Transportation Research Part D 58 (2018) 139–154

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Comparative evaluation of eight legislated driving schedules in terms of cycle metrics and emissions from a diesel-powered turbocharged van

Evangelos G. Giakoumis*, Alexandros T. Zachiotis

Internal Combustion Engines Laboratory, School of Mechanical Engineering, National Technical University of Athens, Greece

ARTICLE INFO

Keywords:
Driving cycle
Nitrogen oxides
Relative positive acceleration
Soot
Transient operation
Turbocharged diesel engine

ABSTRACT

The present work compares, on a fundamental basis, the performance and emissions of a diesel-engined large van running on eight legislated driving cycles, namely the European NEDC, the U.S. FTP-75, HFET, US06, LA-92 and NYCC, the Japanese JC08 and the Worldwide WLTC 3-2. It aims to identify differences and similarities between various influential driving cycles valid in the world, and correlate important cycle metrics with vehicle exhaust emissions. The results derive from a computational code based on an engine mapping approach, with experimentally derived correction coefficients applied to account for transient discrepancies; the code is coupled to a comprehensive vehicle model. Soot as well as nitrogen monoxide are the examined pollutants. Only the driving cycle schedule is under investigation in this work, and not the whole test procedure, in order to identify vehicle speed (transient) effects of the individual cycles only. The recently developed WLTC 3-2 is the cycle with a very broad and at the same time dense coverage of the vehicle's/engine's operating activity, being thus particularly representative of 'average' real-world driving. Even broader is the distribution of the US06, whereas particularly thin and narrow that of the modal NEDC. It is also revealed that the more transient cycles, e.g. the NYCC or the US06, are also the ones with the highest amount of engine-out pollutant emissions and energy consumption. Relative positive acceleration and stops per km are found to correlate very well with energy and fuel consumption and all emitted pollutants.

1. Introduction

For many decades, the certification procedure for new light-duty (LD) vehicles has been accomplished applying a driving cycle procedure. The first test cycles, along with the relevant emission limits, were legislated in the late 60s, and initially concerned (gasoline) passenger cars and later light-duty trucks/vans. The pioneering regions were California (California 7-mode cycle valid from 1966 in California, and from 1968 in the rest of the United States, up to 1971), and Japan (4-mode or J4 cycle, valid from 1966 to 1972) (Degobert, 1995; Berg, 2003; Giakoumis, 2017). Europe followed in 1970, as did, in the following decades, many other areas of the world such as China, India, Australia, Canada, South Korea, and South America (transportpolicy.net).

By employing a driving cycle for the certification of new vehicles, on the one hand a broad range of the engine's speed and torque is under test, and, on the other, its transient behavior. Certification cycles are characterized by relatively long duration (typically 20–30 min), and comprise various speed and load changes, cold and/or hot starting, and sometimes motorway driving as well. Applying a driving cycle for the certification of new vehicles means that simulation of the most frequent daily driving (transient)

* Corresponding author.
E-mail address: vgiakms@central.ntua.gr (E.G. Giakoumis).

https://doi.org/10.1016/j.trd.2017.11.002

conditions is encompassed in the certification procedure (Giakoumis, 2017).

Over the last decades, there has been a huge amount of research articles and projects investigating driving cycle effects on performance and mostly exhaust emissions from light-duty vehicles (e.g. André et al., 1994; Joumard et al., 2000; Filipi et al., 2001; Pelkmans and Debal, 2006; Sileghem et al., 2014; Bielaczyc et al., 2015; Marotta et al., 2015; Dimaratos et al., 2016). In the vast majority of these research efforts, experimental facilities suited to driving cycle measurement and experimentation were used. Owing to the substantial cost involved in experimenting on a variety of test cycles, the object of research was usually the study of emissions on one or two, and only rarely more than a few cycles, although often more than one vehicles were studied.

The scope of the present work is to expand on the previous analyses by comparing a large number of legislated driving cycles with respect to vehicle and engine performance and exhaust emissions; this will be accomplished on a fundamental basis with the emphasis on the engine behavior and performance. The aim is to identify similarities and differences between the various driving schedules, and correlate them with important cycle metrics. More specifically, eight light-duty vehicles drive cycles will be studied, namely: (a) the European NEDC, (b) the U.S. federal FTP-75, (c) the U.S. federal highway HFET, (d) the U.S. supplemental US06, (e) the California LA-92, (f) the New York City cycle (NYCC), (g) the Japanese JC08, and (h) the worldwide WLTC 3-2. With the exception of the NYCC, all the other cycles are used (or intended to be used) for tailpipe emission certification of new light-duty vehicles such as passenger cars and light-duty trucks. To the best of the authors' knowledge, no such extended comparative analysis of legislated driving cycles has ever been performed, covering European, American, Japanese and Worldwide drive schedules.

Unlike the previously mentioned approaches, however, the current analysis is not purely experimental but rather combines "simulation" and experiment, being thus considerably less costly. It is also easily applicable when the purpose is to identify differences between various driving schedules on a fundamental basis, as is the object of the present work. More specifically, it is based on a steady-state experimental mapping of the engine in hand applying suitable correction coefficients to account for the significant discrepancies encountered during transients (detailed in Section 3). These coefficients have been derived from discrete accelerations, such as the ones experienced during a driving cycle. The emissions estimation is combined with a comprehensive vehicle model that 'runs' each time on the requested test schedule (Giakoumis and Lioutas, 2010).

The analysis presented in the next sections is twofold. Firstly, a comparison of fundamental important cycle metrics will be presented in Section 2 for the eight examined driving schedules. Afterwards, the engine/vehicle performance and engine-out emissions from the vehicle model will be investigated in Section 4. The results presented correspond to a large diesel-powered van belonging to category N_1 Class III according to European regulations. For the current study, the examined emissions are soot, nitrogen monoxide (NO) and carbon dioxide (CO_2).

It is highlighted that in the analysis that follows: a) all emitted pollutants discussed are engine-out and concern hot-started operation only (fully warmed-up engine conditions from the beginning of each cycle), and b) only the vehicle speed schedule of the cycles is under test and not the whole procedure, as the aim is to identify cycle differences located in the driving schedule only.

2. Brief historical overview, and comparison of the main attributes of the examined driving cycles

In Europe, the first driving cycle was introduced in 1970 (Directive 70/220/EEC). This was a modal, 'repetitive' cycle (a single 185-s 'ECE-15' schedule run four times), exclusively urban oriented, known as UDC – Urban Driving Cycle. In 1992 (Euro 1 emission standard), a motorway segment, of modal kind too, was added, the extra-urban driving cycle or EUDC (Directive 91/441/EEC); beginning with the Euro 3 emission standard in 2000, the entire cycle has been known as the New European Driving Cycle or NEDC (Directive 98/69/EC). In general, the NEDC, illustrated in Fig. 1, is quite simple to drive and thus easily repeatable. However, it does not account for real driving behavior in actual traffic, containing many constant-speed and constant-acceleration parts. In fact, from several observations it has been shown that in Europe the gap between fuel consumption and emissions experienced by the vehicle on the road and those measured at type approval is higher compared to other areas of the world (summarized in Giakoumis, 2017). The overall simplistic pattern of the NEDC, and the exact gear-shift schedule, make it easy for the manufacturers to implement cycle beating techniques. Moreover, since it is run only once, cold started, its short distance might over-emphasize cold-starting emission effects. Oddly for its outdated structure, maximum speed is relatively high, at least compared to its Japanese (JC08 and earlier J10-15) and U.S. (FTP-75 and HFET) counterparts.

Owing to the simplified and 'stylized' form of the NEDC, the European authorities, even with considerable delay, have decided to adopt a true transient cycle from September 2017. This is going to be the worldwide harmonized light-duty vehicles test cycle, WLTC, together with the corresponding test procedure WLTP (GTR No. 15, 2014). The WLTC is a suite of cycles, constructed based on measurements from many countries in the world (Europe, USA, Japan, S. Korea and India), with different speed/time schedules depending on the tested vehicle's power to mass ratio (PMR); the corresponding speed/time trace of Class 3-2 or 3b (under investigation in the present work), which is suitable to the majority of European cars, is demonstrated in Fig. 1. The WLTC, compared to the NEDC, lasts longer and covers more than double distance (see Table 1 that compares some important technical attributes of the cycles). This is then reflected into cold-start emission effects being relatively lower. From a measurement point of view, the longer duration of the WLTC poses a burden on the test-bed capacity (e.g., sampling bags). Furthermore, the WLTC has higher maximum, average and driving speeds, and almost half the idling period.

The JC08, also illustrated in Fig. 1, is the current certification cycle for light-duty vehicles in Japan, having replaced the earlier, modal J10-15 and J11 cycles employed for almost 30 years. The JC08 is a truly transient cycle but, as confirmed in Fig. 1, the focus is to a large extent on congested-city traffic conditions. The idle period is long, the vehicle speeds relatively low, and the motorway part rather underestimated. This cycle exhibits the longest single stop phase (76s) from all cycles investigated in this study. For certification purposes, the JC08 is run twice, 'hot' and 'cold', with 75–25% weighting factors respectively (transportpolicy.net; Giakoumis,