

Analysis of a Diesel Passenger Car Behavior On-Road and over Certification Duty Cycles

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ABSTRACT

Precise, repeatable and representative testing is a key tool for developing and demonstrating automotive fuel and lubricant products. This paper reports on the first findings of a project that aims to determine the requirements for highly repeatable test methods to measure very small differences in fuel economy and powertrain performance. This will be underpinned by identifying and quantifying the variations inherent to this specific test vehicle, both on-road and on Chassis Dynamometer (CD), that create a barrier to improved testing methods. In this initial work, a comparison was made between on-road driving, the New European Drive Cycle (NEDC) and World harmonized Light-duty Test Cycle (WLTC) cycles to understand the behavior of various vehicle systems along with the discrepancies that can arise owing to the particular conditions of the standard test cycles. The engine controller of a 2.0L diesel vehicle with active de-NO_x and a particulate filter (DPF) has been monitored over 13,700km of driving. The engine speed/torque operating points showed that both the NEDC and WLTC fail to capture the complete static and dynamic usage observed on the road, and are ill-equipped to capture any driver to driver variations. A cyclic analysis of the DPF is proposed, showing up to 70% variation in soot loading at the point of regeneration. This variation can be explained by the controller waiting for favorable driving conditions for regeneration. NEDC and WLTC are poor cycles for capturing DPF effects as the former presents insufficient engine powers to trigger and the later insufficient time to complete a regeneration event. Along with understanding the general contrasts between standard CD cycles and road conditions, this is a key finding for the project overall as understanding and managing DPF loading and regeneration will enable improvements to be made in test precision.

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INTRODUCTION

The ability to demonstrate cost/benefits is vital to the automotive sector increasing rigor demanded of the precision and accuracy of testing operations. In addition, the need to demonstrate real benefits in on-road driving is demanding that realistic, transient operating conditions be reproduced within the test cell environment.

Demonstrating benefits on-road has the advantage of capturing a wide range of conditions and allows for the use of many vehicles over long distances. The major disadvantage is the need for a large quantity of data to detect small differences because of the inherent variability of on-road driving [1]. In contrast, CD testing can achieve high levels of precision over short distance, prescribed cycles [2].

This paper presents the first results from a project which aims to create new experimental methods that will improve the current limits of precision on chassis dynamometer facilities to assist with the development and demonstration of future fuels and lubricants. In going beyond the current limits of precision, it is vital to understand the sources of variability that will affect testing and demonstration work. A portion of this variability will be inherent to the vehicle

whereas the remainder will be a result of the test facility and methodologies in place. The aim of this paper is understand this vehicle variability through on-road testing and to evaluate how this variability will affect chassis dynamometer testing. A crucial part of this work is understanding how real world behaviors could be reproduced in a high precision laboratory environment. In particular this work will identify and quantify areas where current and proposed standard vehicle duty cycles will fail to capture the broadness of on-road usage due to trip characteristics and driver style. This paper does not compare emissions on-road and in the test cell. The quantitative results are, of course, vehicle specific, however the analysis methodologies and lessons learnt are transferable to future testing campaigns.

The project is being undertaken within the Engineering and Physical Research Council (EPSRC) funded Centre for Low Emissions Vehicle Research (CLEVeR) at the University of Bath. The Centre boasts a unique chassis dynamometer facility combining the

capability of reproducing on-road driving conditions with highly accurate state of the art emissions and fuel consumption measurement systems.

LITERATURE REVIEW

The current legislative emissions limits are enforced, as they have been for many years, by testing vehicles over the New European Drive Cycle (NEDC) in a laboratory environment. It is now widely accepted that whilst the NEDC is a useful repeatable standard to compare vehicles against, it does not represent the range of operating conditions found in real world on road driving [3]. To address these concerns the European Commission announced its intention to introduce 'Real Driving Emissions' or RDE legislation as part of Euro 6 and has now amended the standard to suit [3, 4, 5]. At the time of writing, it is planned that this will be implemented as part of Euro 6c, to be effective from 2017 onwards, and to take the form of on-road testing of vehicles utilizing Portable Emissions Measurement Systems (PEMS) equipment with a conformity factor on the emissions limit [3, 4]. In addition the United Nations working party has, for some time, been working on a replacement for the NEDC with the aim of reducing the gap between on-cycle and real world driving. This has culminated in the creation of the Worldwide harmonized Light duty Test Procedure (WLTP) that is also expected to be adopted as part of Euro 6c [3, 4, 5].

The WLTP features the Worldwide harmonized Light duty Test Cycle (WLTC) which is more dynamic and higher load cycle than the NEDC. As such it should better represent real world driving conditions compared to the NEDC, however some authors have shown that compared to the Common Artemis Drive Cycle (CADC) there are some regions of the operating range that are still not covered [6]. Other authors have shown that in terms of NO_x emissions the current fleet of Euro 6 vehicles is not far off meeting the NEDC emissions limit over the WLTC, with a typical conformity factor being less than 3.0, with the inference that conforming to the WLTC will not be nearly as challenging as meeting RDE requirements [3]. There appears to be concern therefore that the real world behavior of vehicles could be significantly different to both the NEDC and WLTC.

The United States are participating in the creation of the WLTC, but their emissions regulations are already more advanced than the European counterparts. The introduction of Tier 2 emissions standards resulted from on-road studies undertaken in the 1990s [7]. This study involved 200 vehicles in two regions of the USA which were monitored over a 2 week period and the resulting data provided the basis for the US06 test for aggressive driving and the SC03 cycle to capture the impact of vehicle air conditioning systems. The WLTC has also been developed based on extensive data collection of on road vehicle use [8]. Measured speed and acceleration data are used along with traffic information to produce these cycles. These new cycles are undoubtable improvements compared to the NEDC cycle, however they each consider the vehicle as a time-invariant parameter. There are practical reasons for this, the most pertinent being the demand for testing facilities that could not cope with excessive testing times. One notable exception is the SAE J1711 standard for hybrid electric vehicle testing where recommendations for operating and evaluating

these vehicles in charge-sustaining mode are proposed [9]. In this case, base legislated test cycles (US06, FTP75, NEDC, WLTC...) are repeated from a fully charged condition until cyclic battery state of charge behavior is observed - meaning that the battery has undergone a charge/discharge event, returning to a similar charge level (defined by a tolerance) over one of multiple standard test cycles. This is necessary for hybrid electric vehicles to achieve any level of performance metric because the effect of the battery on fuel consumption is so large. However when considering the limits of precision in Diesel vehicles, this cyclic nature may also become important for its dynamic components.

It has been shown previously that achieving high precision, through the control of key noise factors is highly important when conducting chassis dynamometer tests [2, 10]. But there is now an additional challenge to accuracy in the form of replication of real world driving conditions which needs further investigation to enable manufacturers to design vehicles which are compliant with RDE requirements.

Modern Diesel vehicles comprise a range of components that have complex control strategies such as filters and catalysts. These components and their controllers have inherent dynamic behavior that affect the engine performance over time periods typically greater than standard CD tests. For example, the Diesel Particulate Filter (DPF) accumulates soot over time, causing an increase in engine pumping losses and requires periodic regeneration, a process strongly affecting fuel consumption [11, 12]. There is no universal solution of how to account for these systems in vehicle testing. The simplest solution is to remove these devices from the vehicle under test [13], but the removal of such a vital system component can have significant influences beyond the emissions it is designed to reduce - in the case of a DPF this would significantly reduce engine back pressure and pumping losses. For on-road testing where large amounts of data are collected, the effects of the DPF can be captured over long driving distances and be included in overall statistical analysis. However, it would be desirable to be able to capture these effects over shorter testing campaigns, such as those conducted in CD facilities. One possible compromise solution is to test with the DPF in place, but to ignore any tests with active regeneration [5] - this is also the practice currently recommended for proposed Real Driving Emissions legislation. The practicalities of this approach depend on the frequency of regeneration events which vary from technology to technology. For the DPF system, this approach allows the effects of soot accumulation to be observed but omits the impact of regeneration events. New technologies appearing on vehicles such as lean NO_x traps and SCR catalysts also have long term dynamic characteristics [14]. There is therefore a requirement for new, high precision testing approaches that capture and account for all of the long term variations of the vehicle system within short distance CD tests.

To develop and demonstrate automotive fuel and lubricant products in this regulatory framework combined with evermore complex vehicle systems, new challenges in precision and accuracy need to be addressed. In order to meet these challenges in precision and accuracy, further investigations are required to improve the understanding of the vehicle behavior on road and on CD test cycles.

This paper will make a contribution to addressing these challenges by improving the understanding of imprecision inherent to the vehicle system.

METHODOLOGY

A 2014 2.0L Diesel vehicle fitted with state of the art exhaust after-treatment systems has been monitored over 13,700km of on road driving. The vehicle after-treatment consisted of a diesel oxidation catalyst, a diesel particulate filter and a Selective Catalytic Reduction (SCR) de-NO_x system. In order to characterize the vehicle's on-road behavior without applying intrusive methods that might modify the vehicle's responses the vehicle was fitted with an Influx Technology Rebel CT data recorder that monitored signals on the vehicle CAN bus via the Onboard Diagnostics port. Data relating to the operating conditions of the engine and the readings from certain sensors that form part of the vehicle control system were recorded. All data has been logged at 2Hz and the key signals used in this paper are summarized in [table 1](#). Some of these variables have physical meaning whereas others are used as indicators of vehicle behavior. It is important to note that even those variables with physical meanings do not necessarily result from a physical sensor, and can be results of models inherent to the engine management system (EMS). Attention is brought in particular to the exhaust temperature: this represents one of three measures available within the EMS which represent different locations along the exhaust system. For the purpose of this work, and for the analysis undertaken with respect to exhaust gas temperature, the location furthest from the engine, post DPF, has been chosen. However the conclusions have been verified with the other sources of exhaust gas temperature estimate.

The soot loading recording that is used as a way to characterize the behavior of the DPF. The raw data from this channel is provided as a mass estimate, expressed in grams, and will be the output of an on-board model of the DPF system such as that presented in [15]. For the purpose of this work, this value has been normalized between 0-1 with 0 representing an empty DPF (not achieved in practice) and 1 representing the highest ever seen DPF soot loading which was observed following persistent in-city driving (see [figure 10](#)). Whilst this scaling is somewhat arbitrary, it will demonstrate the variation in usage of the DPF total capacity.

The vehicle has a manual transmission and has been driven by four different drivers on the road and a different laboratory driver for NEDC and WLTC tests. Initially the vehicle was installed on a 2 wheel drive chassis dynamometer installation and driven through a number of NEDC and WLTC duty cycles as detailed in [table 2](#). For both cycles, the time based vehicle speed profile was followed and the vehicle shift indicator was used to determine gear shifting points. The emphasis in this work was related to the overall vehicle behavior rather than emissions and fuel consumption measurements and the accuracy of these tests is deemed sufficient for comparison with on-road data, however they cannot directly be compared with standard test results that may have been established on other testing facilities.

Following chassis dynamometer testing, the vehicle was driven by four different drivers over a total distance of around 13,700km, spanning an eight month period. The drivers were not selected on a statistical basis but the intention was to represent a selection of driving patterns to stimulate the vehicle over a range of scenarios somewhat representing typical road driving. A range of road types, gradients and distances were represented. In total 314 trips were monitored and a summary of the range of data sets is given in [table 3](#): the values described in column 1 have been calculated for each trip and the statistics detailed in subsequent columns relate to the trip to trip variations.

Table 1. Common data readings including descriptions and recorded ranges

Data Channel	Definition	Range
Distance between regenerations	Odometer within the EMS to measure distance between DPF regenerations	0-1000km
ECT	Engine coolant temperature (sensed by EMS)	-10-100°C
Engine Speed	Measured engine speed from the EMS.	0-5000rpm
Engine Torque	Estimated engine torque from the EMS. (Non-dimensionalised relative to maximum torque)	0-100%
Post injection quantities	Estimated quantity of fuel injected into the cylinder through post injections	0-20mg/st
DPF Regen. indicator	Timer within the EMS to indicate period of active DPF regeneration	-
Soot loading	Model built into the EMS to estimate the state of the DPF (Non-dimensionalised relative to maximum observed loading)	0-100%
T _{ex}	Model or Measured exhaust gas temperature downstream of DPF	0-800°C
Throttle activity	Indicator of engine throttle closing (note this refers to a physical throttle valve in the engine air path, not the accelerator pedal of the vehicle)	-
VSS	Vehicle speed from vehicle speed sensor	0-120km/h

Table 2. Summary of chassis dynamometer test campaign

	NEDC	WLTC
Duration (s)	1180	1800
Distance (km)	11	23.3
Average Vehicle Speed (km/h)	31	47
No. of Hot start tests	7	1
No. of cold start tests (25°C)	5	1

Table 3. Data Statistics from the 314 trips recorded from on-road driving

	Mean	St. dev.	Min	Max
Trip Duration (s)	3680	3460	60	21150
Trip Distance (km)	44	45	0.1	208
Trip Average Vehicle Speed (km/h)	39	17	2	88
Trip Average Ambient Temperature (°C)	10	6	-2	29

Table 4. Driver by driver breakdown of on-road data collection

	All Data	Driver			
		1	2	3	4
No. of Trips	314	80	115	70	49
Total Distance (km)	13700	3330	3680	4430	2260
Average Speed (km/h)	39	44	30	47	37
Average trip distance (km)	44	42	32	63	47

Table 4 gives the breakdown by driver of the trip statistics which is important to show a reasonable contribution to the overall on-road data from each participant. There are however notable differences, as driver 2 has the largest number of trips and the lowest average trip distance of all drivers. Similarly, driver 3 has tended to drive longer trips. It is important to bear this in mind when analyzing driver to driver variability which may not be solely as a result of driver behavior but could also be a result of different routes. It is beyond the scope of this paper to determine the reasons for the driver to driver variation, but this work will seek to illustrate the discrepancies that can arise compared to standard cycles.

RESULTS

The results from on-road and on-cycle driving are presented in the following two sections. The first section describes the differences in overall operating point of the engine and the second presents a detailed analysis of the DPF behavior. The particulate trap is one of the time variant, dynamic non-linear components that is inherent to the vehicle and impacts on the precision of testing. At the same time, being part of the system, the DPF is a key component that determines the on-road behavior of the vehicle and therefore removing it to improve testing precision is not a favorable option. Therefore the aim of this second section is to understand the behavior of the DPF to improve future testing approaches.

Overview of Driving Cycles and On-Road Test

Figure 1 shows the breakdown of engine operating points on the engine speed/torque map. Individual plots have been produced for the NEDC, WLTC and on-road data and these have been split into three categories according to the vehicle speed (below 45km/h, 45-80km/h and above 80km/h). The breakdown by speed is somewhat arbitrary to show discrepancies amongst the vehicle speed regions. It is obvious from the plots that the on-road driving has covered a much broader region of the speed torque map with the most notable differences being:

1. The low speed/high torque region
2. Engine speeds above 2500rpm

These two regions are not visited during NEDC and only briefly during the WLTC cycle.

The frequency of operation in any given location of the speed/torque map is shown through the shading of the points in figure 1. This shading represents the percentage of time that is spent at a particular speed, torque and vehicle speed range with respect to the total driving time for that duty cycle. Also, the scales on the color shading has been normalized across the different duty cycles.

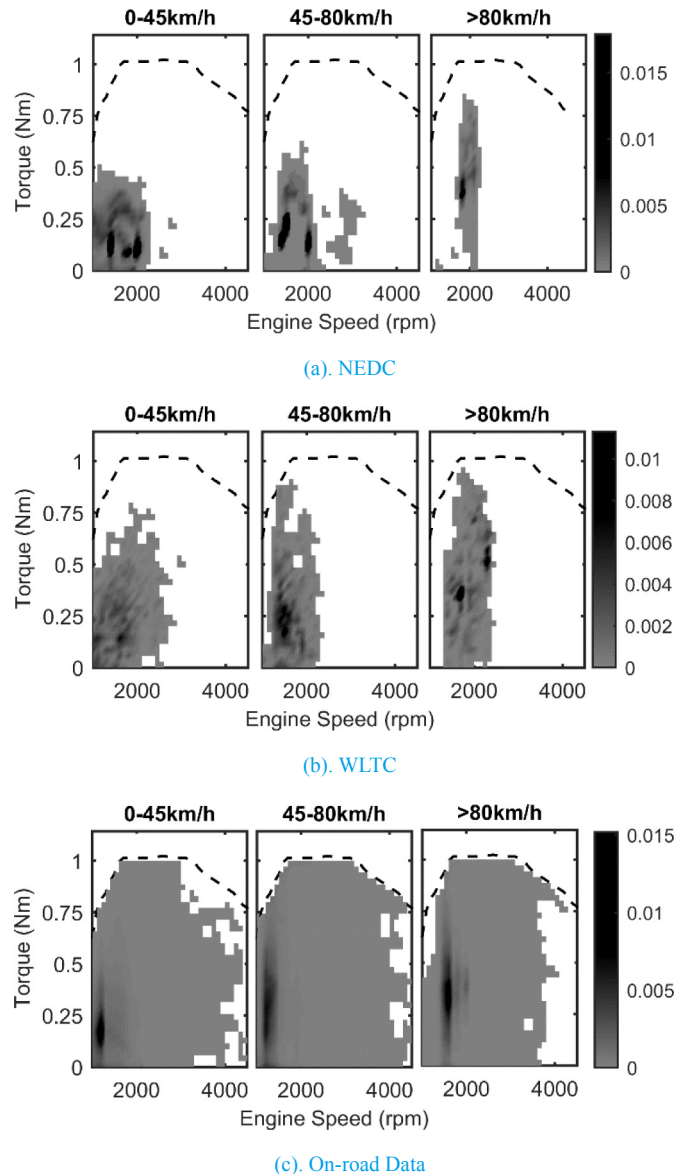


Figure 1. Engine speed-torque operating points for (a) NEDC, (b) WLTC and (c) On-road Data

The NEDC data shows some significant “hot spots” at narrow speed and torque locations which correspond to the steady state cruises of the drive cycle for each of the three speed ranges. In contrast, the WLTC tends to have its operating point spread more evenly owing to the more transient nature of this cycle. The on-road data tends to have “hot spots” which correspond to narrow speed regions but covering a large range of torque. These conditions correspond to the cruising

speeds of the vehicle as dictated by on-road speed limits (causing the narrow speed windows), but with a range of torques to reflect the different road loads that could occur at these speeds on the road. The NEDC and WLTC being idealized cycles, for a given vehicle speed the road load will always be the same, corresponding approximately to vehicle drag on a flat surface with no wind.

The real world data shows the highest density of points at torques below 50% maximum torque which does correspond to the areas visited by the NEDC and WLTC suggesting that whilst incomplete, the drive cycles will capture the most frequently used operating points for this speed. Crucially from this data, it would seem that the WLTC is lacking some of the stable vehicle speed driving that does appear on the road.

In the 45-80km/h region in [figure 1 \(c\)](#), the most frequently used points from on-road data correspond to the full torque range at speeds between 1200-1500rpm. Comparison with [figure 1 \(a\)](#) suggest this is perhaps the most major shortfall of the NEDC as these torque ranges are not captured. In [figure 1 \(b\)](#) it can be seen that the WLTC goes some way to addressing this.

At speeds above 80km/h, the majority of operating points from the on-road data are concentrated in the region of 1500-2500rpm and 40-60% maximum torque. This is a reflection of the more steady state nature of driving at these speeds which will encompass all out of town and motorway cruising. Both the NEDC and WLTC have a concentration of points in this region suggesting that they would be capable of capturing general trends in this region however both fail to cover the full range of operating points seen at these speeds which may result from a range of environmental factors including gradients.

[Figure 2](#) breaks down the on-road usage by driver: this representation aims to show the variability in driving habits that are observed even within a small pool of drivers. It should be noted that for the purpose of this analysis, the term “driver” should be considered as both a variation in the human driver and the routes that they will have driven (i.e. this study is not a comparison of different drivers over the same routes).

There are clear differences between the drivers in terms of the range of engine speed and torque they have used. Drivers 1 and 2 rarely take the engine above 2000rpm whereas drivers 3 and 4 frequently use engine speeds in excess of 2500rpm which will be a direct result of their gear shifting strategies.

For vehicle speeds below 45km/h, the most frequently used points are similar for all drivers, corresponding to speeds below 2000rpm and up to 50% maximum torque however drivers 3 and 4 have a tendency to use a higher torque values and a broader speed range.

The speed range 45-80km/h presents the most significant difference between driver habits: whilst drivers 1 and 2 appear to use the full torque range at engine speeds between 1200-1500rpm, drivers 3 and 4 tend to use a broader speed range. The use of gear shift indicators in vehicles has neutralised these driver to driver variations for the

current NEDC test procedure for manual transmission vehicles. In the proposed WLTP, the gear shifting logic is predetermined by the vehicle power, torque and weight characteristics [16]. However in order to capture this level of variation, CD testing will need to move away from a predetermined single trip towards a more broad approach or even an engine rather than vehicle centred test design specifying engine speed and torque rather than vehicle speed and acceleration.

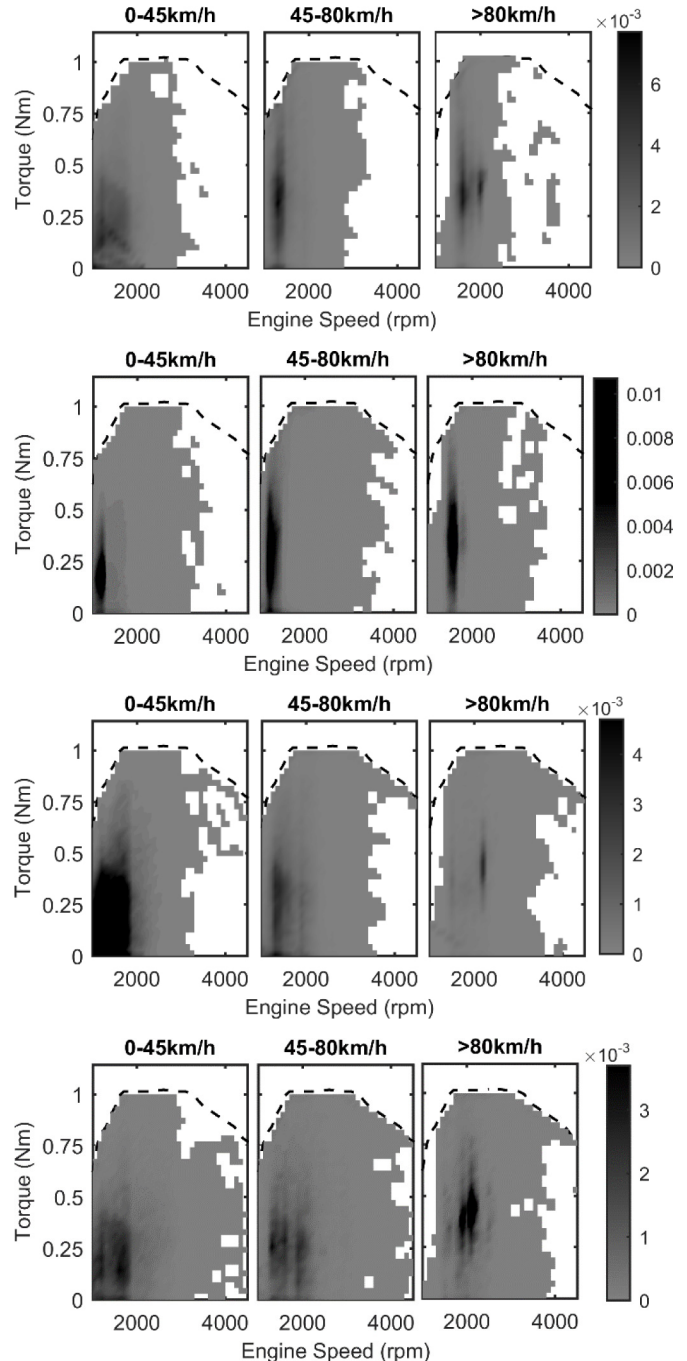


Figure 2. Speed-Torque operating frequencies for individual drivers from on-road data