle 4 featured a downsized turbocharged SI engine; vehicles 5 and 6 both featured larger CI engines with DPFs and automatic gearboxes. Key vehicle parameters are summarized in Table 3. All test vehicles had manual gearboxes and power/weight ratios ≥34 kW/tonne and preliminary investigations confirmed the drivability of the WLTC speed trace for all test vehicles – both when running on gasoline and on CNG in the case of vehicle 2. Standard, commercially available European fuels were used for all testing: gasoline, Diesel and CNG. These fuels complied with the demands set out in both [36] and [3] and had
typical densities and octane (RON) (or cetane) numbers. However, since this study represents a
comparison of the test procedures and the impact on CO₂ and fuel consumption, the fuel type is relatively
unimportant and the only significant considerations are the facts that the fuels were commercially
available and that the same fuels were used for testing over both test cycles. For the CI vehicles, any
tests where DPF regeneration was found to have occurred were rejected and repeated.

Table 3. Summary of key parameters of vehicles 1-6.

| Vehicle No. | Engine type          | Approx. displacem ent [dm³] | Aftertreatment system       | Gearbox type       | Model year | Legislative mass (test inertia) [kg] |
|-------------|----------------------|-----------------------------|----------------------------|-------------------|------------|-----------------------------------|
| 1           | CI, turbocharged     | 1.3                         | DOC+DPF (close coupled)    | Manual, 5-speed   | 2010       | 1020                              |
| 2           | SI, bifuel, naturally aspirated | 1.4   | TWC (close coupled)      | Manual, 5-speed   | 2011       | 1130                              |
| 3           | DISI, turbocharged   | 1.8                         | TWC (close coupled)        | Manual, 6-speed   | 2010       | 1470                              |
| 4           | SI, turbocharged     | 1.0                         | TWC (close coupled)        | Automatic, 5-speed| 2013       | 1020                              |
| 5           | CI, turbocharged     | 2.0                         | DOC+DPF (close coupled)    | Automatic, 8-speed| 2012       | 1590                              |
| 6           | CI, turbocharged     | 2.1                         | DOC+DPF (close coupled)    | Automatic, 7-speed| 2012       | 1700                              |

3.4. Experiments performed
In experiment 1, five repeat tests were performed for each vehicle over each test cycle. Only one
emissions test was conducted per day. In experiment 2, two tests were performed over a modified
version of the NEDC (two repetitions of the test cycle, the second immediately after the first, and
without shutting off the engine between the two) and a further two over the WLTC, with modal
(continuous) analysis of diluted exhaust gas emissions in all cases. Modal analysis is not a technique
used for legislative (type approval) testing, but is a recognized technique for development tests and
scientific research. The modal testing performed here was based on the most recent international
industry standard [37]. Integrated modal results were compared with bag results and the deviation was
found to be very small, for all vehicles, over both cycles and all phases – thus testifying to the
reliability of the modal data. Data from experiment 1 were used in the analysis that constituted
experiment 3.

For the vehicles which featured manual transmissions, gear shifts were calculated for each vehicle
(and in the case of vehicle 2, for each fuel, as the gearshift calculation approach takes the full load
power curve into consideration) using the latest version of the gearshift calculation tool specified in
the latest version of the WLTP, in accordance with the methodology presented in [36]. The standard
gearshifts, defined as part of the test cycle [3] were used for all testing over the NEDC.

4. Results and Discussion

4.1. General observations on the experimental approach
The WLTP was executed for all test vehicles without encountering any significant problems. Where any
difficulties occurred, the number of violations was very limited and the total distance covered during
the cycle was very close to the theoretical value, and so all tests were deemed acceptable. The test facility
was able to maintain the ambient temperature and humidity within the range specified for the WLTP,
for the duration of both test cycles.
The total CO₂ emissions (units [g]) per test and fuel consumption (units [liters]) per test were much higher for the WLTC test than the NEDC test, for all six test vehicles. When expressed as distance-specific emission/consumption, the difference in the values obtained over the two test cycles was much smaller. In the following sections, distance-specific results are discussed (units [g/km], [l/100km]).

4.2. Experiment 1 – a comparison of the current European test procedure (NEDC) and the WLTP for four test vehicles

Carbon dioxide emissions results from vehicles 1-6 are presented in Figure 6 and are compared in Table 4.

![Figure 6. A comparison of CO₂ emissions from the NEDC and WLTC for all test vehicles.](image)

| Vehicle | Raw ranking result | Difference [%] |
|---------|--------------------|---------------|
| 1 – CI+DPF | NEDC>WLTC | <0.1 |
| 2 – CNG | NEDC>WLTC | 2.4* |
| 2 – Gasoline | NEDC>WLTC | 1.9* |
| 3 – DISI | NEDC>WLTC | 5.7* |
| 4 – Gasoline | NEDC<WLTC | 0.7 |
| 5 – CI+DPF | NEDC>WLTC | 2.4* |
| 6 – CI+DPF | NEDC>WLTC | 0.1 |

As shown in Figure 6, distance specific results from all vehicles were in fact similar over both test cycles. In five out of six cases, mean CO₂ emissions results were found to be higher over the NEDC
than over the WLTC. While the differences observed are small, the fact that only one of the vehicles showed higher CO₂ emissions over the WLTC is highly significant. Four of the observed mean differences were found to be statistically significant. For vehicles 1, 4 and 6, the lack of a statistically significant difference forces the acceptance of the null hypothesis – namely that CO₂ emissions per km are indistinguishable over the NEDC and WLTC cycles. Interestingly, vehicles 4 and 6 featured automatic transmissions – whose gearshift strategies would be expected to be very closely optimized to the NEDC – and yet the difference in the CO₂ emissions results for those two vehicles was insignificant, being less than 1%. This implies either a lack of optimization to the NEDC, or that the characteristics of the WLTC cancel out any kind of non-optimization penalty (e.g. the WLTC’s reduced number of pull away events and higher mean speed allowing overall usage of higher gears, with a corresponding increase in engine efficiency.)

In view of the substantial quantitative and qualitative differences in the two cycles (cf. Tables 1 and 2), it is somewhat surprising that results from the WLTC are no higher – or in fact slightly lower – than those from the NEDC. However, these results agree with those of a previous study and detailed technical analysis [26] and two other recent experimental studies [38,39]. Anderson et al. [39] investigated two Euro 6 vehicles with CI engines and in comparing results from the NEDC and WLTC found both types of trend reported here – statistically indistinguishable results and lower results over the WLTC.

As regards the difference for each of the vehicles employed in this study, it is of note that vehicles 1 and 4 both showed statistically insignificant differences. While these vehicles’ engines run on different fuels, the size and mass of the two vehicles was quite similar. On the other hand, the same tendency was observed for vehicle 6, which was much larger and featured a much more powerful engine. Further testing would be required to determine the impact of various engine and vehicle parameters on the CO₂ emission/fuel consumption discrepancy over the two test cycles. Based on the reasonably limited number of vehicles tested here, it is not possible to draw any more conclusions at this point.

The publicly accessible Spritmonitor online database [40] was interrogated to find mean reported real world fuel consumption data for vehicles 1-6. This database has been used as a source of information in other analyses (e.g. [5,26]). While results from such a database must be treated with caution and are somewhat unscientific, they have the advantage of potentially providing a real indication of R FC for a given vehicle type. The results which appear in the database are fuel consumption results. Volumetric fuel consumption was calculated for vehicles 1-6 according to [41], and the mean laboratory results were compared to the mean database results; a numerical comparison of the two datasets is shown in Table 5. While the number of entries in the database was generally reasonably high (n>30, even after filtering out all vehicles which had not yet accrued 1500 km), an insufficient number of results for vehicle 2 running on gasoline were available in the database, and so this vehicle was analyzed only for operation on CNG. Table 4 also briefly compares the R FC data to the WLTC Low phase, being the phase for which the highest CO₂/FC results were observed.

Laboratory results obtained over the entire cycle for vehicles 1-3 were all lower than reported real world results. The discrepancies were of a similar magnitude (albeit well on the low side of) the average discrepancy reported in [5], with a mean value of some 10.5%. The mean value for vehicles with SI engines was 6.8% and the value for CI engines was 14.2% (compare with the respective values of 11% and 16% reported in [6]). The discrepancies were larger for the more powerful engines and there was a weak but recognizably positive correlation between vehicle power to weight ratio and the observed discrepancy. The existence of these discrepancies is unsurprising, since there are a range of factors which conspire to make laboratory tests a very favorable testing environment. The difference between results obtained over the two test cycles was limited compared to the difference between laboratory results and reported R FC values. While the WLTC is – in many respects – considerably more demanding than the NEDC, the fact that drivability has to be maintained in the laboratory (and for a wide range of vehicles – from ultra-economical city cars to sports cars and large SUVs) imposes constraints on how demanding the cycle can be. The highest energy version of the cycle (class 3, as employed in this study) is for vehicles of power/weight ratios ≥34 kW/tonne. However, recent data for the EU market [29] reveal that the average power/weight ratio of new cars for the year 2012 was above
60 kW/tonne – approaching twice the minimum power/weight criterion to be able to run class 3 of the WLTC (i.e. 68 kW/tonne). The majority of cars in the ‘sport’ and ‘luxury’ segments sold in 2012 had power/weight ratios over 100 kW/tonne[29] – some three times the class 3 cut-off point (i.e. 102 kW/tonne). Vehicles with a power to weight ratio so far above the minimum amount required to execute the WLTC class 3 will surely have at least some of that power excess put to use on the road – with an accompanying rise in fuel consumption and hence CO₂ emissions. Regarding the comparison of the Low phase to R FC, in every case, FC over the Low phase was higher than that the average R FC value reported by vehicle users, mostly likely because the average trip length for most passenger cars is longer than the 3 km covered during the WLTC Low phase. The Low phase represents the most unfavorable part of the test in terms of fuel consumption, to such a degree that the mean FC observed during real world driving is in fact lower, notwithstanding the moderating effect of ‘favorable’ laboratory conditions.

### Table 5. Discrepancies between results obtained here (WLTC) and R FC values reported by the public [40]. All discrepancy values are statistically significant at the 95% confidence level.

| Vehicle          | Discrepancy between WLTC FC result and reported R FC value [%] | WLTC Low result higher than R FC result? |
|------------------|---------------------------------------------------------------|----------------------------------------|
| 1 – CI+DPF       | 14.5                                                          | Yes                                    |
| 2 – CNG          | 4.3                                                           | Yes                                    |
| 3 – DISI         | 10.5                                                          | Yes                                    |
| 4 – Gasoline     | 5.6                                                           | Yes                                    |
| 5 – CI+DPF       | 22.3                                                          | Yes                                    |
| 6 – CI+DPF       | 5.7                                                           | Yes                                    |
| Mean value (1-6) | 10.5                                                          | -                                      |
| Mean value (Si; 2,3,4) | 6.8                                                     | -                                      |
| Mean value (CI; 1,5,6) | 14.2                                                   | -                                      |
| Mean value (<60 kW/tonne; 1,2,4) | 8.1                                                | -                                      |
| Mean value (>60 kW/tonne; 3,5,6) | 12.8                                                | -                                      |

The difference between the NEDC and WLTC results presented in this section are all smaller than the calculated differences between laboratory WLTC results and real world fuel consumption data. In fact, since results from the WLTC were very slightly lower than from the NEDC, results from the NEDC are in fact overall somewhat closer to the real world values reported by users of the same vehicles. From this, it appears clear that vehicle rolling resistance, environmental parameters and various other vehicle usage characteristics have a greater impact than the laboratory driving cycle employed. The 10.5% mean discrepancy reported here for the test vehicles employed in this study could likely be reduced somewhat by using a stepless inertia approach, with more realistic inertia masses and road load data obtained according to the stipulations of GTR 15.

4.3. **Experiment 2 – a brief examination of the impact of cycle duration/distance on emissions from a single test vehicle**

Carbon dioxide emissions results obtained by means of modal (continuous) analysis of exhaust emissions from vehicle 2 are shown in Figure 7.
Figure 7. Instantaneous values of distance-specific CO\(_2\) emissions over a modified version of the NEDC and the WLTC for vehicle 2, running on CNG.

The physical significance of any given point on the lines in Figure 6 is the CO\(_2\) emissions which would have resulted had the test been terminated at the given point. Hence, the lines trace the evolution of the CO\(_2\) emissions during the course of both tests, being a balance between the rate at which cumulative CO\(_2\) emissions increase and the rate at which the distance covered increases. The end of the line represents the end of the test. Distance-based emissions of CO\(_2\) are extremely high for the first parts of both test cycles, since very little distance is covered and the impact of the cold start is highest at that point. As the first few hundred meters are covered and the engine begins to warm up, these values fall rapidly. However, the behavior is non-monotonic and is strongly controlled by the speed trace, gear usage, periods of idling, etc.

Significantly, the trace for the WLTC lies below the trace for the NEDC (and indeed the second NEDC), with only two exceptions, where the lines converge momentarily. For the ~200 s to ~1000 s interval, specific CO\(_2\) emissions were much lower, suggesting that the vehicle is accumulating distance in a more fuel efficient manner during this time. Abandoning the WLTC after 1180 seconds (to make it the same length as the NEDC) would have caused the results from the two tests to be numerically identical. From around 1180 seconds onwards, CO\(_2\) emissions are relatively stable. Where the NEDC was performed twice, the total distance (the denominator in the CO\(_2\) emissions calculation) is very close to the value from the WLTC, yet the CO\(_2\) emissions result remains higher. These results suggest that for the vehicle in question, distance alone is not the main controlling factor regarding the somewhat surprisingly low results from the WLTC. (Nor is time, since the duration of two NEDC cycles is significantly greater than one WLTC). In light of this, speed trace characteristics discussed in proceeding sections and factors related to the usage of the gearbox and the resulting distribution of engine speeds are likely the main controlling factors, at least for vehicle 2 when operating on CNG. Focusing on Figure 7 after the end of the first NEDC, even with a fully warmed up engine, the UDC is a CO\(_2\)-intensive driving pattern (blue line, after 1180 seconds) and the frequent stop, idle and pull away events, together with usage of only low gears (1\(^{st}\) to 3\(^{rd}\)), cause the CO\(_2\) emissions trace for the 2×NEDC cycle to lie well above the trace for the WLTC.

Further investigation of this hypothesis and related effects will be investigated in forthcoming publications, employing other vehicles, including those with automatic gearboxes. It would also be possible to modify the WLTC somewhat to examine the impact of the four phases and their speed traces.
on the CO₂ results. Furthermore, the NEDC could also be executed using the WLTC customized gearshift approach, to examine the impact of more rational usage of the gearbox on the CO₂ emissions trace.

4.4. Experiment 3 – a brief examination of the impact of the two test cycles’ cold start phases (UDC, Low)

Results from the initial (cold start) phase of each cycle are shown in Figure 8 and compared in Table 6.

![Figure 8. CO₂ emissions from all test vehicles over the first phase of the two procedures’ test cycles (UDC and Low).](image)

| Vehicle | Raw ranking result | Difference [%] |
|---------|--------------------|----------------|
| 1 – CI+DPF | UDC<WLTC Low | 2.0* |
| 2 – CNG | UDC<WLTC Low | 0.1 |
| 2 – Gasoline | UDC>WLTC Low | 1.3* |
| 3 – DI SI | UDC>WLTC Low | 4.8* |
| 4 – Gasoline | UDC<WLTC Low | 0.2 |
| 5 – CI+DPF | UDC<WLTC Low | 2.9* |
| 6 – CI+DPF | UDC<WLTC Low | 6.9* |

The correlation between the two sets of results shown in Figure 7 and compared in Table 6 is inconsistent from vehicle to vehicle. The overall relatively close results from the two cycles’ initial phases are noteworthy. While the UDC and the Low phase are fundamentally different in terms of the driving trace, they both constitute the same overall conditions in that the engine is started at ambient temperature, allowed to idle for a few seconds and is then used to propel the vehicle over a distance of a few kilometers (approximately 3 km for the WLTC Low; approximately 4 km for the UDC.

Notwithstanding the different speed trace and its direct impacts (load, engine speed) and indirect impact (rate of engine/drivetrain warmup), results were numerically similar over the two cycles’ initial
phases, with differences never exceeding 6.9% – despite the difference in distance covered. Three vehicles showed higher results over the UDC and three showed higher results over the WLTC Low, with no clear split regarding SI/CI or automatic/manual. However, there was a clear partitioning according to power:weight ratio, with all three vehicles >60 kW/tonne showing higher results over the UDC than the WLTC (a mean difference of almost 5%). Since these vehicles featured larger engines of greater mass and therefore greater thermal inertia, the distance and temporal duration of the two cycles’ initial phases is likely to be the cause of this observation. (Recall that the UDC covers around 33% more distance than the Low phase and also lasts around 25% longer.)

5. Conclusions
Two test procedures with their eponymous driving cycles were assessed, both theoretically and via controlled laboratory experiments. The experiments focused on the driving cycles themselves. The analysis of the test procedures and the driving cycles revealed that in general, the WLTP and its cycle (the WLTC) might be expected to produce (somewhat) higher specific emissions of CO$_2$ and fuel consumption, mainly due to the aggressiveness and dynamicity of the cycle. However, based on the results presented in this paper (and in other recent analyses – see [42]), various other factors would appear to counteract this effect (at least somewhat): more efficient use of the engine, reduced cold start impact, more rational use of the gears, etc.

The results revealed the following:

- The WLTC and NEDC were executed successfully on all test vehicles in accordance with their respective test procedures
- For the tests which were conducted with modal (continuous) analysis, the correlation between bag and modal CO$_2$ emissions and fuel consumption was indistinguishable for the two test cycles
- CO$_2$ emissions and fuel consumption from the two cycles were either statistically indistinguishable or in fact slightly lower for the WLTC
- Performing the NEDC twice, to produce a cycle of longer distance and temporal duration, failed to produce results which were very much different from those of the WLTC, indicating that cycle distance and length are perhaps not important factors in the context of comparison of these two test procedures
- CO$_2$ emissions and fuel consumption from the first phases of the two cycles (UDC, Low) were overall remarkably similar for the test vehicles. The vehicles with higher power:weight ratios and larger engines showed higher results over the Low phase than over the UDC.

Whether the WLTC or the NEDC was employed under standard laboratory conditions, CO$_2$ results were still much lower than reported values of R CO$_2$. This suggests that various factors other than driving cycle are more important in explaining this difference, such as: additional rolling and aerodynamic resistance, low ambient temperature, short trips, extra payload (mass), parasitic electrical load, macroscopic road topography, sub-optimal usage of gears, underinflated tires, frequent stops and idling, etc. Usage of the WLTC test cycle together with more realistic inertia and road load settings could begin to close the gap between laboratory results and in-use CO$_2$ emissions/fuel consumption. Indeed, based on the limited impact of the test cycle reported here (and elsewhere), the chassis dynamometer setting procedure may be the most important factor. Overcoming vehicle inertia accounts for approaching 60% of the power delivered to the wheel of a passenger car during a realistic driving cycle [43] – so it is clear that significantly increasing vehicle inertia will have a noticeable impact on energy demand and hence the TA CO$_2$/FC result.

This topic is of great importance for a multitude of reasons, from political factors such as the creation of future GHG emissions reduction targets, to fiscal reasons such as road tax revenue projections, to commercial reasons such as consumer satisfaction and the vehicle and engine types which consumers choose to minimize running costs (and reduce GHG emissions). The proposed new test cycle does not appear to generate results which are significantly closer to real usage than the current cycle. However,
the broader test procedure includes other changes; furthermore, other methods – namely the use of on-road emissions measurement using PEMS systems – could also be used to check compliance with declared CO2/F fuel values.

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