# Improving cold start and transient performance of automotive diesel engine at low ambient temperatures

Ramadhas, Arumugam; Xu, Hongming

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# Improving Cold Start and Transient Performance of Automotive Diesel Engine at Low Ambient Temperatures

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**Arumugam Sakunthalai Ramadhas and Hongming Xu**
University of Birmingham

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## Abstract

Ambient temperature has significant impact on engine start ability and cold start emissions from diesel engines. These cold start emissions are accounted for substantial amount of the overall regulatory driving cycle emissions like NEDC or FTP. It is likely to implement the low temperature emissions tests for diesel vehicles, which is currently applicable only for gasoline vehicles. This paper investigates the potential of the intake heating strategy on reducing the driving cycle emissions from the latest generation of turbocharged common rail direct injection diesel engines at low ambient temperature conditions. For this investigation an air heater was installed upstream of the intake manifold and New European Driving Cycle (NEDC) tests were conducted at -7°C ambient temperature conditions for the different intake air temperatures. Intake air heating reduced the cranking time and improved the fuel economy at low ambient temperatures. Intake air temperatures of 5° and 15°C reduced HC emissions by 40% and 65%, and NOx by 8.5% and 10%, respectively compared to that of at -7°C in the first part of NEDC. The instantaneous emission values were almost close to each other during the later stages of the NEDC cycle and followed the similar trend. Relatively higher intake air temperatures, reduced the diameter and number count of particles and the particulates of 10-23 nm size is accounted for ~45% for the all intake air temperature conditions. The particle number for the first part of NEDC was ~25% of the total cycle for the intake air temperatures of -7°C and was reduced to ~20% with intake air heating. The particulate mass for the first stage of the NEDC cycle was ~20% of that of NEDC at -7 °C whereas it was reduced to 12-14% of that of NEDC at -7 °C with the intake air heating. The intake heating improved the engine cold start performance as well as reduced the gaseous and particulate emissions significantly over the NEDC at low ambient temperatures.

## Introduction

Diesel engines have dominated for many decades in the light commercial vehicles and heavy duty vehicles market for its reliability and fuel efficiency. Recent years there is a large of developments in automobile technologies for improving the engine performance and reducing emissions. Market share of passenger cars is also shifting towards diesel engines due to this advancement in the engine technologies and consumer's preference over enhanced fuel efficiency [1]. The cold start emissions is also related with the engine design, fuel injection strategies, fuel characteristics, lubricant, ambient temperatures, aftertreatment devices and cold start aids. Lower initial combustion chamber wall temperature, poor performance of battery and higher viscosity of engine oil are also the cause for lower cranking speed at cold ambient conditions. Temperature and pressure achieved at the end of compression stroke of the cold start process are much lower than that under normal operating conditions. These inferior conditions for the flammable mixture preparation led to the unstable fuel combustion and even misfiring [2, 3]. Downsizing of diesel engine reduce the fuel consumption and Korfer et al. achieved approximately 9% with a displacement reduction from 2 to 1.6 L [4] cited in [5]. Honeywell turbo technologies advocates that the smaller size makes the engines more efficient and also brings additional advantages such as a quicker engine warm-up (which reduces cold-start emissions) and lower weight (which further helps fuel economy)[6]. Lower compression ratios offering acceptable cold-start performance more challenging in spite of improved glow plugs and glow plug controls [7].

Cold start emissions can be controlled to some extent by using glow plugs and air heater, heating of the fuel line, use of block heater and intake manifold burner. Glow plugs are extensively used cold start aid in small and medium sized engines. High voltage metallic plugs are used for standard high compression ratio engines and low voltage metallic and ceramic glow plugs are used for modern low compression ratio engines [2, 8, 9, 10]. Combustion charge air temperature depends upon the temperature and mass of fresh air and recirculated air. The electrical way of heating the charge air is more reliable and precise control of charge air temperature [11]. Broatch et al. investigated the use of electrical heaters in a turbocharged diesel engine for running the MVEG driving cycle and reported that from 177 W at idle speed to 430 W (which is the maximum capacity of the system) at 2000 rpm. Intake air heating provided better benefits in reducing carbon monoxide (CO), hydrocarbon (HC) and combustion noise during engine warm up and improving the engine stability after warm-up [12]. Lindl reported that glow plugs could not guarantee a satisfactory cold start in bigger size combustion chambers because of the comparable small initial heat release. Intake air heaters like intake manifold burners or electrical heaters provided the engine with sufficiently high air temperature to achieve nearly warm start conditions [9]. Typical heaters manufactured by M/s Beru will run on 12-24 V supply and generate heat 2.5kW and can run upto 15 min [13]. Andrews et al. conducted cold-start tests at ambient temperatures ranging between -2°C and 32°C over a year and reported that HC emissions were reduced by a factor of 4 [14]. Ni et al. preheated the intake air for conducting cold start tests on SI engines at -7°C and reported that preheating of the intake air reduced CO and HC emissions significantly [15].

European Union (EU) has introduced a number based approach for particulate in addition to mass based method with the Euro 5b/ Euro 6 legislation to limit the ultra-fine particles [16, 17, 18]. The EU has also amended the emissions measurement test procedure in the year 2000 to synchronize sampling of the exhaust gas from the start of cranking, thereby eliminating the 40 s warm-up period which had existed previously. This modified emission test procedure is named as New European Driving Cycle (NEDC). It consists of 4 repeat Urban Driving Cycles (UDC) (also known as ECE) each of the 195 s and 1 Extra-urban Driving Cycle (EUDC) of 400 s. The total duration of the test cycle is 1180 s. It is mandatory that passenger cars are required to pass the emission limits over the NEDC on a chassis dynamometer test benches. Tian et al. investigated transient performance of a CRDI diesel engine at low ambient temperatures and reported that cold start emissions increased with drop in ambient temperature [19]. Weilenmann et al. conducted low ambient temperature tests on gasoline and diesel vehicles of different generations and concluded that cold start excess emissions from diesel vehicles was lower than gasoline vehicles [20, 21]. The EU has mandated the low ambient temperature transient emissions testing (at -7°C) for the gasoline passenger cars only. However, it is likely to adopt low temperature emission cycle tests for the diesel passenger cars in near future. EGR systems and after-treatment systems (like NOx reduction system) were deactivated or not operated in cold weather conditions resulted in elevated NOx emissions [22]. The environmental effects of the diesel particulates are poor visibility, soiling of buildings and adverse health effects on humans, livestock, etc. These effects are influenced greatly by the particulate size distribution, e.g. smaller particulates are more harmful for human health (due to their larger surface to volume ratio) however they do not adversely impact visibility [23]. These stringent emission legislations drive the automobile industries, oil industries, cold start aid manufactures and academician to carry out research on cold start. Peckham et al. investigated the cold start emissions from gasoline engines during the NEDC and reported that the 50% of the cumulative particle formation was emitted within first 200 seconds of the start [24].

Many published works related to cold starting are conducted on a single cylinder or multi cylinder engine at ambient temperatures and a very few publications only highlighted the cold starting of multi-cylinder diesel engines at very cold ambient temperatures. Moreover, a few papers only investigated the diesel engine driving cycle emissions at subzero ambient temperatures.

Since low temperature emissions cycles are likely to be adopted to diesel vehicles, it is imperative to investigate the performance of air heaters during the transient cycles and to characterize the exhaust particulates in terms of particle number and size at low temperatures. Hence, a study was proposed to investigate the emission reduction potential of intake air heater at cold ambient temperatures. The objective of this paper is to investigate the impact of the intake air temperatures on a cold start of common rail direct injection (CRDI) diesel engine running on the New European Driving cycle (NEDC) at -7°C ambient temperature conditions for the engine performance, gaseous and particulate emissions.

## Experimental Setup

The cold chamber transient dynamometer engine test facility in the University of Birmingham is the one of the unique testing facilities in the United Kingdom, and is used for this study. The schematic of the cold cell transient dynamometer-engine test facility is shown in Figure 1. A six cylinder, turbo charged, common rail, direct injection diesel engine for the passenger cars is used for this study and the specification of the engine is given in Table 1.

Table 1. Test engine specification

| | |
|---|---|
| Fuel system | Common rail direct injection |
| No. of cylinders | 6 |
| Bore x stroke | 84 x 90 mm |
| Compression ratio | 16.1:1 |
| Total displacement | 2993 cc |
| Maximum power | 199 kW@4000 RPM |
| Maximum torque | 600 Nm@2000 RPM |

### *Dynamometer & Test Bed Automation System*

The test bench is installed on a DynoDur 290 dynamometer, which is an AC machine capable of full four-quadrant operation. Torque measurement is made with a torque flange. AVL Puma Open 5.1 test bed automation system acts as a Host PC to control the dynamometer, fluid controlling systems and emission measuring equipment which is interfaced with the engine test bed. The test cycles are programmed in the Puma for the automatic operation of test run. The engine is mounted inside an insulated enclosure, where the temperature can be varied from ambient to -20 °C. For conventional testing under ambient conditions the insulated panels are removed from the frame to allow test cell ventilation air to pass around the engine.

### *Coolant and Oil Conditioning Systems*

This unit is equipped with two circuits each for coolant and oil separately and is capable of conditioning the engine coolant at normal ambient temperatures during conventional testing and also circulating coolant at temperatures down to -20°C through a stationary engine to perform a low temperature soak prior to an emissions test or a cold start. To cope with the large viscosity difference between oil at -20 and +140°C, the pump is inverter controlled to run at a speed proportional to oil temperature.

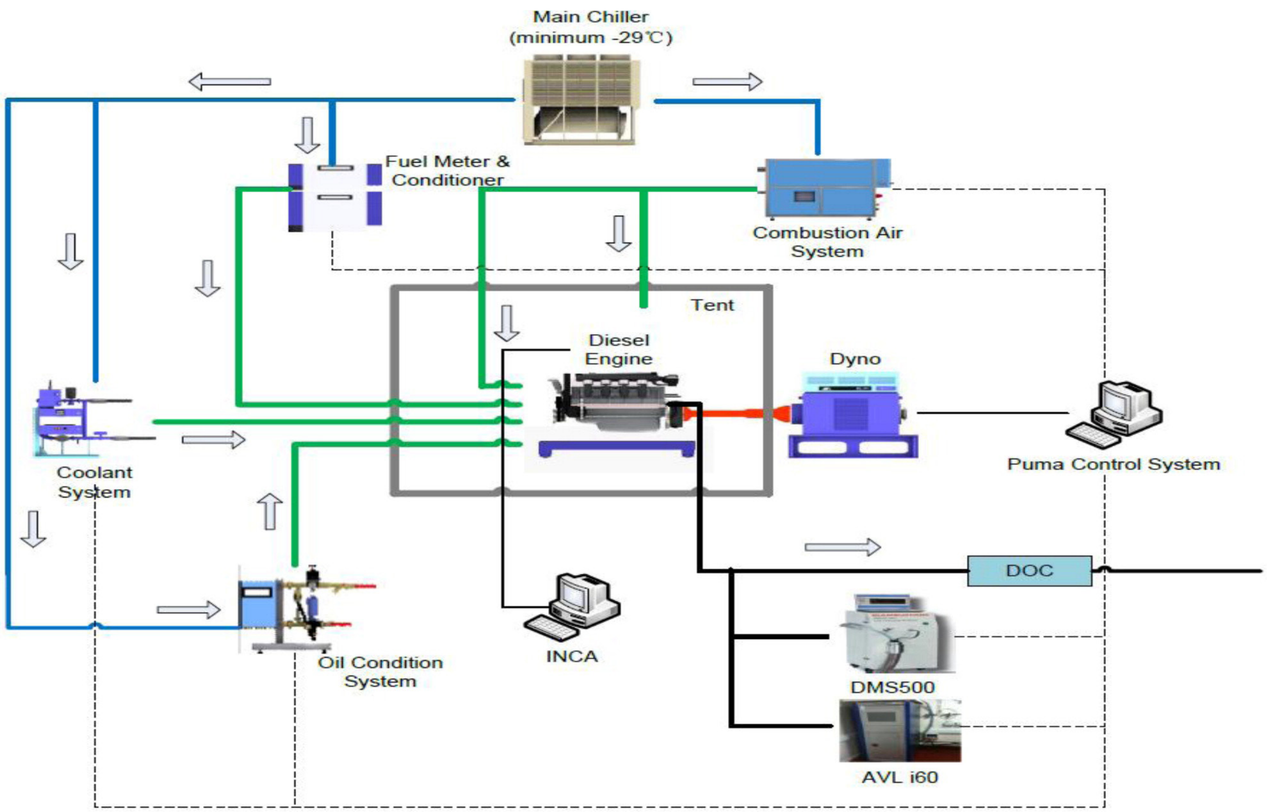



Fig 1. Schematic of cold cell transient dynamometer-engine test facility

### *Fuel Measurement*

Fuel metering is performed by the AVL735S, which utilizes the Coriolis principle to measure mass flow of fuel consumed by the engine. The AVL 753C is capable of conditioning the fuel temperature between -10 and +80 °C and it recirculates fuel to and from the engine feed pressure control module.

### *Combustion Air System*

The combustion air system is located in the plant room adjacent to the test cell and consists of an AVL ACS1600 unit and an air dryer to reduce the humidity of the incoming air. The system has capacity to supply chilled air up to 500 $m^3/h$ for below 0°C testing and up to 1600 $m^3/h$ for ambient testing.

### *Emission Measurement*

The AVL AMA i60 is an integrated gas analyzer that combines various emission detectors together by using the same sample point is used for gaseous emission measurement. The instantaneous particulate emission was measured by the Cambustion Differential Mobility Spectrometer (DMS500). The sample probe is installed ahead of the after treatment devices and the sample probe is thermally insulated to avoid condensation of particulates during measurement in the cold chamber. The sampling probe is connected to the electrically heated sample line. The secondary dilution ratio was set at 250 for the cold start studies. The signal from the starter was taken as an analogue input channel into the DMS500 to synchronize the test starting time.

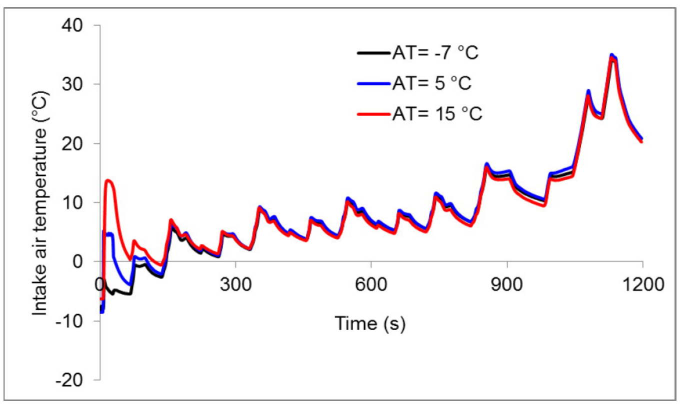
### *Intake Air Heater System*

Ignition is a function of temperature, pressure, mixture stoichiometry, and time. Normally, 450- 500° C is the sufficient temperature for reliable ignition [24]. The important parameters considered for calculating the energy required for the air heater are total intake air mass flow rate during the cold start, thermal power dissipated in the air and the temperature of supply air to the heater. The power supplied to the heater is proportional to the engine speed. The performance of the air heater depends upon the air mass flow rate and electrical power supplied. An intake air heater is installed in-between intake manifold and turbocharger. The electric power for the air heater is controlled with the external variable voltage source. The power supply to the heater can be varied in order to achieve different intake air temperatures. AT refers to the intake air temperature in the -7°C environment and the intake air ahead of intake manifold preheated to 5 and 15 °C temperatures. Pre-tests were carried at different power ratings of the heater and measuring the electrical energy needed for preheating the supply air to the desired intake air temperatures.

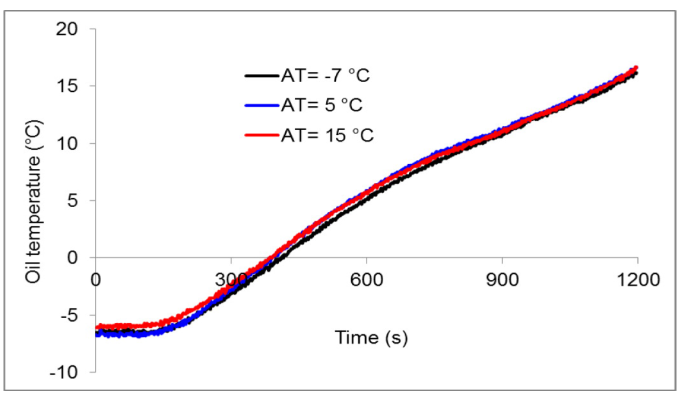
## Test Methodology

The engine is soaked at the desired test temperature of -7°C for 8 hours in the cold cell and ensured that air, coolant, oil and fuel temperatures were maintained prior to start of the test. For this study, the NEDC test was conducted on a test vehicle of same model diesel engine on a chassis dynamometer, and the recorded engine speed and torque values were given as a test sequence input to the PUMA engine control system in the cold cell in order to complement the real vehicle driving. This approach is a typical hardware (engine)-in-the-loop system that simulates the testing of a passenger car on the transient dynamometer following the NEDC cycle.

The intake air heater was preheated (~40 sec) to achieve the desired intake air temperature in the -7°C environment and the NEDC test was started. The heater was allowed to operate for 20 sec after starting of the engine. The mass of air entered the engine at idle is about 70 kg/h. During the test, the exhaust emissions were measured at the upstream of the after treatment device. The NEDC tests were repeated for 3 times, and the average of test results was taken into consideration for the analysis. After completion each test, the engine was cranked without fuel to remove the any residual gases if any in the engine. The analysis of the cold start and idle behaviour of the engine at different ambient conditions presented in this article is within the European Commission (EC) research program investigating the diesel engine cold startability and transient operation. Figure 2a, 2b and 2c shows the temperature profiles of intake air, coolant, oil in the sump during the test. It is seen that during the progress of the NEDC test the intake air temperatures were closer to each other and the coolant and oil temperatures were almost closer to each other throughout the NEDC cycle.

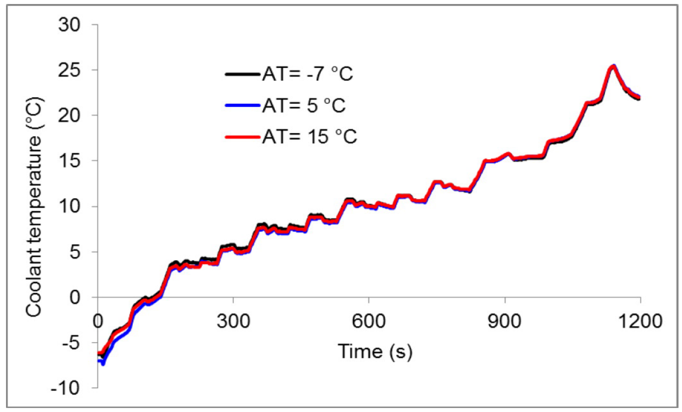



a.




b.

Figure 2.




c.

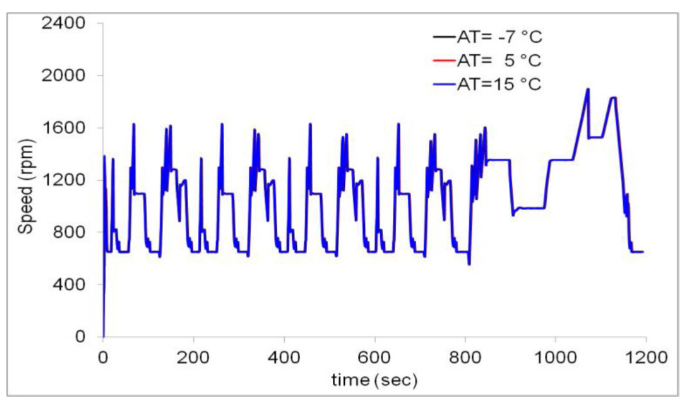
Figure 2. (cont.) Temperature profile in -7°C environment during the test (a) intake air (b) engine coolant (c) engine oil

## Results & Discussion

### *Engine Performance*

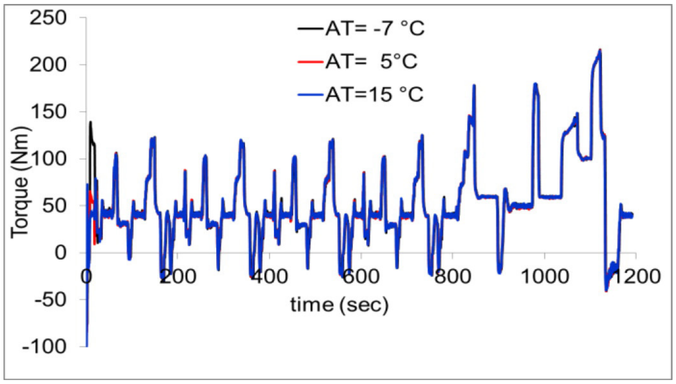
#### Speed

Figure 3(a) depicts the observed engine speed for the NEDC test conducted for the intake air temperatures of 5 and 15°C at -7°C environment. While starting of the engine more quantity of fuel was injected to initiate the combustion, and to overcome the higher friction resistance offered by the engine components and lower combustion chamber temperature at the low ambient temperatures. After several revolution of the crankshaft compression temperature and pressure inside the cylinder increased and the accumulated fuel burned abruptly that caused the rapid rise in engine speed to reach a peak value. Longer cranking period, higher fuel injection quantity, poor lubrication, fuel evaporation and combustion conditions are the crucial problems for the cold start. The intake air heating has significantly influenced the engine start performance and fuel consumption. Higher peak speed was observed during the cold start for the tests conducted with preheated intake air compared to intake air temperature of -7°C and the intake air heating decreased the cranking period of the engine. Torque fluctuations and unconformities are evident at the beginning of the NEDC test. The peak speed during the cold start for the intake air temperatures of 5 and 15°C were 17% and 22% higher than that of -7°C. The lower peak speed at cold intake air temperature might be due to higher frictional forces and incomplete combustion of fuel at very cold ambient. However, during the later stages of the driving cycle both the engine speed and torque profiles became identical for all the intake air temperatures.




a.

Fig 3. Engine speed and torque at different intake air temperatures (a) speed (b) torque

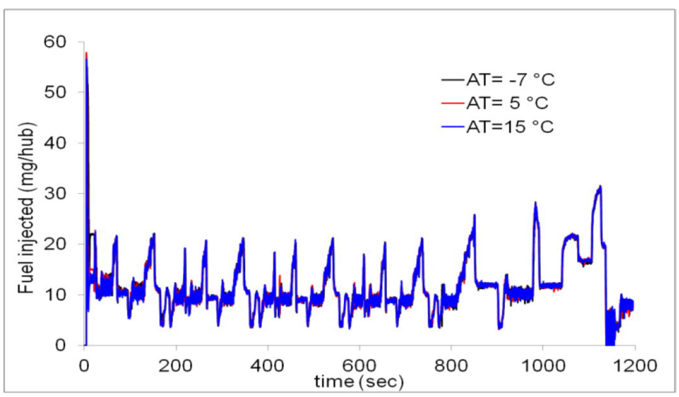



b.

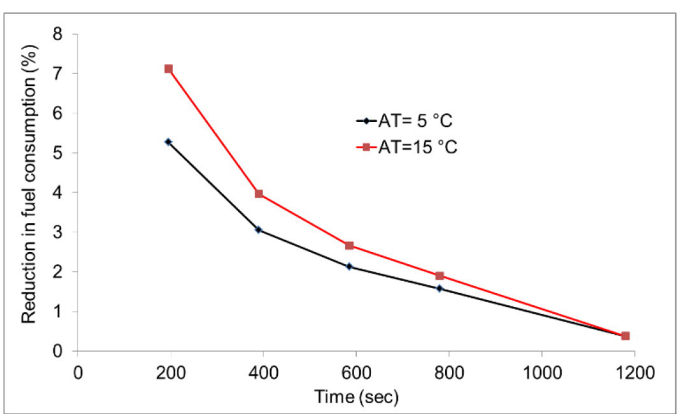
Fig 3. (cont.) Engine speed and torque at different intake air temperatures (a) speed (b) torque

### Fuel Consumption

Figure 4(a) depicts the quantity of the fuel injected over the NEDC cycle at different intake air temperatures in the -7°C environment. More quantity of fuel was injected at -7°C intake air temperature compared to preheated intake air. Figure 4(b) shows the percentage reduction in fuel consumption for the preheated intake air of 5 and 15°C compared to -7°C. The warm intake air increased the vaporisation of fuel and improved the fuel combustion as well. The higher fuel economy was achieved by preheating the intake air during the initial stages of the NEDC and the fuel economy was decreased during the progress of the cycle.




a.




b.

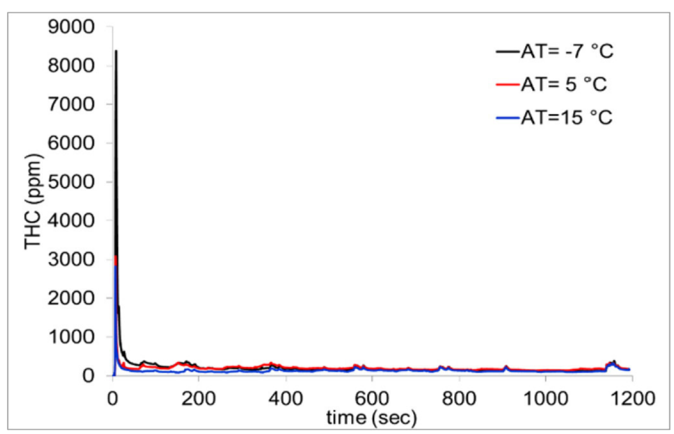
Fig 4. Fuel consumption at different intake air temperatures (a) Instantaneous (b) % reduction compared with -7°C

## *Gaseous Emissions*

The gaseous emissions from the diesel engine were measured ahead of the diesel oxidation catalyst in the exhaust pipe using the AVL AMA i60 emission analyzer.

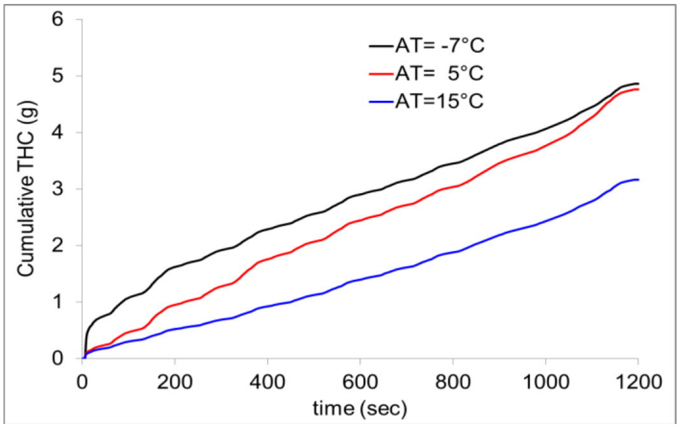
### Hydrocarbon Emissions

Figure 5 illustrates the HC emissions from the diesel engine over the NEDC cycle in the -7°C environment for different intake air temperatures. It is observed that the engine emitted higher and longer transient spikes at the beginning of the cycle at cold ambient temperatures (Figure 5a). This could be attributed to the higher fuel injection at the low ambient temperatures, especially during the cold start period. Furthermore, the fuel could have higher viscosity and thus higher surface tension at low temperature conditions. As a result, the fuel would undergo slow evaporation, poor atomization or even impingement into the cylinder wall before combustion. On the other hand, poor performances of lubricating oil could cause the blow-by problem which deteriorates the engine combustion. The high heat transfer between the cylinder and the environment at the cold ambient temperature scenario could also lead to poor engine combustion. Thus, the lower wall temperatures enhance the flame quenching and increase the HC emissions. Moreover, over-lean mixture will not auto ignite, and it can be only oxidized by relative slow thermal-oxidation reactions that will be incomplete. All the above-mentioned factors will finally result in poor fuel-air mixing and incomplete combustion that led to higher HC emissions. Warm intake air to the engine improved the fuel combustion and reduced the peak value of HC emissions significantly in the -7°C environment. Figure 5(b) shows the cumulative HC emissions over the NEDC cycle for the intake air temperatures at 5 and 15°C. The intake air heating accelerated the pre-combustion chemical reactions and contributed to a reduction in ignition delay. Therefore, increasing the intake temperature led to a reduction in both ignition delay and HC emissions. Figure 5(c) shows the percentage reduction in cumulative HC emissions over the cycle. The intake air temperatures of 5 and 15°C reduced the first phase of NEDC cold start phase emissions by 40% and 65% compared with the NEDC test conducted at -7°C. Higher amount of HC emissions at cold start / first part of NEDC cycle had significant influence on overall emissions of the regulatory emission cycle. The intake air temperature of 15°C decreased the HC emissions during the NEDC by 35% of that at -7°C intake air temperature.




a.

Fig 5. Total hydro carbon emissions at different intake air temperatures (a) instantaneous (b) cumulative (c) %age reduction

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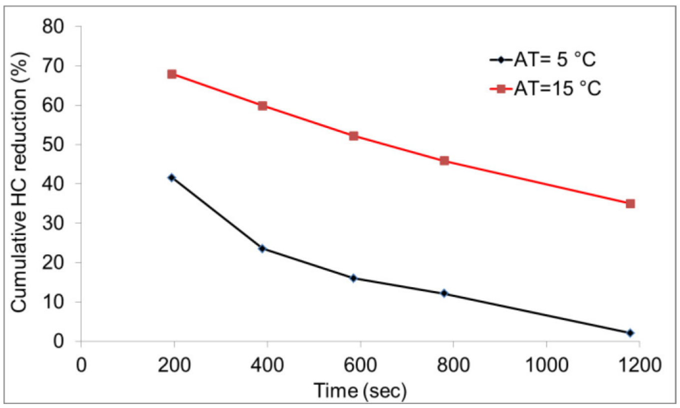


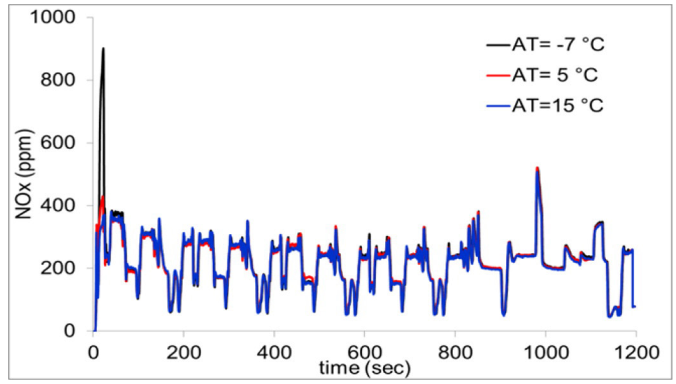

c.

Fig 5. (cont.) Total hydro carbon emissions at different intake air temperatures (a) instantaneous (b) cumulative (c) %age reduction

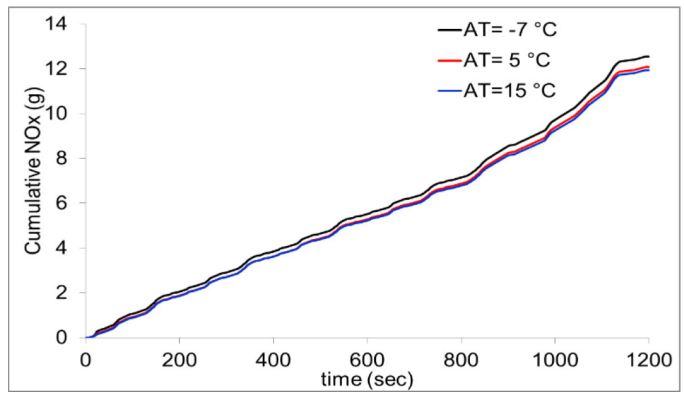
### *Nitrogen Oxides Emissions*

The nitrogen oxides (NOx) emissions from the diesel engine over the NEDC test conducted in the -7°C environment is shown in Figure 6. NOx emission spikes were found during the cold start for the all intake air temperature conditions (Figure 6(a)). It is also observed that EGR valve was closed for the all tests conducted at -7°C ambient temperature conditions. This is due to the engine calibration such that EGR valve to open at the temperatures equal to or higher than normal ambient temperatures. The cold ambient temperature conditions and no EGR rate at low ambient temperatures increased the NOx emissions significantly. Also, increased quantity of fuel was injected into the cylinder at the beginning of the NEDC could largely increase the combustion temperature suddenly and finally increased the NOx emission. NOx emissions reached a high peak value for the intake air temperature of -7°C whereas noticeably lower peak was observed with the intake air heating. However, during progress of the NEDC cycle instantaneous NOx emission was almost closer to each other for all the tests but the cumulative emission for the low intake air temperature was higher than that of preheated intake air (Figure 6(b)).

Figure 6(c) shows the percentage reduction in NOx emissions over the NEDC cycle. The intake air heating at 5 and 15°C decreased the cumulative NOx emissions by 8.5% and 10% respectively, and the overall NOx emission reduction obtained was 3.75 and 5% respectively in comparison with the -7°C environment. Intake air heating helped in instantaneous and continuous burning of fuel-air mixture thereby reduced the sudden rise in peak NOx emissions during the cold start phase of the NEDC cycle.




a.

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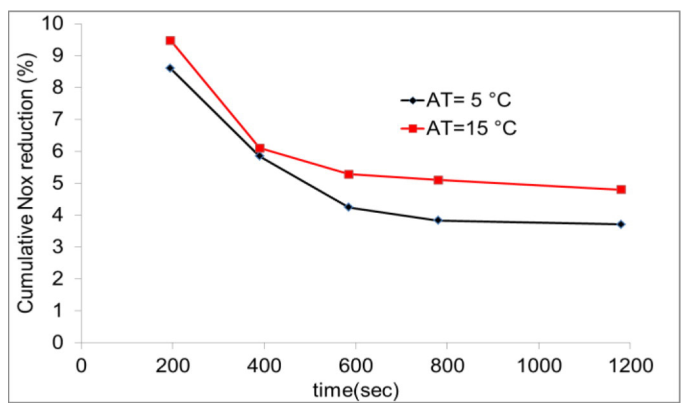



c.

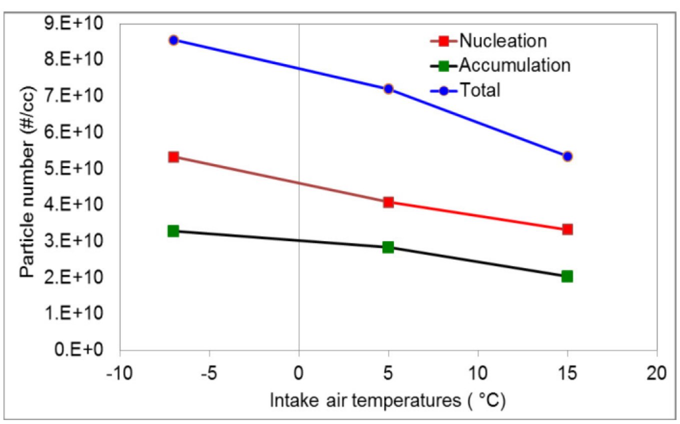
Fig 6. Nitrogen oxides emissions at different intake air temperatures (a) instantaneous (b) cumulative (c) % age reduction

## *Characterization of Particulate Emissions*

The exhaust particulate emission was measured using a Cambustion DMS 500 analyzer to characterize the particulate emissions in terms of its number concentration, size distribution, surface area and mass.

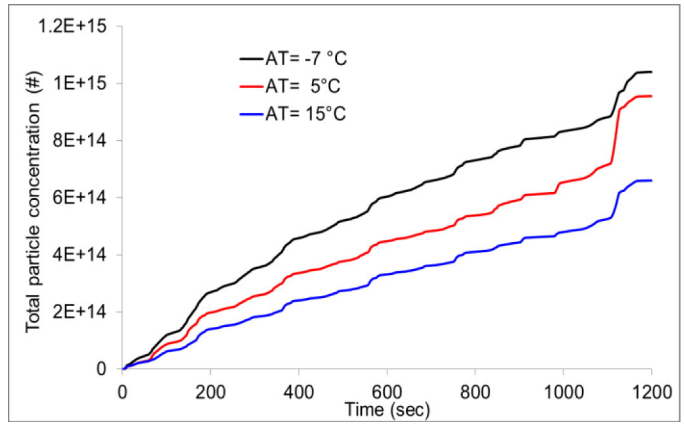
### Characterization of Particulate Emissions Particle Number

The exhaust particulates are composed of nucleation mode and accumulation mode particles. The nucleation mode particles range between 5 and 50 nm, and accumulation mode particles range between 50 and 1000 nm. The nucleation mode particles are primarily composed of soluble or volatile organic fraction (SOF/VOF), which is formed mainly from exhaust dilution and cooling processes by the small amount of fuel or evaporated lubricating oil which escape oxidation process. Accumulation mode particles are formed by agglomeration of many fine particles and semi volatiles absorbed on the soot particles. Figure 7(a) shows the nucleation mode, accumulation mode and total particle emission from the diesel engine for the NEDC tests conducted at different intake air temperatures in the -7°C environment. The particle number is higher for the low intake air temperature in the low ambient temperature environment and it decreased with intake air heating. Increased fuel injection quantity, low intake combustion air and in-cylinder temperature at low ambient temperature are likely to produce incomplete combustion, eventually leading to excessive particle emissions. Figure 7(b) shows the cumulative particle emissions over the NEDC in the -7°C environment for the different intake air temperatures. Heated intake air supply and lower fuel consumption of the engine decreased the particle emissions and the similar trend was followed throughout the NEDC cycle. Figure 7(c) shows the total particle number for the first part of NEDC and the whole NEDC cycle at different intake air temperatures. It is calculated that total particle number concentration for the first part of NEDC (initial 195s in 1180s) was accounted for ~25% for -7°C intake air temperatures whereas ~20% for the preheated intake supply. Intake air heating at cold ambient conditions reduced the particle number (both nucleation and accumulation) significantly compared with very cold intake air temperatures and hence reduced the total particle number in the NEDC cycle.




a.

Fig 7.

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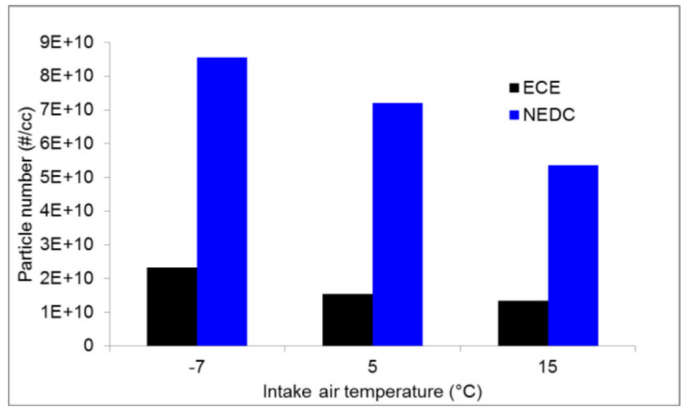
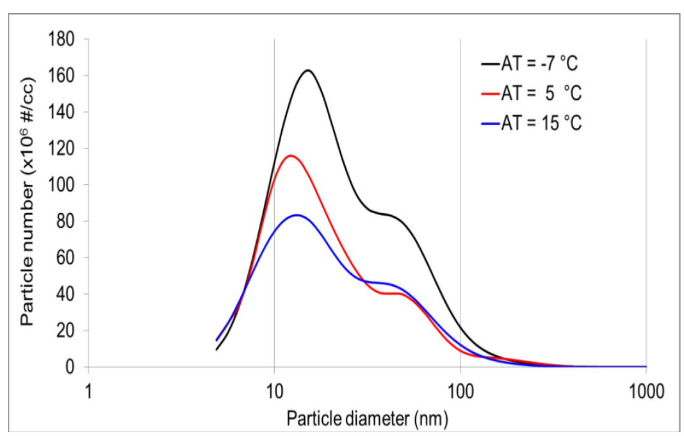



c.

Fig 7. (cont.) Instantaneous particle emissions at different intake air temperatures (a) nucleation mode (b) accumulation mode (c) breakup

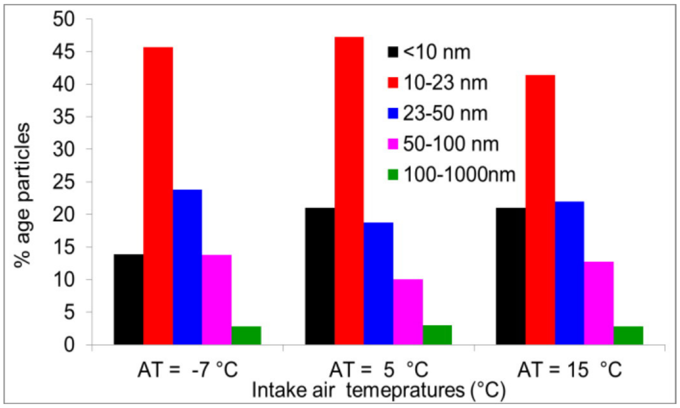
### Particle Size Spectral Density

Particle size spectral density depends on the exhaust particle number and its size. Figure 8(a) depicts the particle spectral density observed over the NEDC at -7°C for the different intake air temperatures (AT). The exhaust particles in the size range of 10-100 nm diameters were higher for the cold start phase for all the intake air temperature conditions. The peak value of particle number was shifted towards the smaller particle diameter and the particle spectral density was also decreased with intake air heating.




a.

Fig 8. Particle size spectral density (a) size distribution (b) % share




b.

Fig 8. (cont.) Particle size spectral density (a) size distribution (b) % share

The particle formation is strongly influenced by the localized temperature distribution and fuel/air ratio which vary greatly inside the combustion chamber. With the increase in combustion chamber temperature the rate of oxidation of fuel- air mixture increased more rapidly than the rate of soot formation and hence the diameter of particle was decreased.

It is seen from the Figure 8(b) that ~45% particles were in 10- 23 nm over the NEDC for the all temperature conditions and 30-40% particles were in 23-100 nm diameters. The percentage contribution of smaller size particles (diameter less than 10 nm) was increased with the rise in the intake air temperatures. Relatively higher intake air temperatures reduced the diameter and number count of particles at -7°C environment.

### Particulate Mass

The particulate mass (PM) over the NEDC for the different intake air temperatures in the -7°C environment is depicted in Figure 9. The particulate mass was increased significantly at the beginning of the NEDC cycle for the all tests and the growth was much higher at -7°C intake air temperature. The particulate mass for the 1st stage of the NEDC cycle was ~20% of that of NEDC for the intake air temperature at -7 °C whereas it was about 12-14% with the intake air heating. Reduced fuel injection quantity and improved fuel combustion with the intake air heating are the reasons for the reduction in the total particulate mass. Also, the mass of particulate generated increased sharply at the later stage of the EUDC which was caused by the increased accumulation particulate number which accounted for a large amount of total particulate mass. Moreover, the engine produces small number of nucleation mode particulates and high number of accumulation mode particulates at the EUDC stage. During this period of time, the non-volatile carbonaceous particles increase and absorb the volatile particles to form accumulation mode particulates and reduce the nucleation mode particulates as a consequence. Under acceleration and low AFR engine conditions, more fuel is injected thus achieves high in-cylinder temperature. As a consequence, non-volatile carbonaceous particulates were burned which eventually reduced the accumulation mode particulates and promote the volatiles to form the nucleation mode particulates

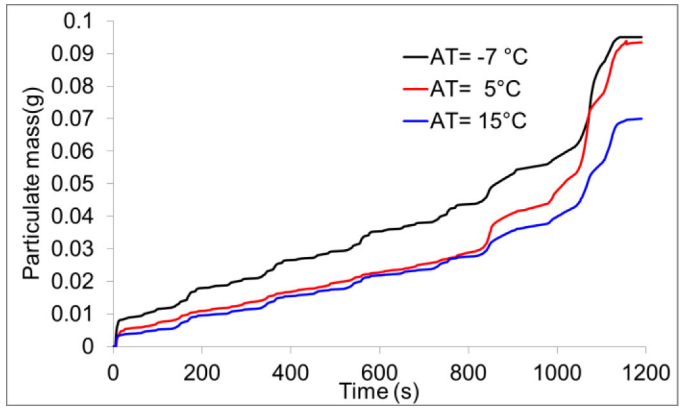



Fig 9. Particulate mass at different intake air temperatures

## Conclusions

A study has been conducted to investigate the effect of intake air temperature on transient cycle emissions from a CRDI diesel engine at cold ambient temperatures. A heater was installed in the upstream of the intake manifold to vary the intake air temperature and the NEDC tests were carried on a transient dynamometer test bench.

Intake air heating at cold ambient temperature conditions helped in evaporation of fuel and thereby reduced the engine cranking period. Fluctuation in torque was observed while starting of the engine and it was reduced during the progression of the test and the measured torque was almost closer to each other for the all tests. Higher fuel economy was achieved by intake air heating during the first part of NEDC and the variation in fuel consumption was decreased during later stages of the test. Intake air heating reduced the spikes of HC emissions during the cold start and at the intake air temperatures of 5° and 15° C reduced the first part of NEDC emissions by 40% and 65% respectively compared to that of at -7°C. The intake air temperatures and no exhaust gas recirculation increased the NOx spikes at the low ambient temperatures and the intake air heating reduced the NOx by 8.5% and 10% during the first part of NEDC, and an overall reduction in 3.5% and 5% achieved during the NEDC than that of at -7°C. The instantaneous emission values are almost close to each other during the later stages of the NEDC cycle and followed the similar trend. Relatively higher intake air temperatures reduced the diameter and number count of particles and the particulates of 10-23 nm size is accounted for ~45% for the all intake air temperature conditions. The particle number for the first part of NEDC was ~25% for -7°C intake air temperatures and was reduced to ~20% for the heated air supply. The particulate mass was significantly higher (~20% of NEDC) during initial stages of NEDC due to higher number of accumulation particulates at -7°C and was reduced to 12-14% by intake air heating.

In summary, implementation of intake air heating strategy in a CRDI diesel engine improved the cold start performance and reduced the fuel consumption of the engine as well as reduced the gaseous and particulate emissions significantly during the NEDC test at low ambient temperatures.

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## Contact


Prof. Hongming Xu
Head of Vehicle and Engine Technology Centre
School of Mechanical Engineering
University of Birmingham
Birmingham
B15 2TT, UK
h.m.xu@bham.ac.uk


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## Abbreivation

**AFR** - Air Fuel Ratio

**CC** - Cubic Centimetre

**CO** - Carbon Monoxide

**COV** - Coefficient of Variance

**DMS** - Differential Mobility Spectrometer

**ECU** - Electronic Control Unit

**EGR** - Exhaust Gas Recirculation

**EU** - European Union

**FMEP** - Frictional Mean Effective Pressure

**NEDC** - New European Driving Cycle

**NOx** - Nitrogen Oxides

**PAH** - Poly Aromatic Hydrocarbons

**PM** - Particulate Matter

**PMEP** - Pump Mean Effective Pressure

**PN** - Particulate Number

**SSD** - Size Spectral Density

**THC** - Total Hydro Carbon

**VOC** - Volatile Organic Fraction

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