

Low Ambient Temperature Effects on a Modern Turbocharged Diesel engine running in a Driving Cycle

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ABSTRACT

Engine transient operation has attracted a lot of attention from researchers due to its high frequency of occurrence during daily vehicle operation. More emissions are expected compared to steady state operating conditions as a result of the turbo-lag problem. Ambient temperature has significant influences on engine transients especially at engine start. The effects of ambient temperature on engine-out emissions under the New European Driving Cycle (NEDC) are investigated in this study. The transient engine scenarios were carried out on a modern 3.0 L, V6 turbocharged common rail diesel engine fuelled with winter diesel in a cold cell within the different ambient temperature ranging between +20 °C and -7 °C. The engine with fuel, coolant, combustion air and lubricating oil were soaked and maintained at the desired test temperatures during the transient scenarios. Instantaneous engine performances including torque and speed, gaseous emissions such as CO, THC and NO_x, and particulate emissions for its number and mass are analyzed during each transient scenario under different ambient conditions. Total cumulative gaseous and particulate emissions during the NEDC are examined quantitatively along with the engine parameters for each ambient temperature. The results show that almost all of the engine emissions increase with the decreasing ambient temperature, the highest specific gaseous and particulate emission is at the earlier stage of the NEDC.

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INTRODUCTION

The engine emission legislations have become ever stricter during the past decades in order to reduce the pollution. The EURO VI emission standard will be established in September 2014. The improved emission limits enforce vehicle manufacturers to put more effort into reducing the engine emissions. Currently, the majority of the engine calibrations are based on steady state conditions for the purpose of achieving the required engine output with optimized fuel consumption and emissions [1]. Nevertheless, high frequency of occurrence and the considerably high instantaneous emissions make the engine transients attractive for researchers to focus upon. Turbo-lag, injection strategy and other suddenly changed engine parameters worsen the engine transients in terms of various engine performance parameters and emissions. Generally there are three typical transient patterns of experiments for research, i.e. engine cold or warm start, specific customized transients and regular driving cycles. Higher engine emissions and poor engine performances are expected during cold starts and transients.

Armas et al. (2013) conducted normal ambient cold start and warm start experiments. The research pointed out that cold start would result in a 100 rpm higher idling speed than that at warm start due to the calibrated injection strategy [2]. Typically, an engine started at a low ambient temperature could lead to a longer cranking and starting time compare to the higher temperature engine start [3, 4]. In a severe cold environment, the poor battery performance will result in lower cranking speed of the starter. High engine friction and oil viscosity will lead to a high demand of starting torque, high blow-by level as well as the high heat losses of from the cylinders. All the above phenomena may deteriorate the engine cold start performances [2, 3, 5, 6, 7].

Chartier et al. (2009) conducted cold start at very low temperatures (-25 °C) on their optical diesel engine and reported that fuel was only likely to be ignited close to the glow plug with limited fuel evaporation ability at the cold ambient temperature [8]. As a result, poor engine-out emissions are expected at low ambient cold start. Dai et al. (2013) investigated the gaseous and particulate emissions of a diesel engine during cold and warm start. The result showed that as the coolant temperature decreasing there was a significantly increased THC and PM and a reduced NO emission [9]. Similar

results were found by Lea-Langton (2009) and Bielaczyc (2001) [10, 11]. On the other hand, the EGR valve position performed an important role during engine starting. Armas et al. (2012) used their turbocharged diesel engine to investigate the relationship between the EGR valve and the environment temperature. They concluded that as the ambient temperature decreased the EGR valve was generally closed [12].

In terms of engine transients, the turbo-lag problem is a vital factor. Rakopoulos et al. (2010) investigated the gaseous and particulate emissions under different acceleration conditions. The results showed that turbo-lag was a crucial issue regarding transient spikes during transients [13]. Tian et al. (2013) investigated the size of particulate spikes during transients. The results showed that the initial engine condition determined the particulate transient size. The lower initial engine condition could result in the higher transient spikes [14].

Moreover, the transient emission spikes are also highly dependent on the transient time interval. Tan et al. pointed out that it was increased with the decreasing transient time interval due to the delayed response of the turbocharger [15]. Armas et al. (2013) tested their turbocharged engine under the NEDC and reported that THC, NO_x and particulates spikes were always observed during the acceleration process [16].

In this study, in order to investigate the cold ambient temperature effects on the modern commercial diesel engine, the New European Driving Cycle (NEDC) is used as a test sequence to research engine transient performances and emissions at the temperature range between - 7 and 20°C.

EXPERIMENTAL SETUP AND PROCEDURE

Test Engine and Dynamometer

Table 1. Engine Parameters

Type of the engine	Jaguar V6 3.0L Diesel
Bore	84.0 mm
Stroke	90.0 mm
Displacement volume	2993 cm ³
Maximum torque	600 Nm @ 2000 rpm
Maximum power	199.1 kW @ 4000 rpm
Maximum cylinder pressure	180 bar
Compression ratio	16.1:1
Connecting rod length	160.0 mm

A Jaguar V6 diesel engine was used in this study. The specification of the test engine is given in Table 1. The engine was equipped twin variable turbochargers with a common rail direct injection system. A 290 kW DynoDur 290 AC

dynamometer was used for transient loading the engine. The speed and torque of the engine were controlled by the PUMA control system.

The Cold Cell

The test cell used in the study was specifically designed for the purpose of cold start and transient research at very low ambient temperatures (see Figure 1). The facility can be operated at normal ambient condition as well as at cold climate temperatures down to -20 °C for engine start and -7 °C for engine transient cycles. Four cold start critical temperatures were controlled by the PUMA system; namely combustion air, fuel, coolant, and engine oil. All the above temperatures were cooled and conditioned by a main chiller which is able to provide chilled water down to -29 °C. The engine ECU data was recorded by the PUMA control system through ETAS INCA software.

Fuel

The tested winter diesel fuel in the study has better cold flow performance compared with normal diesel, making it suitable for use in low temperature. The fuel specifications are listed in table 2 which are provided by Shell Ltd.

Table 2. Fuel Properties

Properties	Winter Diesel
Cetane Number	52
Cold filter plugging point (CFPP)	-34°C
Viscosity at 40°C (mm ² /s)	1.86
Oxygen Content (%)	0

Gaseous and Particulate Analyzers

The AVL i60 gas analyzer was used in the study to detect the gaseous emissions, which combines various emission detectors together by using the same sample point. It used a Chemiluminescence Detector (CLD) to measure NO and NO_x, a Flame Ionization Detector (FID) for THC (C₃) and an Infrared Detector (IRD) for CO respectively. The detailed information about the operating principle of the analyzers can be found in [17].

The instantaneous particulate emission was measured by the Differential Mobility Spectrometer (DMS500) from Cambustion Ltd. Sample probes of both AVL i60 and DMS500 are well insulated by thermal insulation materials in order to prevent water condensation at low ambient temperatures. The signal from the starter was taken as an analogue input channel into the DMS500 to synchronize the scenario starting time. All the emission sample points were placed upstream of the after-treatment system as shown in Figure 1.

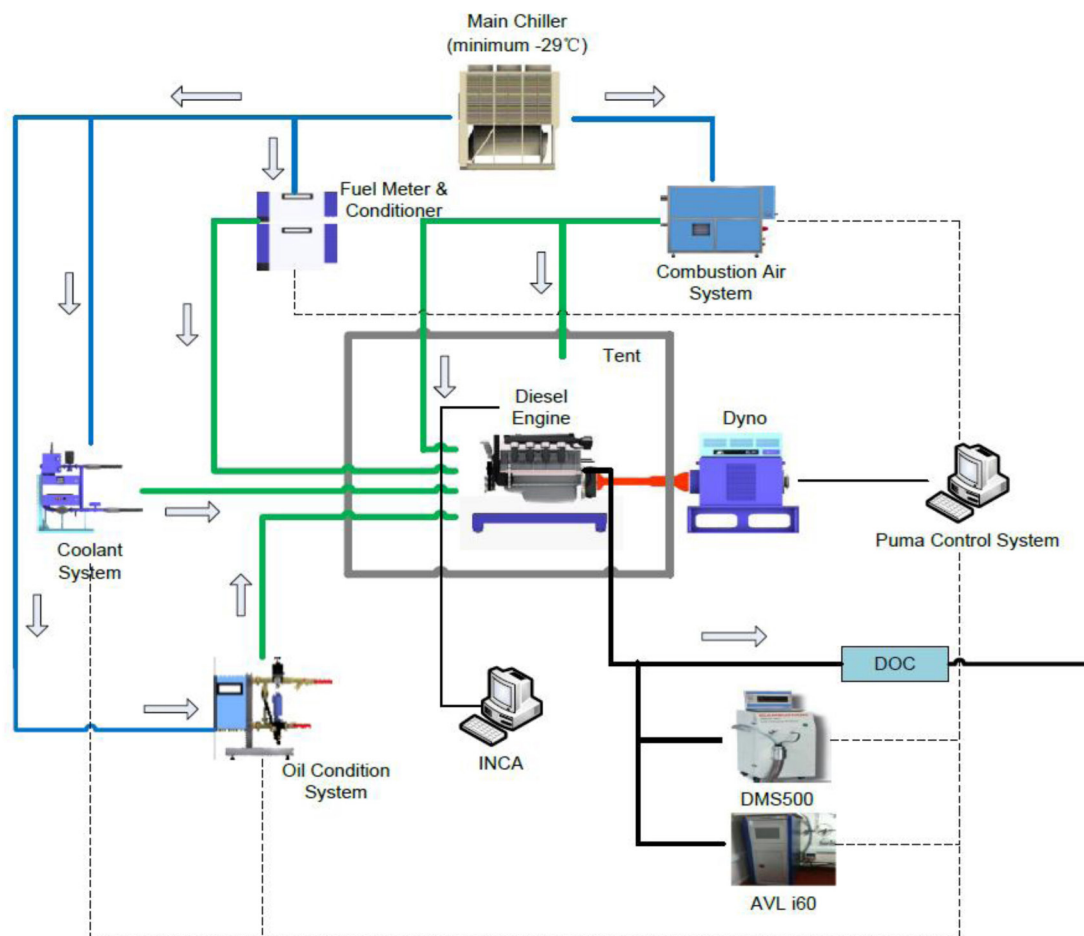


Figure 1. The Cold Cell Schematic Diagram

Test Procedure

The NEDC was used to evaluate the engine transient performances. It consists of 11 seconds of cold start, 4 repeated Urban Driving Cycles (UDC) (also known as ECE) and 1 Extra-urban Driving Cycle (EUDC). A test vehicle (from Jaguar) equipped the same diesel engine model as in this study with a chassis dynamometer used to run the NEDC. Engine speed and torque results were recorded as a test sequence to put into the PUMA engine control system in the cold cell in order to complement the real vehicle driving. The engine before each transient scenario was soaked at the desired temperature for at least 8 hours. The scenarios at normal ambient temperature were repeated for 3 times and the average results were taken for analysis. Due to the poor repeatability at low ambient temperatures, transient scenarios were repeated 5 times and the intermediate results were taken for analysis and discussion. The engine control system was set in the N/T mode, which means the dynamometer was used to control the engine speed and the engine was used to control the engine torque.

Data Processing

Gaseous Emission

The cumulative CO, THC and NO_x emissions are calculated based on formula (1) [14, 15], where the C is the concentration of the CO, THC and NO_x. $MW_{gaseous}$ and $MW_{exhaust}$ are the molar mass of the gaseous emission and exhaust gas respectively. In this study, the $MW_{exhaust}$ is assumed to be 29 g/mol.

$$m = \int_0^t (10^{-6} \times C \times \frac{MW_{gaseous}}{MW_{exhaust}} \times (\dot{m}_{air} + \dot{m}_{fuel})) dt \quad (1)$$

Particulate Number and Particulate Mass

The cumulative total particulate number and particulate mass can be calculated by equation (3) and (4) respectively. The 22.7 L/mol term is required because the DMS500 corrects its particulate measurements at 0 °C and 100 kPa, it is these temperature and pressure that matter, rather than the temperature and pressure in the exhaust pipe.

$$PN(\#) = \int_0^t (10^3 \times PN(\# / cc) \times \frac{22.7}{MW_{exhaust}} \times (\dot{m}_{air} + \dot{m}_{fuel})) dt \quad (3)$$

$$PM(g) = \int_0^t (10^{-3} \times PM(ug / cc) \times \frac{22.7}{MW_{exhaust}} \times (\dot{m}_{air} + \dot{m}_{fuel})) dt \quad (4)$$

RESULTS AND DISCUSSION

Speed & Torque

Engine performances in terms of speed and torque for the required vehicle speed profile under the NEDC are presented in Figure 2. High engine starting speed is observed for the low ambient temperature scenarios. Furthermore, torque fluctuations and unconformities are evident at the beginning of the NEDC. It is interesting that the magnitude of the fluctuations increased when the ambient temperature decreased only within the first a few seconds. This is mainly caused by the unstable phenomenon of the engine cold start. Longer cranking period, higher fuel injection quantity, poor lubrication, fuel evaporation and combustion conditions are the critical problems for the engine cold start. As the driving cycle continues, both the engine speed and torque profiles become identical for all temperatures.

AFR and EGR

Figure 3 presents the Air Fuel Ratio (AFR) and Exhaust Gas Recirculation (EGR) during the NEDC. Generally, the engine EGR is calibrated for meeting the NEDC emission requirement in the required temperature range. In this study, it is obvious that during the cold start and the 1st UDC stage the AFR decreases at lower ambient soaking temperatures. As the engine warms up, the AFR is getting higher for the low ambient scenario meanwhile it is getting smaller for the normal ambient NEDC. On the other hand, the EGR valve is closed during the entire -7°C scenario based on the original engine calibration. For the 0°C scenario, the EGR is off until the second UDC is completed. During the normal ambient temperature scenario, the EGR valve is open throughout the whole NEDC. The EGR valve of the test rig is located upstream of the turbocharger compressor. This indicates that there is no exhaust energy by-pass through EGR at the beginning of the 0°C and -7°C NEDC scenarios. Moreover, the low ambient temperature will lead to higher air density. Therefore, higher intake air mass flow is expected in the lower temperature scenario. Nevertheless, in spite of the fact that the intake air mass flow of the cold ambient scenario is higher than that of the normal ambient temperature scenario, the AFR of the cold ambient scenario is still lower than that of the normal ambient temperature scenario due to the dominative high fuel injection quantity. In addition, at the beginning of the EUDC stage, the AFR is reduced with the increasing ambient temperature. This phenomenon can be explained by the higher EGR valve opening position. At the later stage of the EUDC, the AFR is extremely high because of the delayed turbocharger speed reduction which is caused by the turbo-lag.

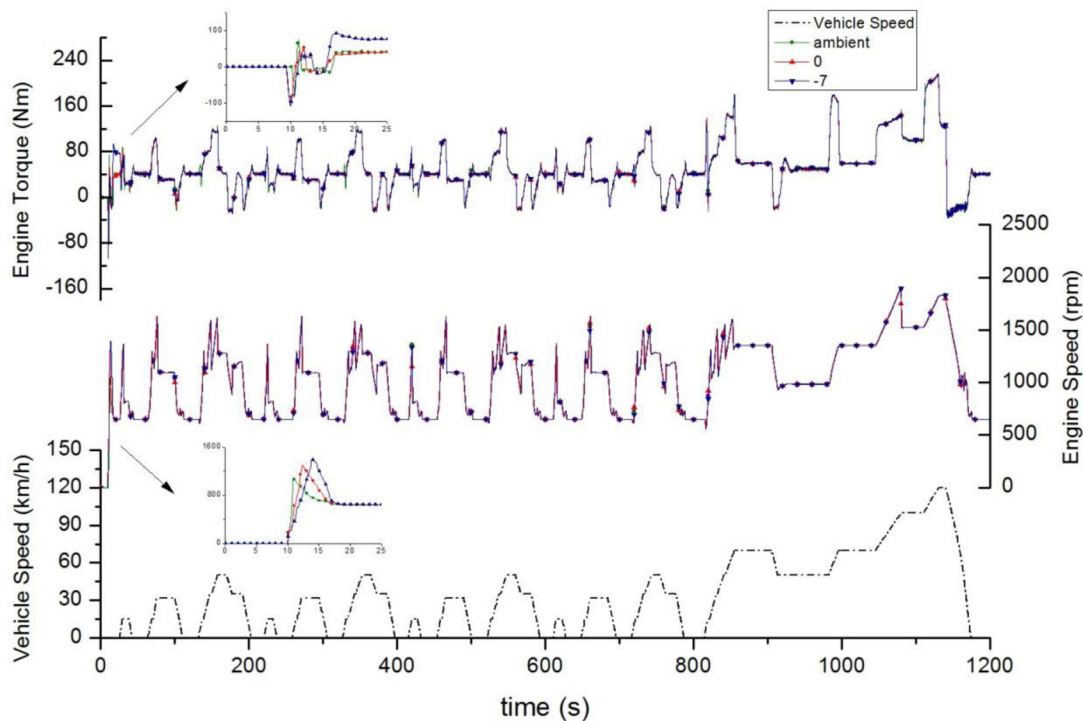


Figure 2. Engine Torque, Speed, and Vehicle Speed