공학석사학위논문

Emissions Characteristics of Light-Duty Diesel Engine during Transient Operation

승용 디젤엔진의 과도운전 시 배기 배출물 특성

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기계항공공학부

김 동 수

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지도교수 민 경 덕

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김 동 수

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위 원 장 고 상 근 (인)

부위원장 민 경 덕 (인)

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Abstract

Emissions Characteristics of Light-Duty Diesel Engine during Transient Operation

Dongsu Kim
Department of Mechanical and Aerospace Engineering
The Graduate School
Seoul National University

As concerns about global environment issues have been becoming more serious, emission regulations, especially for automotive industries, have been continuously strengthened. For example, the current emission legislation is EURO-5b but the upcoming regulation, EURO-6, mandates reduction of NOx emissions by 55.6 % compared to the current standard while maintaining the same level of PM emissions. However, despite all the efforts to cut-down the emission level, the real world emission level has not dropped down much. This is due to the fact that the emission test cycle does not represent real-life driving conditions very well. As a result, emissions characteristics during transient operation are drawing more attention from automotive engineers.

Therefore, in this research, emissions characteristics of light-duty Diesel engines during transient operation were studied. In order to measure NOx and PM emissions

at both steady and transient states, Cambustion's DMS-500 and CLD-500 were used along with Horiba's exhaust gas analyzer. In addition, an EGR estimation model was adopted to measure EGR rates at transient states. For the first acceleration part of EUDC, transient NO emissions were lower than that of steady states due to increased EGR rate caused by higher boost pressure as a result of turbo-lag from a VGT. As EGR or boost pressure were matched, discrepancy in NO emissions between steady and transient states was disappeared. The opposite phenomenon was true for PM emissions considering NOx-PM trade-off. Also, an emission peak was observed for PM emissions due to instantaneously richer mixture yielded by delay in response of the amount of air. For deceleration, exactly opposite trend was found except that there was no emission peak.

Furthermore, from post EURO-6 onward, harsher transient operation is going to be included in the emissions test cycle; hence, it is crucial to study emissions characteristics at sudden and rapid acceleration such as tip-in which frequently occurs at over-taking. As for tip-in, steady state NO emissions were higher than that of transient NO emissions. However, unlike normal transient operation, NO peak was observed for tip-in acceleration due to difference in the amount of air caused by turbo-lag of a VGT. Also, a PM emission peak was observed for tip-in operation but the order of magnitude was so small compared to the peak level for the conventional

acceleration case.

In addition, as vehicles operate under various environment temperature, intake temperature was varied to simulate both cold and hot conditions. When different surrounding temperatures rather than the ambient condition were applied, EGR was no longer supplied causing drastic increase in NO emissions while almost zero PM emissions were observed. Also, no emission peak was observed under non-ambient temperature.

Keywords: Light-duty Diesel engine, NOx, PM, Steady state, Transient state, NEDC, tip-in, temperature

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Acronym

BMEP	Brake Mean Effective Pressure
CI	Compression Ignition
CLD	Chemi-Luminescence Detector
CO_2	Carbon dioxide
DMS	Differential Mobility Spectrometer
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EUDC	Extra Urban Driving Cycle
FTP	Federal Test Procedure
NEDC	New European Driving Cycle
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen Oxide
O_2	Oxygen
PM	Particulate Matter
PMR	Power to Mass Ratio
RPM	Revolution Per Minute
SI	Spark Ignition
VGT	Variable Geometry Turbine
WLTP	Worldwide harmonized Light vehicles Test Procedure

Chapter 1. Introduction

1.1 Research Background and Literature Review

Compression ignition (CI) engines are well known for superior thermal efficiency and low carbon dioxide (CO_2) emissions compared to spark ignition engines (SI). However, nitrogen oxides (NOx) and particulate matter (PM) emissions are the major drawback of CI engines [1].

Over the past decades, environment issues such as depletion of fossil fuel and global warming have drawn much of global attention. As a result, stringent emission legislations have particularly been imposed on automotive industries to reduce exhaust gas emissions, especially NOx and PM. The current emission regulation is EURO-5b but upcoming emission standard, EURO-6, which is going to be enforced by September 2014 mandates reduction of NOx emissions as a half of the current level while maintaining the same level of PM emissions for light-duty Diesel vehicles [2].

In order to fulfil such demand, various after-treatment systems are used to cut down or capture emissions. In general, exhaust gas recirculation (EGR) is used for NOx emissions and Diesel particulate filter (DPF) is applied for PM emissions.

EGR reduces NOx emissions in two ways; one is by dilution and the other by acting as a thermal barrier. Formation of NOx depends on oxygen (O_2) concentration and in-cylinder combustion temperature. Higher O_2 concentration and combustion temperature stimulate formation of NOx [3]. When more EGR is adopted, in-cylinder O_2 concentration is effectively reduced (dilution effect) and heat capacity of the mixture is increased, thereby lowering the in-cylinder combustion temperature (thermal effect) [4, 5]. However, use of higher EGR rate inevitably yields higher PM emissions due to NOx-PM trade-off relation.

Therefore, a sieve-like DPF is utilized to deal with increased PM emissions. PM is deposited on the surface of a DPF and once PM is deposited enough, regeneration takes place to oxidize the accumulated PM. To favor PM oxidation, amount of post injection is increased to rise exhaust temperature up to 650 ℃. Nowadays, catalyzed particulate filter which is a combined after-treatment device of Diesel oxidation catalyst (DOC) and DPF is installed instead of DPF to minimize the increase in the amount of post injection to rise the exhaust temperature above the threshold point by utilizing the heat energy produced from the exothermic reaction taking place at DOC. In that way, it can minimize penalty on fuel consumption so that it can cope with tightened fuel economy restriction as well [6].

However, despite all the efforts to reduce exhaust emissions, real world emissions level have not dropped down in accordance with the stricter emission laws. This is due to the fact that driving cycle modes for emission tests such as NEDC and FTP-75 do not represent the real world driving situation well. In a real life driving condition, transient operations such as tip-in acceleration and rapid deceleration frequently occur. For tip-in operation, EGR supply is suddenly dropped down causing dramatic soaring of NOx emissions [7]. Although the emission test cycles do include transient operation section, both acceleration and deceleration periods are long and steadily changed. Consequently, for post EURO-6 onward, a new driving cycle mode called worldwide harmonized light vehicles test procedure (WLTP) which covers harsher transient operation is going to be introduced [2]. In WLTP, test cycles differ according to vehicles' power to mass ratio (PMR). Vehicles with higher PMR are required to go through more brutal transient conditions. By doing so, much realistic driving cycle will be simulated so that the real life emission level would be similar to the laboratory emission standard.

Hence, numerous researches have been conducted on Diesel transient operations but most of them focused on the acceleration part. Thus, in this research, not only emissions characteristics during acceleration are studied but also emissions characteristics during deceleration are examined compared to the steady state operations. In this study, transient operations are classified into two parts. The first part concentrates on comparison of the emission level between steady and transient states at the first acceleration section of EUDC which represents highway driving conditions of NEDC. The second part focuses on tip-in operation.

Furthermore, considering the fact that emission test cycles are only performed at room temperature condition, environment temperature was controlled to simulate cold and hot surrounding so that change in emissions characteristics can be observed. This is because vehicles operate under various environment conditions in a real life.

1.2 Objective

In real driving conditions, transient operation dominates steady state operation and NEDC actually tried to reflect this fact by having many transient cycles. NEDC consists of four repeated urban driving cycles which last for 780 seconds and EUDC which describes motorway driving patterns for last 400 seconds. However, as most of Diesel engines are now equipped with a turbocharger, turbo-lag inevitably occurs during transient operations. In general, turbo-lag deteriorates both drivability and emissions [8-12].

The objective of this research can be divided into two parts. The first part is to study NOx and PM variation between steady and transient states, and find the possible cause of discrepancy. The second part is to study NOx and PM variation under different environment temperature, and compare the operation conditions at the stated temperature.

Chapter 2. Experimental Setup and Condition

2.1 Experimental Setup

Figure 2.1 represents the engine used for the experiment. Specification of the engine is listed in Table 2.1 and the schematic of the experimental setup is depicted in Figure 2.2. Displacement and layout of the engine is 1.6 L in-line 4 cylinder Diesel with a solenoid common rail injection system. AVL dynamometer was connected to the engine to control both speed and load. Fuel flow rate was measured by Coriolis type flow meter (OVAL) and fuel temperature was controlled to be 40 ℃. An absolute pressure transducer (Kistler, 4045A5) and a relative pressure transducer (Kistler, 6055Bsp) were used to measure the ambient pressure and in-cylinder pressure, respectively. Signals from the pressure transducers were recorded by a Labview based data acquisition system with a scale of one crank angle for 100 cycles. Cambustion's DMS 500 and CLD 500 which are capable of measuring exhaust emissions at transient state were used to analyze PM emissions, especially mass of PM, and NOx emissions, respectively. For the purpose of the research, only upstream emissions were measured.

Figure 2.1 4 cylinder 1.6 L Diesel engine

Table 2.1 Specification of the engine

Criteria	Specification
Layout	In-line 4 cylinder 1.6 L
Maximum power (hp / rpm)	126 / 4,000
Maximum torque (kgm / rpm)	26.6 / 1,900 ~ 2,750
Bore (mm)	77.2
Stroke (mm)	84.5
Displacement volume (cc)	1,582
Compression ratio	17.3

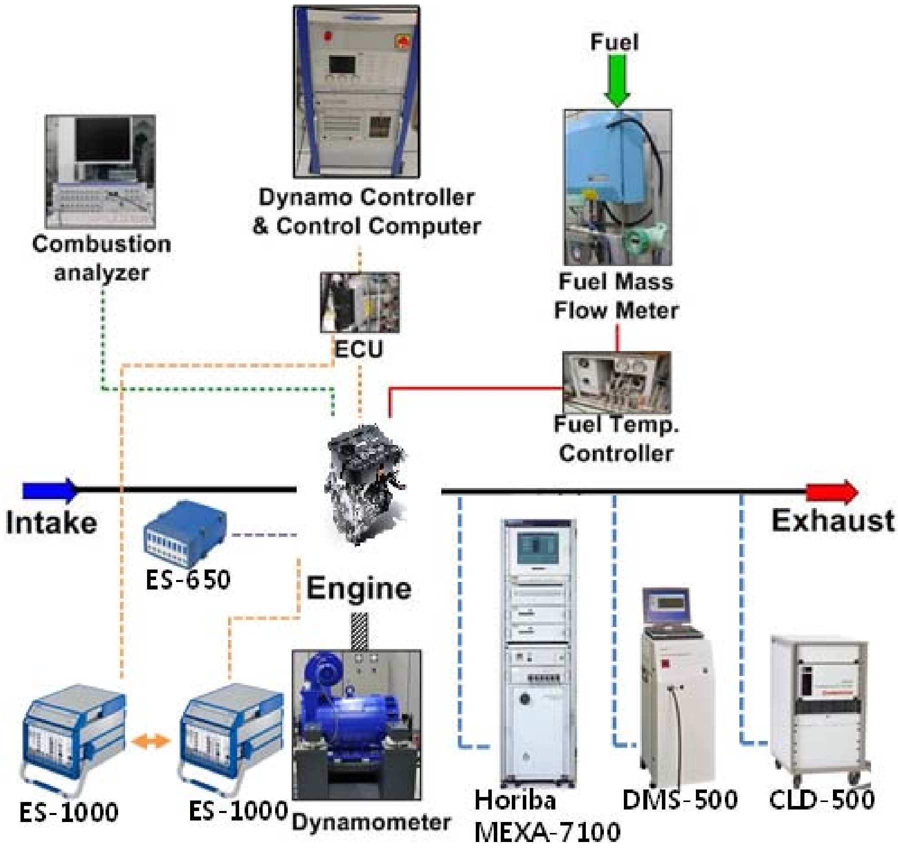

Figure 2.2 Schematic of experimental setup

2.2 Experimental Condition

Figure 2.3 shows NEDC profile and the section marked with red box indicates the experimental case for NEDC experiments. The chosen region is the first acceleration period of EUDC part which represents motorway driving cycles of NEDC. Figure 2.4 represents the change in engine speed and the amount of fuel injection during the acceleration. Among the transient sector, 6 steady points were selected to compare emissions characteristics between transient states and steady states. Detailed information about transient and steady conditions are described in Table 2.2 and 2.3, respectively. In addition, in order to determine transient emissions characteristics, deceleration experiment was also conducted. Experimental conditions for deceleration were same as acceleration but in opposite order as depicted in Figure 2.5.

Similar procedure was adopted for tip-in experiments as NEDC experiments. However, unlike NEDC case, 4 steady state points were compared with transient state. In this study, tip-in is defined as acceleration that produces a NOx peak. Tip-in operation was found by a trial and error method and specific experimental conditions for tip-in acceleration are explained in Table 2.4. Figure 2.6 is the graphical representation of experimental conditions for tip-in acceleration.

Finally, intake temperature was varied by a ventilator which could supply both cold and hot air to create cold and hot environment conditions. Furthermore, intercooler temperature was controlled to match the surrounding temperature. Temperature variation was applied to both NEDC and tip-in cases. Specific intake and intercooler temperature are listed in Table 2.5.

EGR rate was estimated by Lee's EGR model [13] where intercooler outlet temperature, EGR outlet temperature and manifold inlet temperature were measured by R-type thermocouples to calculate the EGR rate.

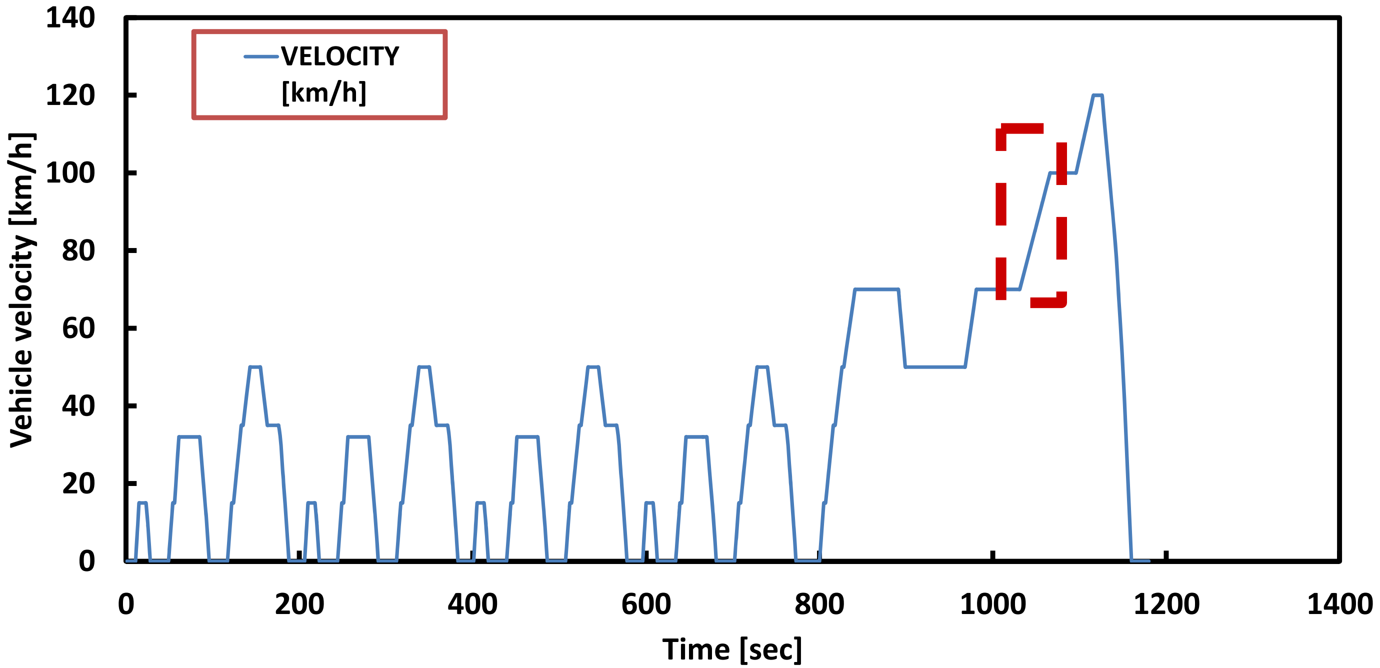

Figure 2.3 NEDC profile & selected experimental region

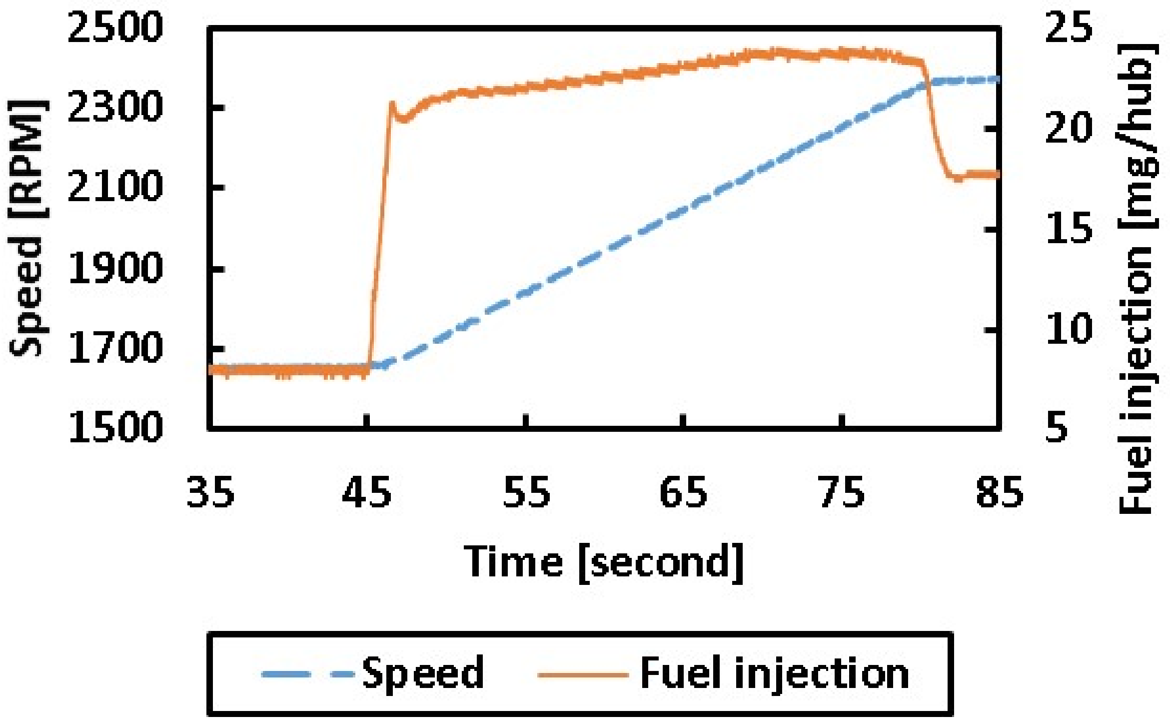

Figure 2.4 NEDC experimental condition

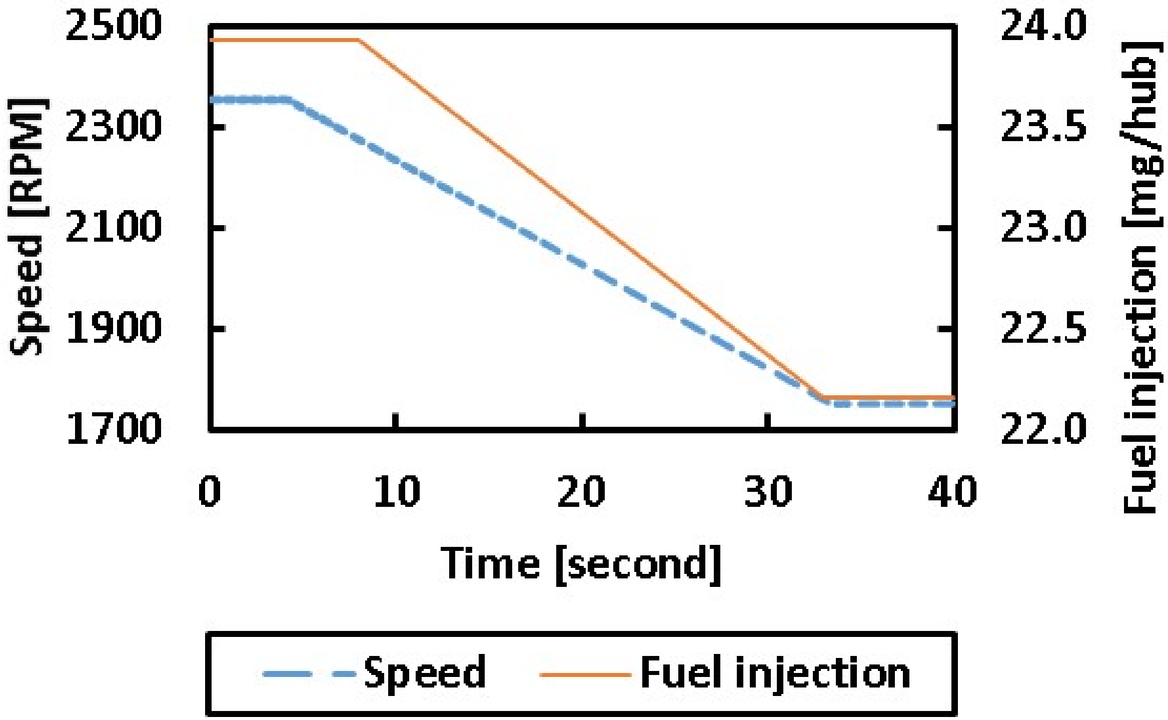

Figure 2.5 Experimental condition for NEDC deceleration

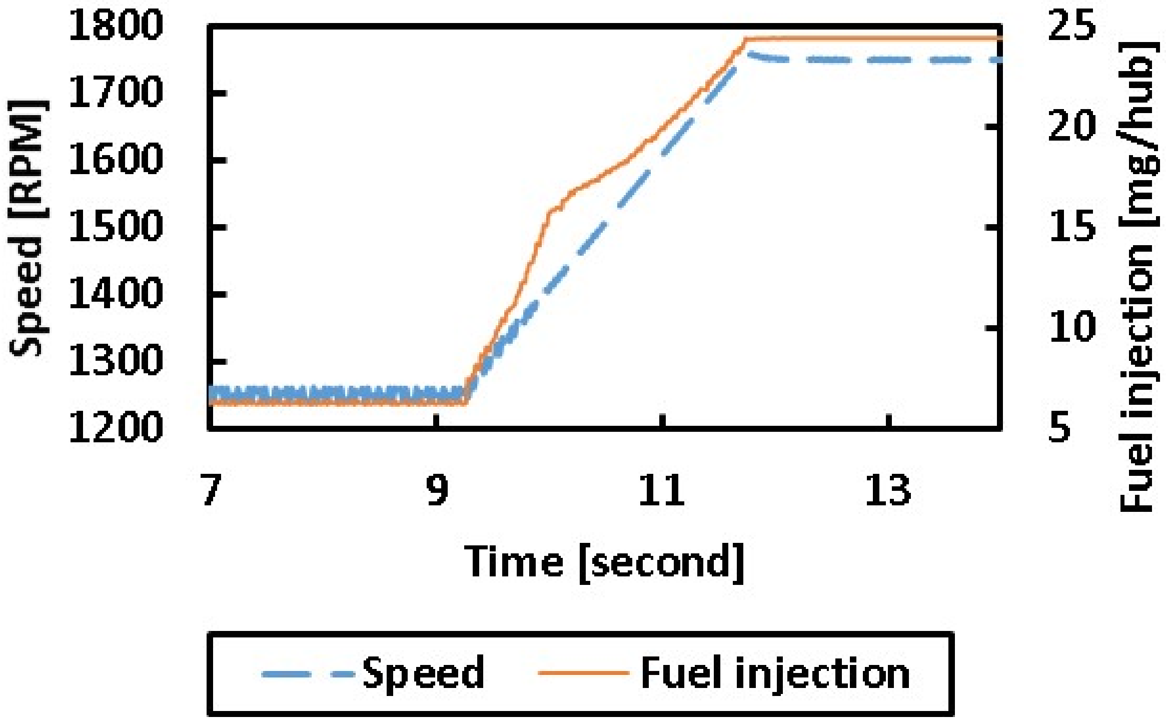

Figure 2.6 Experimental condition for tip-in operation

Table 2.2 Experimental conditions for the first acceleration part of EUDC

Initial speed (rpm)	1,650
Terminal speed (rpm)	2,370
Initial load (BMEP, bar)	2.5
Terminal load (BMEP, bar)	10
Ramp time (second)	33

Table 2.3 Experimental conditions for steady states

Case NO.	Speed (rpm)	Load (BMEP, bar)
1	1750	2.5
2	1850	4
3	1950	5.5
4	2050	7
5	2150	8.5
6	2250	10

Table 2.4 Experimental conditions for tip-in acceleration

Initial speed (rpm)	1,250
Terminal speed (rpm)	1,750
Initial load (BMEP, bar)	2.5
Terminal load (BMEP, bar)	10
Ramp time (second)	2.5

Table 2.5 Intake and intercooler temperature

	Ambient	Cold	Hot
Intake temperature (℃)	25	10	40
Intercooler temperature (℃)	30	10	50

Chapter 3. Experimental Result and Discussion

3.1 NEDC transient and steady state comparison

3.1.1 Acceleration

In general, when vehicles accelerate, amount of EGR supply is decreased to produce required power. Therefore, whenever acceleration takes place, there will always be increase in NOx emissions compared to steady states [7, 14, 15]. NOx emissions consist of nitrogen monoxide (NO) and nitrogen dioxide (NO_2) where NO is the major product and NO_2 is the minor product [3, 12, 16].

However, NO emissions at transient states were lower than that of steady states as shown in Figure 3.1. This was due to the fact that more EGR was supplied during the transient operation as represented in Figure 3.2. Therefore, steady state EGR rates were tuned to match EGR rates at transient conditions. As a result, transient and steady state NO emissions were almost identical to each other as depicted in Figure 3.3 meaning that NO discrepancy was caused by the difference in the EGR rate. Thus, it is important to find out what factors yielded such phenomenon. Therefore, it is necessary to know the EGR supply mechanism.

EGR supply is controlled by an EGR valve as shown in Figure 3.4 but the amount of EGR is actually determined by the amount of intake air which is calculated by engine control unit (ECU). This means that the stated EGR discrepancy could possibly be caused by difference in the amount of intake air. As aforementioned in the objective section, when turbocharged vehicles undergo transient operation, there will always be turbo-lag. Turbo-lag is defined as time delay in actual power output to follow desired power outcome [18]. Therefore, turbo-lag for this case where there is difference in the amount of air could be caused by boost pressure. This is because in a constant volume cylinder, once the amount of air is determined, the rest of the volume is filled with EGR meaning that density of the air differs by the applied boost pressure.

Consequently, boost pressure at transient and steady states were compared, and boost pressure at steady conditions were lower than that of transient states as represented in Figure 3.5. This confirms that higher EGR rate supplied during the transient operation was due to higher boost pressure compared to the steady state operation. Thus, it is crucial to find out parameters that yielded difference in the boost pressure. In fact, discrepancy in boost pressure was caused by the turbocharger for the used engine. The engine was equipped with a variable geometry turbine (VGT) whose vane was controlled by membrane vacuum actuators. The principle of VGT working mechanism is to control vane area in accordance with mass flow rate of the air entering the turbocharger [19]. Thus, when there is an increase in air mass flow rate, vane opens up to maintain the target boost pressure. However, in this case, VGT response was not fast enough to follow the desired value. Consequently, even though the mass flow rate of the air was increased, the vane did not open up due to slow response time; hence, boost pressure shot up yielding higher boost pressure than necessary. Therefore, boost pressure at steady states was calibrated to be the same as the boost pressure at transient states. As a result, steady state NO emissions were similar with transient NO emissions and, hence, EGR rates were also pretty much the same as depicted in Figure 3.6 and 3.7, respectively. Thus, by comparing NO emissions for both EGR and boost pressure tuned results, the plausible factor which yielded discrepancy in NO emissions between steady and transient conditions was the difference in the EGR rate caused by higher boost pressure as a result of turbo-lag.

Unlike NO emissions, steady state PM emissions were lower than that of transient PM emissions, reflecting NOx-PM trade-off, and a peak value was observed as shown in Figure 3.8. In order to find reasons for the PM peak, it is essential to know formation principles of PM. PM emissions are favored at locally rich and low combustion temperature region whereas NOx emissions are favored at locally lean and high combustion temperature condition as represented in Figure 3.9 [21]. From the stated formation mechanism, it could be deduced that richer mixture was formed instantaneously, thereby producing a PM peak. Therefore, air and fuel response were investigated to check a sudden change in equivalence ratio. When there was a change in throttle position, amount of fuel injection altered in accordance with the variation in throttle position. However, there was about 1 second delay in amount of intake air to respond to the change in throttle position as indicated in Figure 3.10, thereby forming relatively richer mixture for that instant causing soaring of PM emissions as depicted in Figure 3.11.

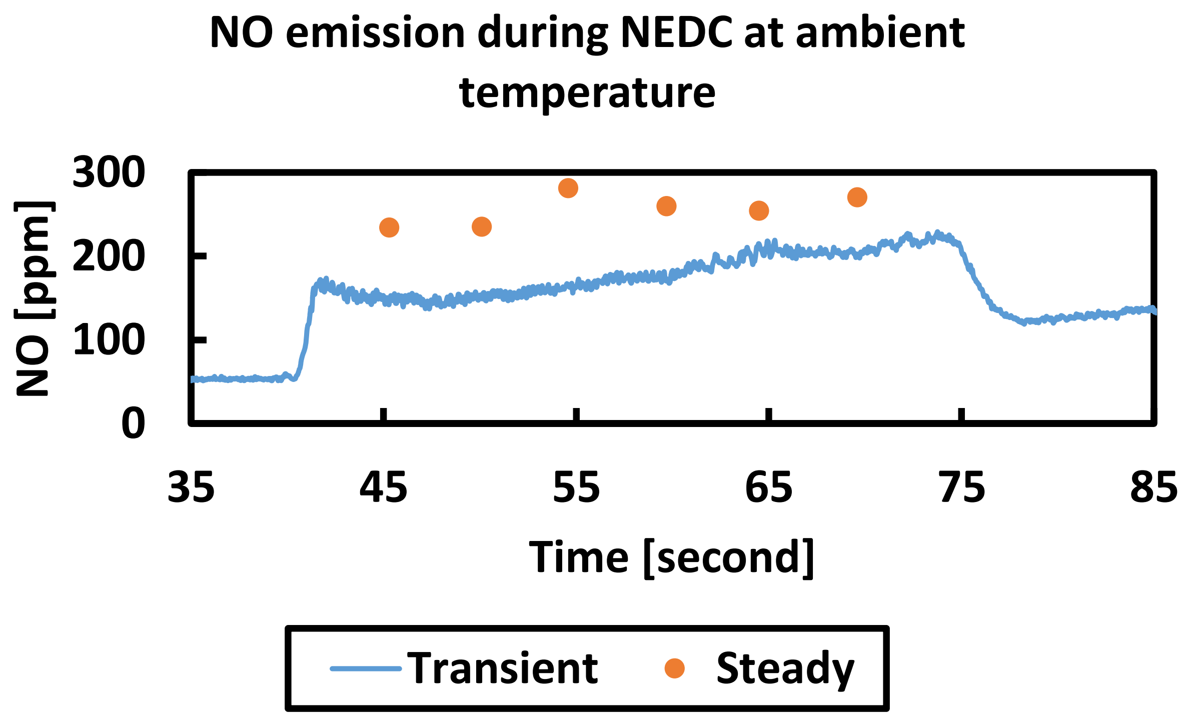

Figure 3.1 NO emissions during NEDC at ambient condition

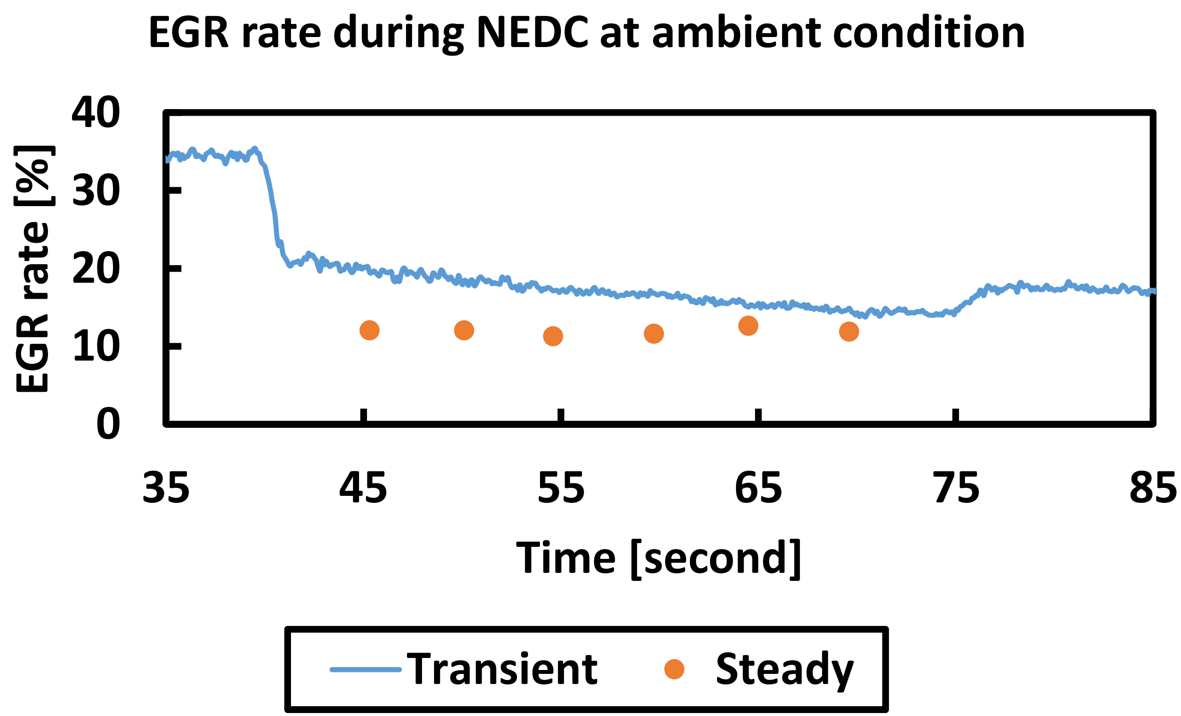

Figure 3.2 EGR rates during NEDC at ambient condition

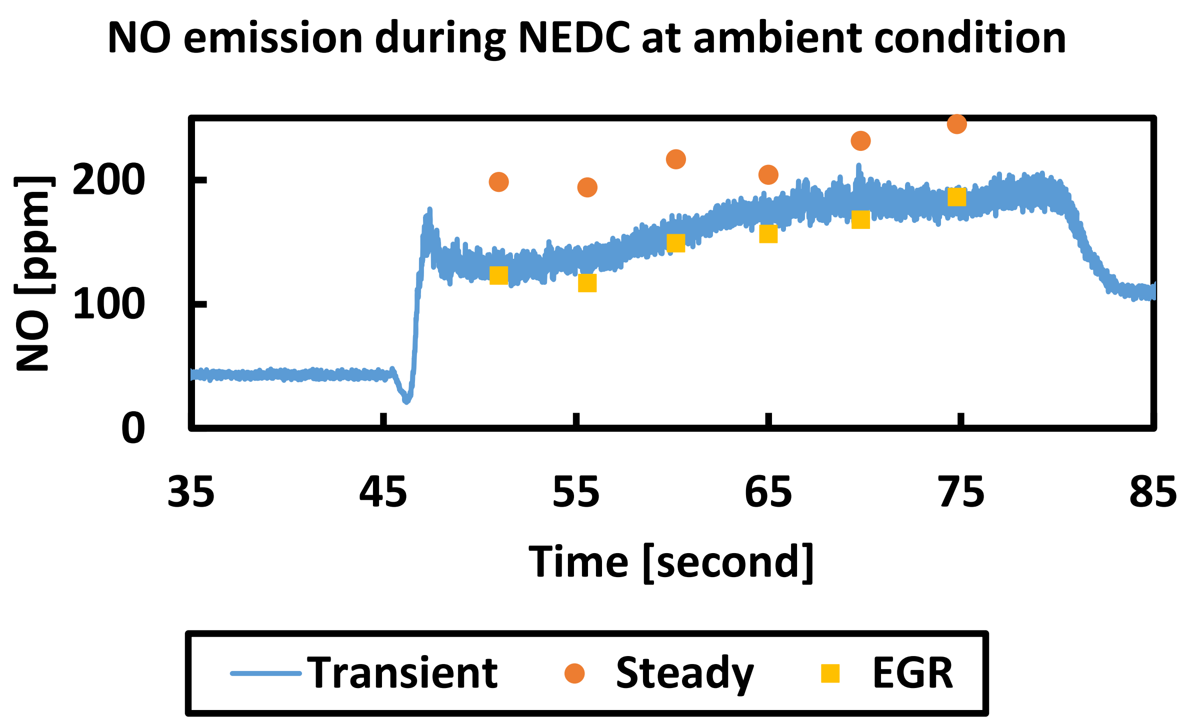

Figure 3.3 NO emissions after EGR matching

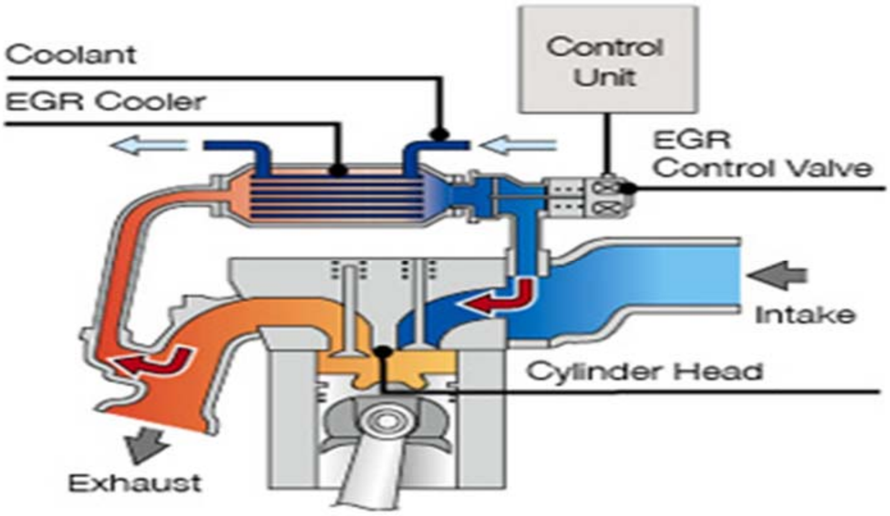

Figure 3.4 EGR supply mechanism [17]

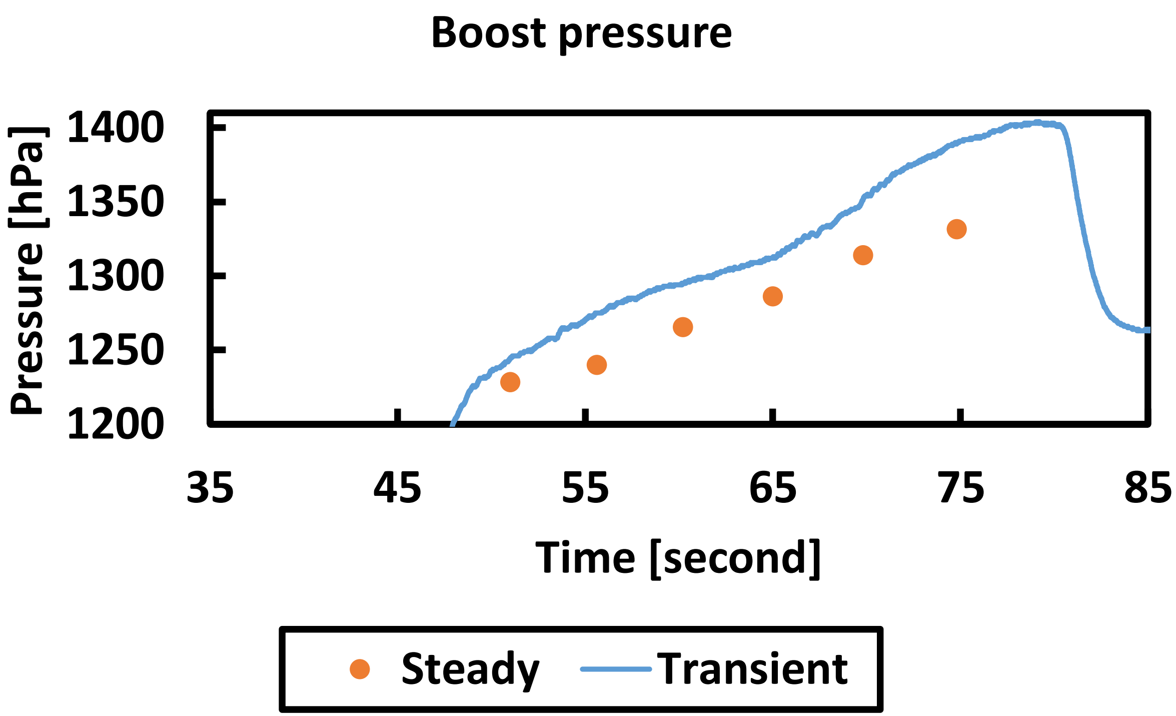

Figure 3.5 Boost pressure during NEDC at ambient condition

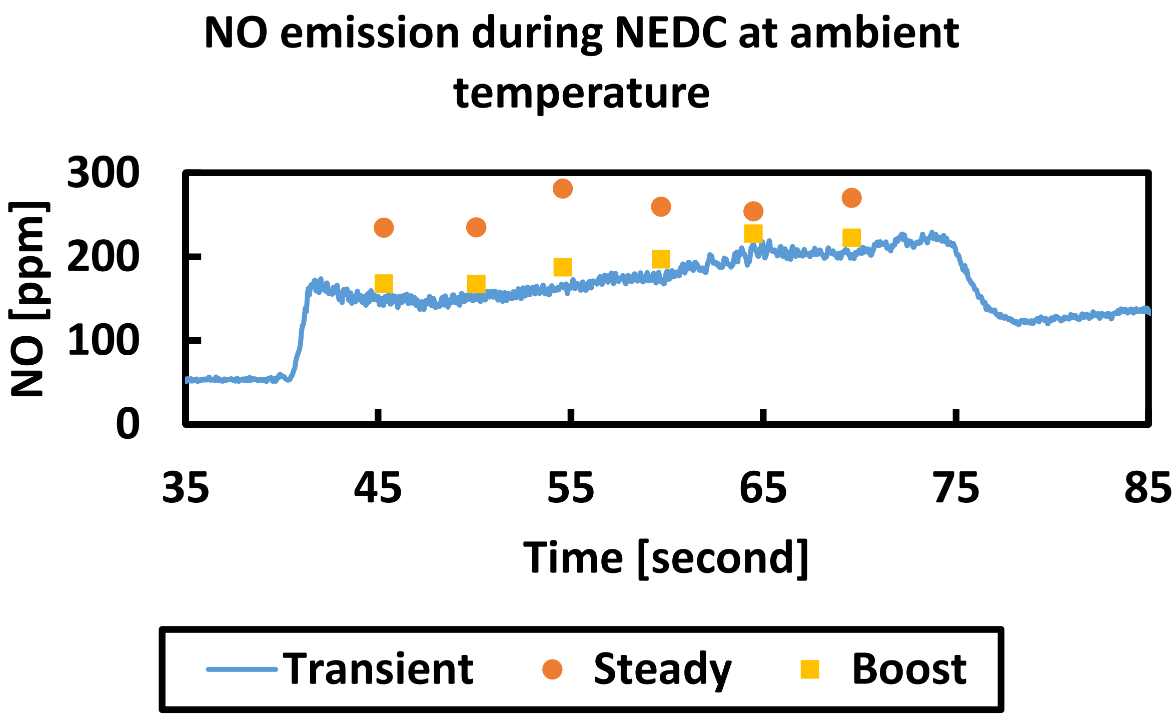

Figure 3.6 NO emissions after boost pressure matching

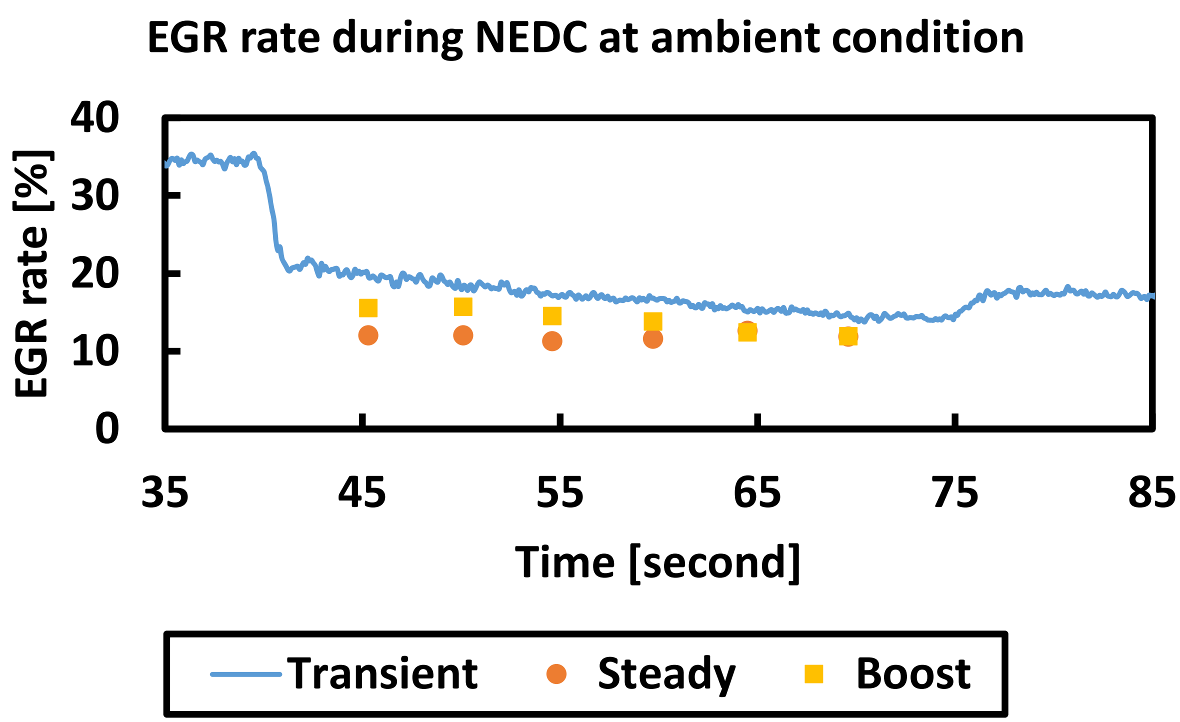

Figure 3.7 EGR rates after boost pressure matching

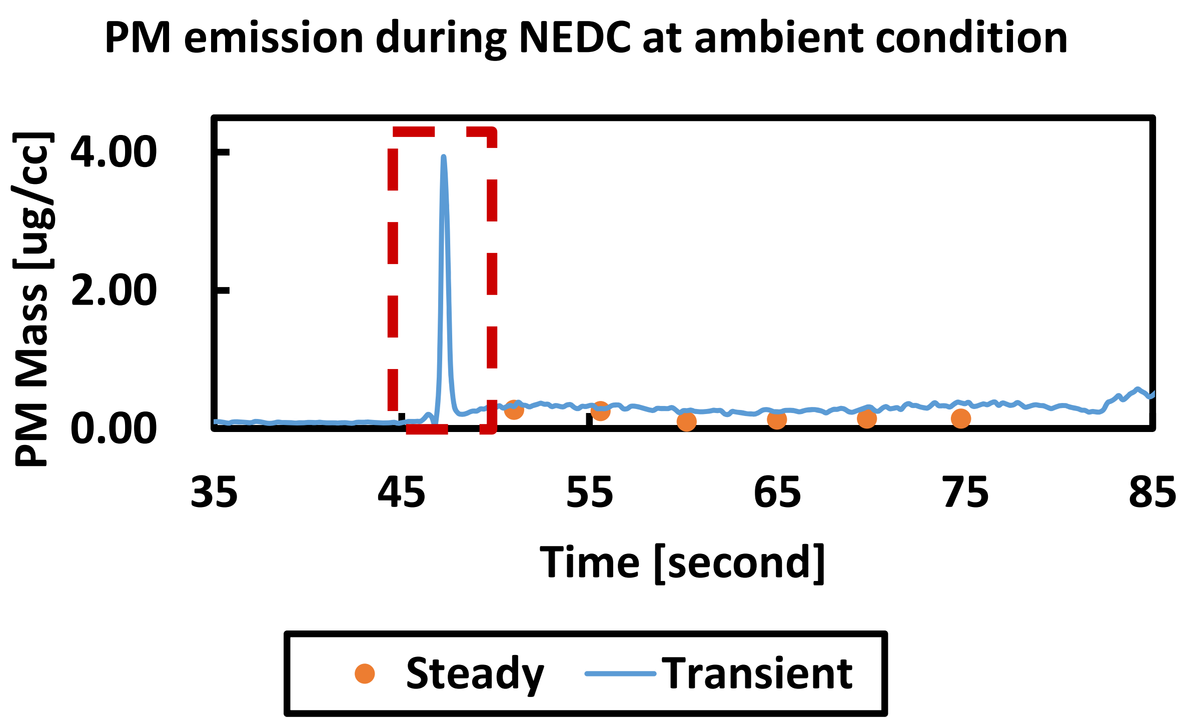

Figure 3.8 PM emissions during NEDC at ambient condition

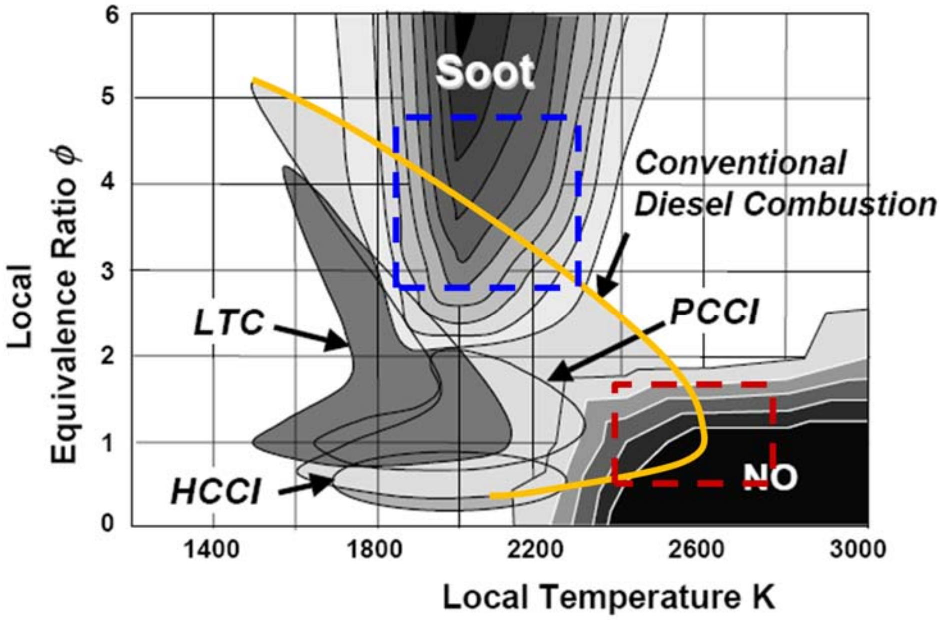

Figure 3.9 NOx-PM trade-off [20]

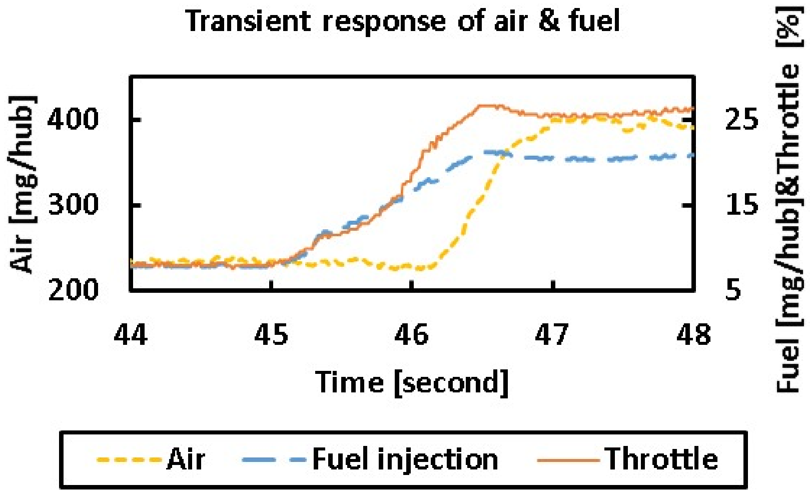

Figure 3.10 Response of air and fuel

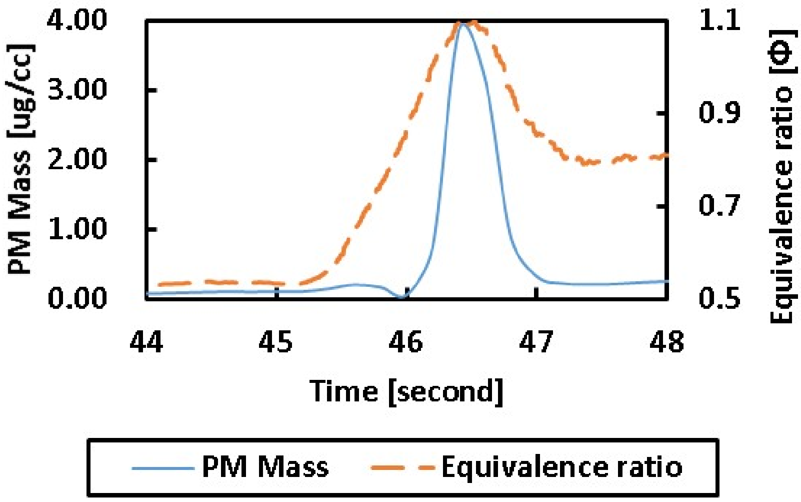

Figure 3.11 Change in equivalence ratio and mass of PM

3.1.2 Deceleration

In order to verify emissions characteristics during transient operation, a deceleration experiment was performed. If the trend observed for acceleration is the innate transient characteristics, then the opposite phenomenon should be noticed for deceleration.

Steady state NO emissions were lower than that of transient NO emissions as shown in Figure 3.12 and this was due to higher boost pressure for steady states compared to transient states as indicated in Figure 3.13. The reason for such phenomenon was because of slow response time of the VGT which was explained in section 3.1.1 but the causes were opposite. For deceleration, when the air mass flow rate was decreased, the vane was supposed to be closed to maintain the target boost pressure but due to the sluggish response, the vane remained open causing lower boost pressure than expected.

Nevertheless, considering both NOx-PM trade-off and PM emissions for acceleration, steady state PM emissions were higher than that of transient PM emissions as represented in Figure 3.14. In addition, no PM emission peak was observed for deceleration.

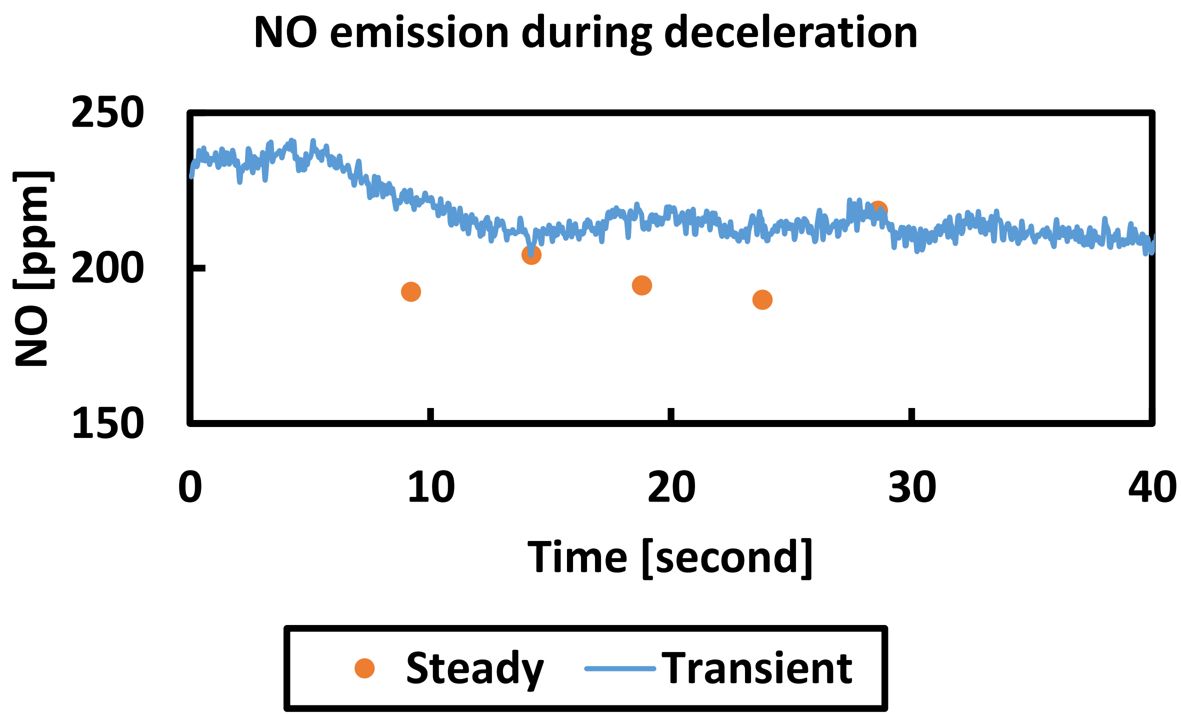

Figure 3.12 NO emissions during deceleration

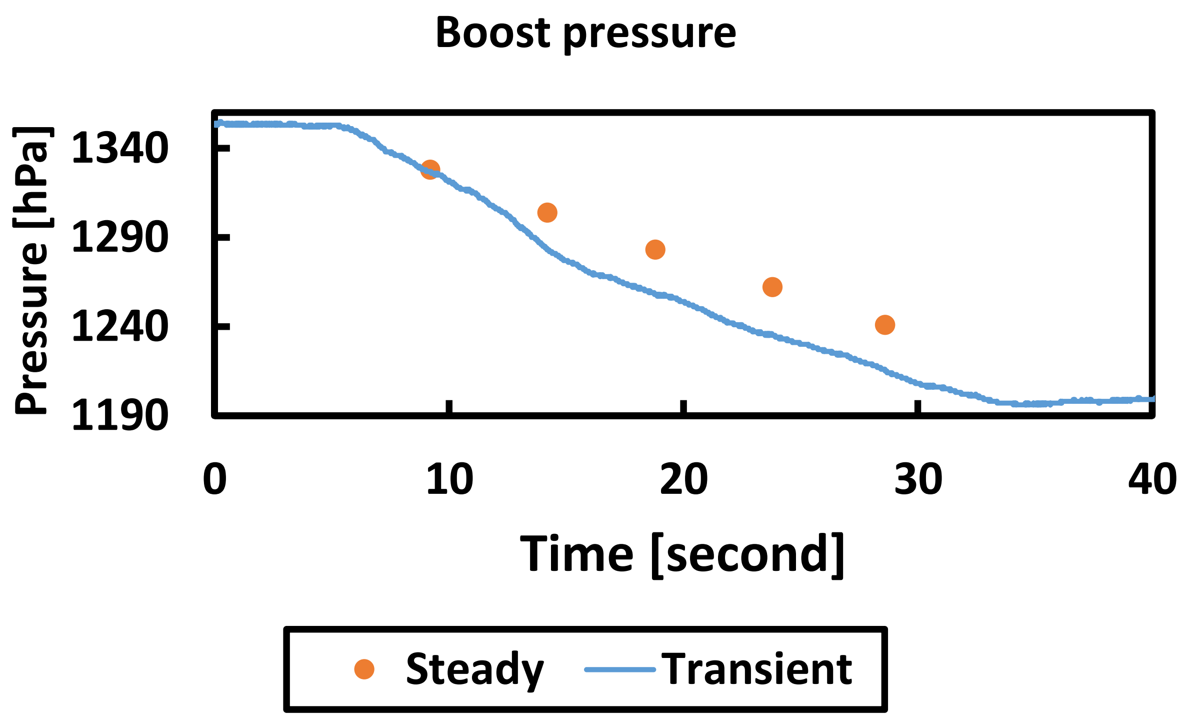

Figure 3.13 Boost pressure during deceleration

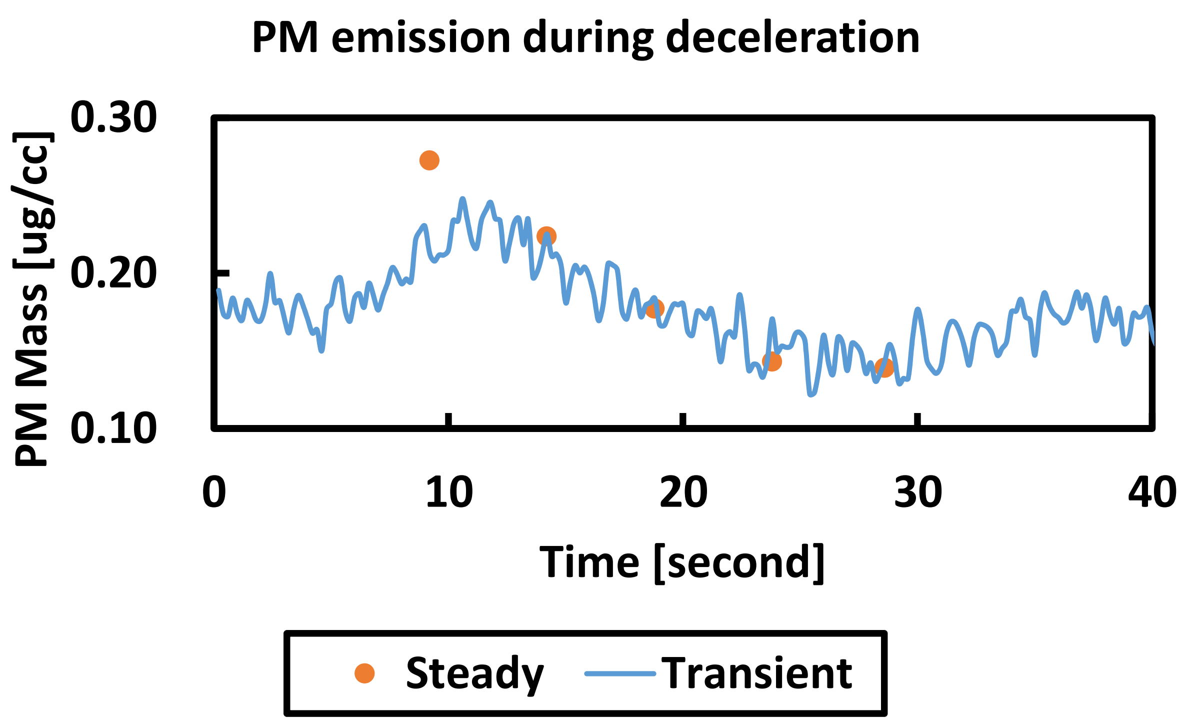

Figure 3.14 PM emissions during deceleration

3.1.3 Different environment temperature

Intake temperature is one of the most important factors influencing combustion, efficiency and emissions [22-25]. This is because volumetric efficiency and ignition delay are strongly affected by intake charge temperature [26, 27]. However, as emission tests are only conducted under room temperature condition whereas vehicles on the road actually experiences large variation in weather, it is crucial to evaluate how much alteration exists in emissions characteristics when different environment temperature was applied.

For both cold and hot environment conditions, EGR supply was no longer available resulting in drastic increase of NO emissions as shown in Figure 3.15 and 3.16, respectively. Compared to the ambient condition, NO emissions were escalated by a factor of 3 for both cold and hot surrounding temperature.

However, almost zero PM emissions were observed regardless of environment temperature as represented in Figure 3.17 and 3.18. This was due to no EGR condition which reflects NOx-PM trade-off well. In addition, unlike the standard condition, a peak in PM emissions was not detected for both cold and hot conditions.

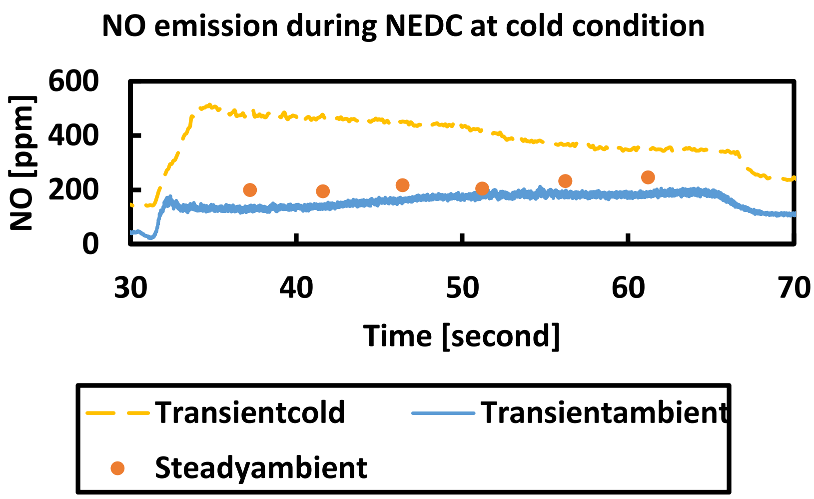

Figure 3.15 NO emissions during NEDC at cold condition

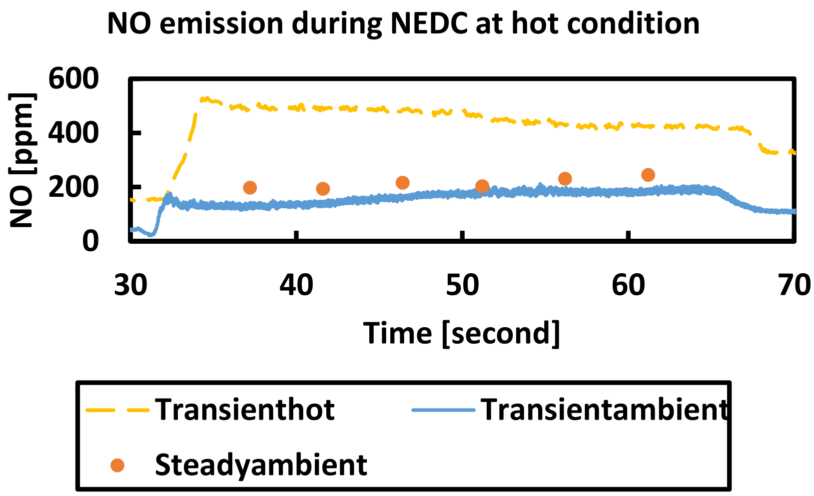

Figure 3.16 NO emissions during NEDC at hot condition

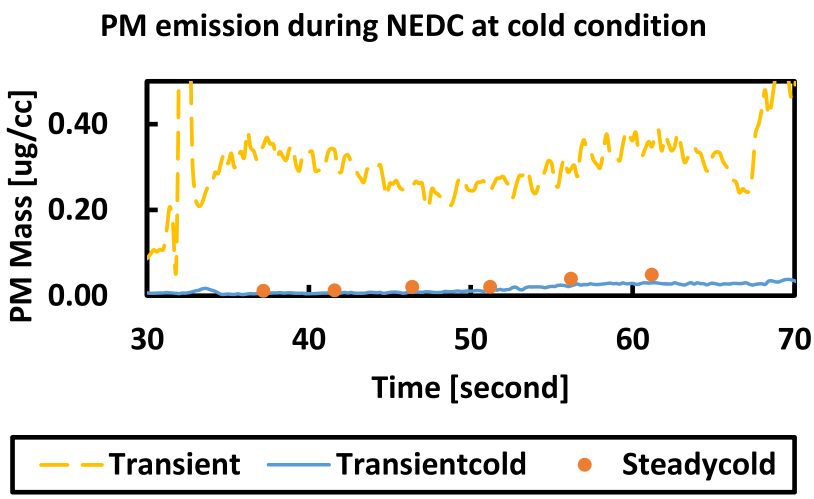

Figure 3.17 PM emissions during NEDC at cold condition

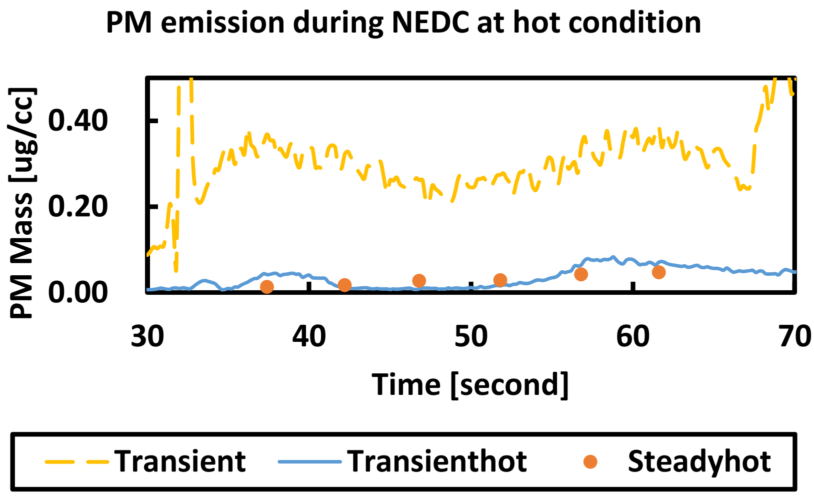

Figure 3.18 PM emissions during NEDC at hot condition

3.1 Tip-in operation

3.1.1 Ambient operation

In a real life, rapid acceleration, so called tip-in, frequently occurs. Tip-in operation is classified as acceleration which accompanies sharp throttle input [28]. Tip-in acceleration typically occurs when drivers require substantial amount of power in a short moment such as overtaking. As tip-in has the steepest acceleration gradient, it is the harshest transient operation, so it is vital to grasp the emissions characteristics during tip-in operation.

Unlike NEDC cases, a peak was observed for NO emissions while steady state emissions were still higher than that of transient states except for the peak point but the NO discrepancy between transient and steady states was relatively smaller compared to the NO discrepancy for NEDC cases as depicted in Figure 3.19. This was owing to comparatively smaller difference in EGR rates between transient and steady conditions as shown in Figure 3.20.

The reason for NO emission peak was related with turbo-lag but the causes were different compared to the turbo-lag occurred for NEDC cases. For NEDC acceleration, the slow response time in VGT vane caused the difference in emission level between transient and steady states but for tip-in operation, amount of air was the primary factor that yielded the emission peak as indicated in Figure 3.21. Similar amount of air was supplied for both transient and steady condition but at the peak, amount of air supply for the steady state was considerably insufficient compared to the transient state. Consequently, a NO peak was produced due to excess amount of air supply since NO emissions are largely dependent on in-cylinder O_2 concentration.

Similar to NEDC cases, a PM emission peak was observed for tip-in operation but the peak level was considerably smaller compared to the NEDC acceleration cases as represented in Figure 3.22. In fact, PM emission level is so low that it could be regarded as PM was almost not emitted at all. Therefore, it is meaningless to compare the difference in PM emissions between transient and steady states.

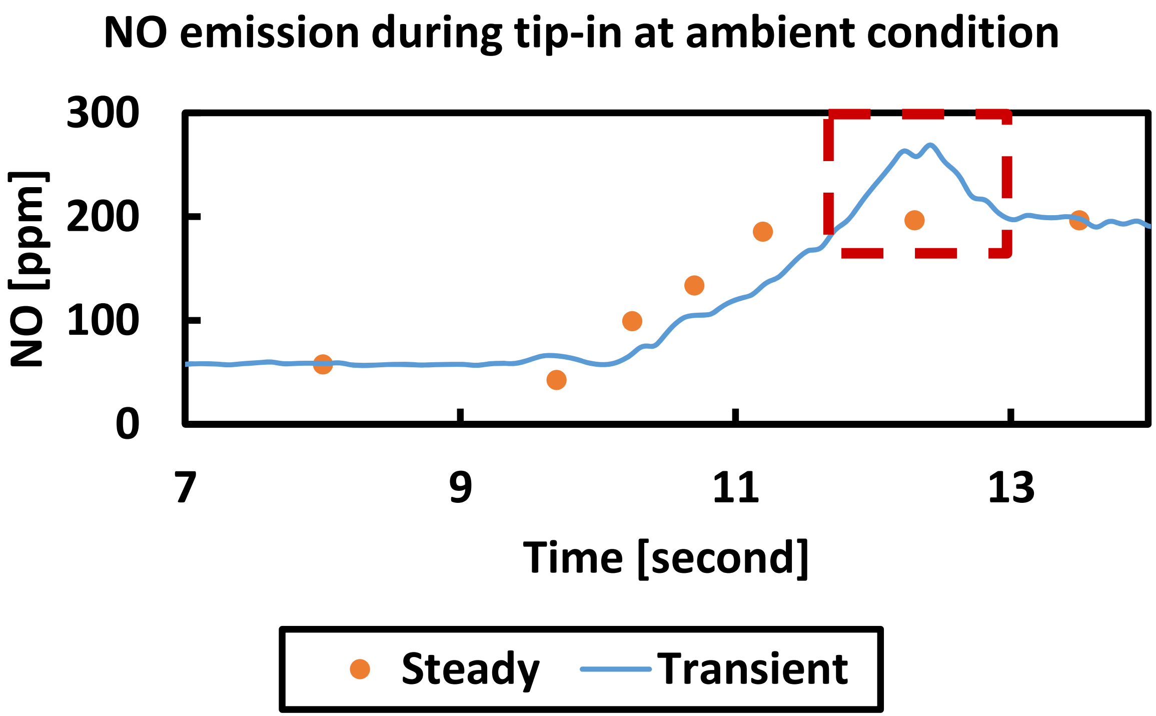

Figure 3.19 NO emissions during tip-in at ambient condition

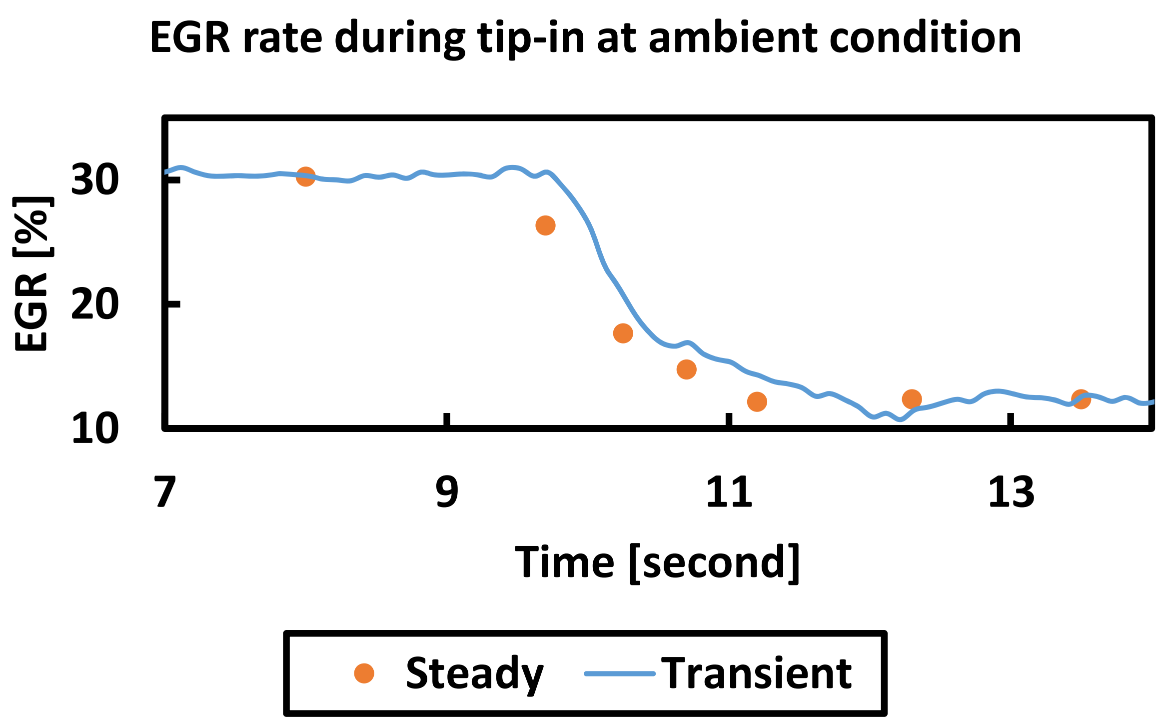

Figure 3.20 EGR rates during tip-in at ambient condition

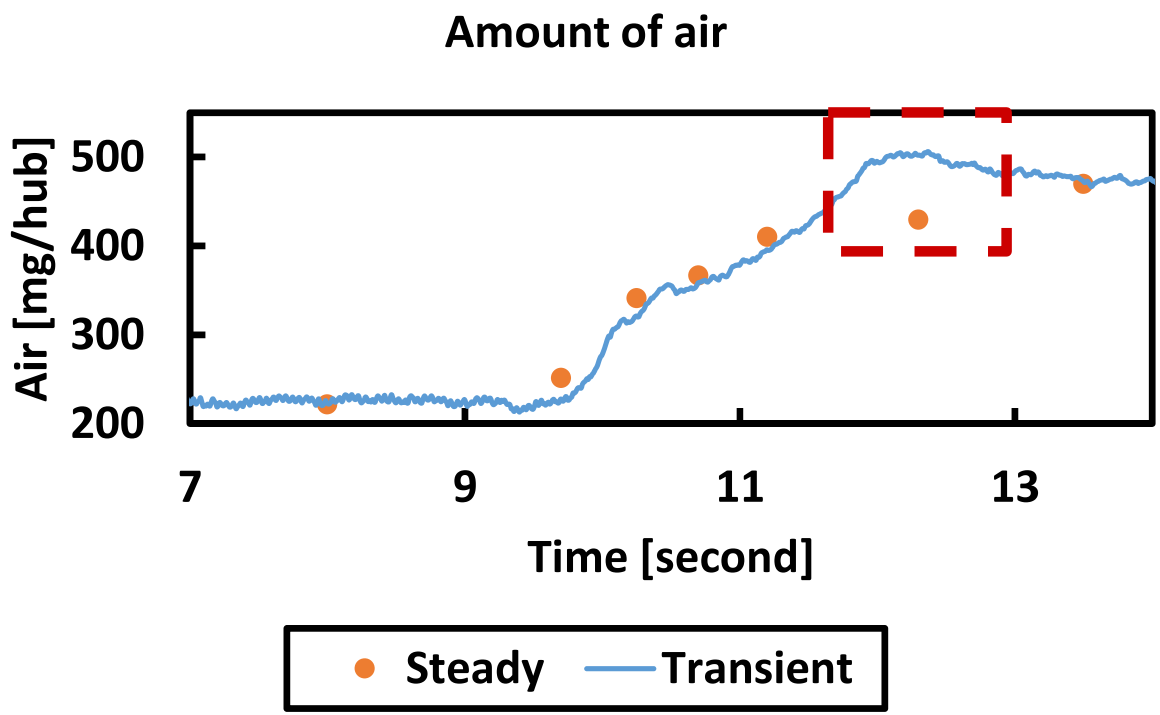

Figure 3.21 Amount of intake air during tip-in at ambient condition

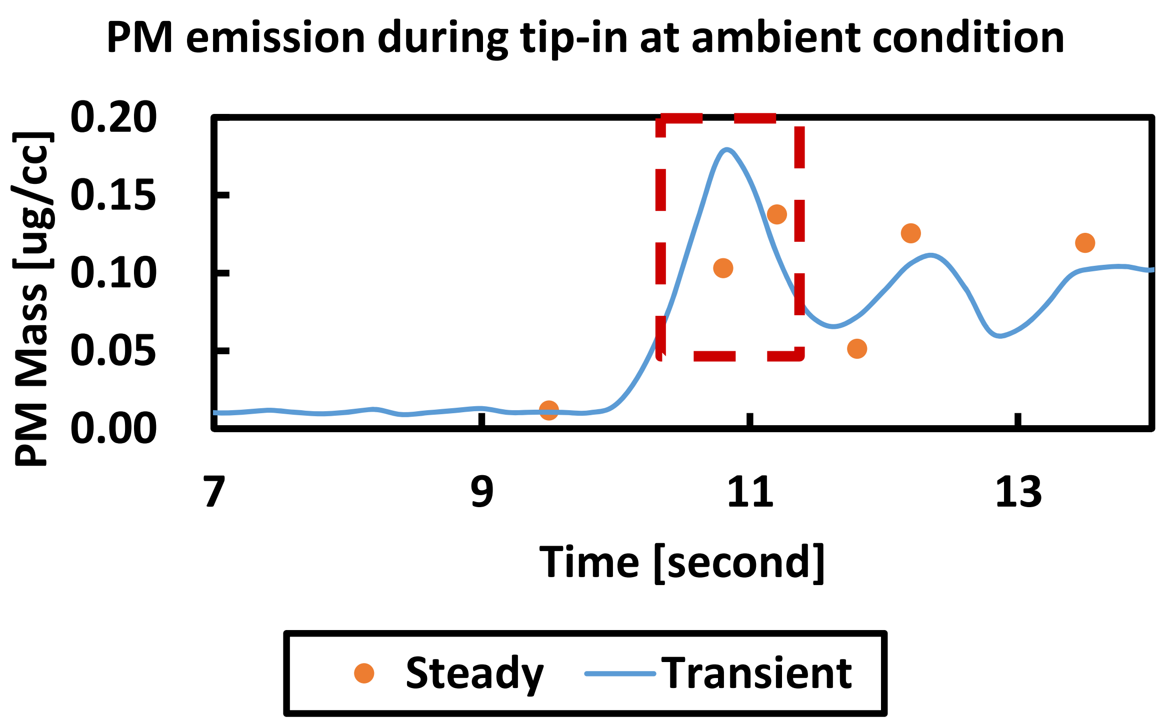

Figure 3.22 PM emissions during tip-in at ambient condition

3.1.2 Different environment temperature

Similar with NEDC, under different environment temperature, the same trend in emissions characteristics were observed for tip-in operation under various surrounding temperature. NO emissions were increased by a factor of 3 for both cold and hot intake temperature since EGR was no longer supplied as depicted in Figure 3.23 and 3.24, respectively. Furthermore, unlike the room temperature condition, NO peak was not produced.

For PM emissions, a peak was detected which contrast the results obtained from NEDC cases but the level is too small that it could hardly be called a peak. In fact, due to absence of EGR, it could be considered that almost zero PM emissions were observed for both cold and hot temperature conditions as shown in Figure 3.25 and 3.26, respectively.

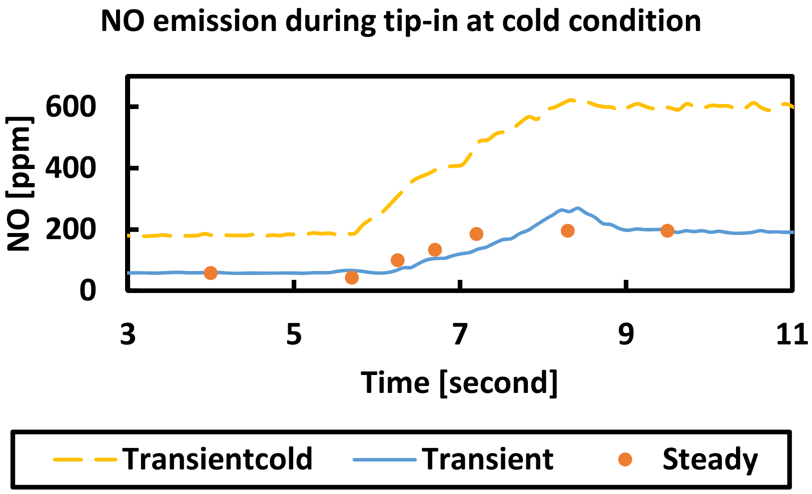

Figure 3.23 NO emissions during tip-in at cold condition

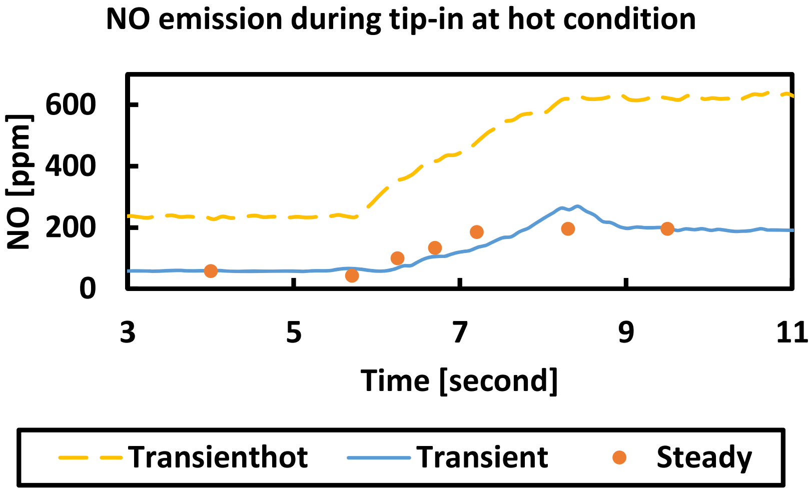

Figure 3.24 NO emissions during tip-in at hot condition

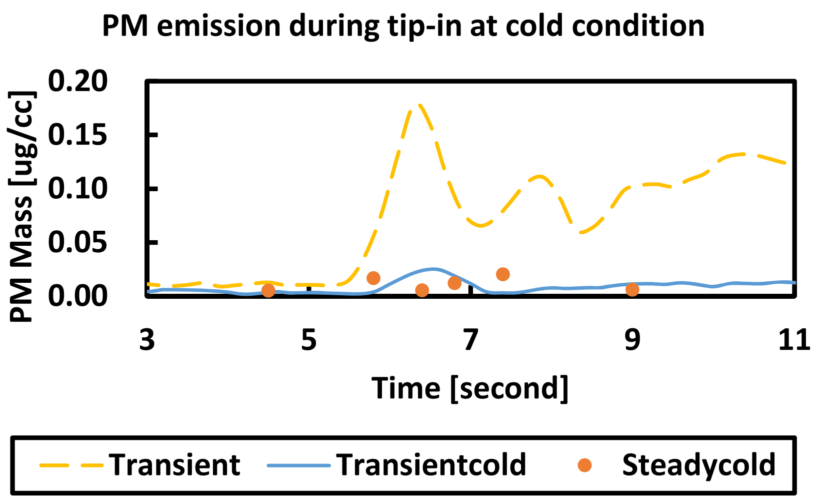

Figure 3.25 PM emissions during tip-in at cold condition

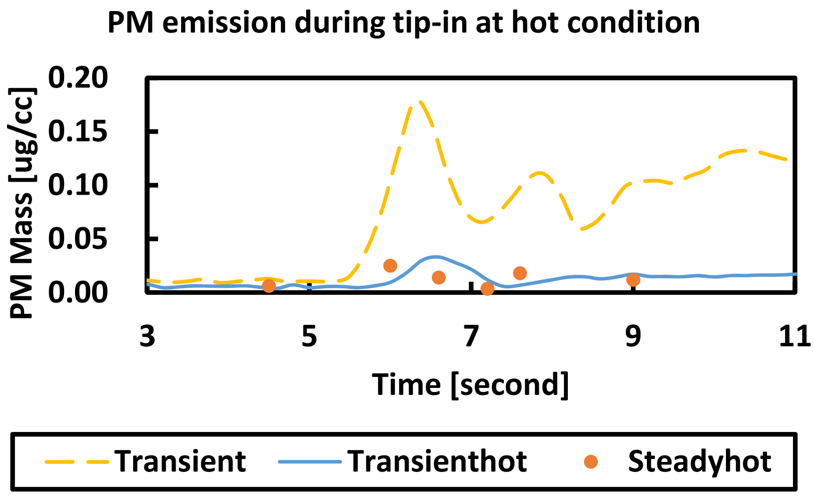

Figure 3.26 PM emissions during tip-in at hot condition

Chapter 4. Conclusion

In this research, emissions characteristics of light-duty Diesel engines during transient operation were studied. Two different types of experiments were conducted under ambient, cold and hot intake temperature. The first part was about comparing emission level between steady and transient point of NEDC. The second part was about tip-in operation. In general, transient state emissions are considerably higher compared to steady state emissions. However, it turned out that transient state emissions were lower than that of steady state emissions. In addition, when different environment temperature was applied rather than the room temperature, emission level was increased by a factor of 3 compared to the ambient condition.

Nevertheless, the following conclusion could be drawn from this research:

1) For NEDC acceleration, NO emission level was lower at transient states compared to steady states. This was because more EGR was supplied during transient state due to higher boost pressure caused by turbo-lag of a VGT. Once EGR rate was matched, NO emission level between steady and transient states were almost identical to each other. Furthermore, transient boost pressure was tuned to be same as steady state boost pressure since EGR discrepancy was

caused by the difference in boost pressure. As a result, steady and transient state NO emissions became similar with each other. For PM emissions, transient PM emissions were higher than that of steady state PM emissions reflecting NOx-PM trade-off well and an emission peak was observed. Again, Turbo-lag was to blame for the PM emission peak. Since there was about 1 second delay for the amount of air to respond to the change in throttle position, relatively richer air/fuel mixture was formed causing dramatic increase in PM emissions.

2) In order to verify the emissions characteristics at transient state, NEDC deceleration experiments were performed. For deceleration, the opposite phenomenon of the acceleration was observed for both NO and PM emissions. Lower NO emissions at steady state was due to increased EGR rate yielded by higher boost pressure as a result of turbo-lag. However, unlike the acceleration, a PM emission peak was not observed for deceleration.

3) Tip-in is one of the harshest transient operations which frequently occurs in a real-life driving condition. As for tip-in, the same phenomenon as the NEDC acceleration was observed meaning that transient NO emissions were smaller compared to steady state NO emissions. However, unlike the normal acceleration, a NO emission peak was detected for tip-in acceleration. The difference in NO emissions was caused by turbo-lag but not by discrepancy in

boost pressure. In this case, discrepancy in the amount of air was responsible for the emission peak. Except for the peak point, the amount of air was pretty much similar between steady and transient states but at the peak, the amount of air supply at steady state was considerably lower than that of the transient state. Since NO emissions are largely affected by in-cylinder O_2 concentration, a NO peak was therefore observed. In addition, a PM emission peak was also found for tip-in but compared to the NEDC cases, the peak level was so small that it could barely be called a peak. The order of magnitude for PM emissions at tip-in acceleration was $1/20^{th}$ of NEDC acceleration.

4) Finally, both NEDC and tip-in experiments were repeated under different environment temperatures to see the effect of intake temperature on the emissions characteristics. The temperature of cold and hot condition were 10 ℃ and 40 ℃, respectively. At the stated temperatures, EGR was no longer supplied; hence, NO emissions were increased by a factor of 3 for both NEDC and tip-in cases compared to the ambient condition. In addition, almost zero PM emissions were observed due to no EGR condition for both tip-in and NEDC. Furthermore, no emission peaks were observed for both NO and PM regardless of the intake temperature, and the emission level between cold and hot surrounding was similar to each other.

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초 록

최근 점점 더 대두되는 환경오염 문제에 따라 자동차업계에 대한 배기 배출물 규제가 갈수록 강화되고 있다. 2014년 9월에 시행될 EURO-6 규제에서는 현행 EURO-5b 대비 질소산화물은 55.6 % 저감, 입자상 물질은 동등수준을 유지할 것을 요구하고 있다. 하지만, 이러한 노력에도 불구하고 실생활 배기수치는 비슷한 수준을 유지하고 있다. 이는 현 배기규제가 실생활에 사용되는 과도상태를 잘 반영하지 못하기 때문이다.

따라서, 본 연구에서는 승용 디젤엔진의 과도운전 시 배기 배출물 특성에 관하여 연구를 진행하였다. 과도 및 정상상태에서의 NOx와 PM을 측정하기 위해 각각 Cambustion 社의 DMS-500과 CLD-500 그리고 Horiba 社의 배기가스분석기가 사용되었다. 또한, 과도상태에서의 EGR율을 측정하기 위하여 EGR 모델이 사용되었다. 배기측정 모드인 NEDC의 고속도로 구간 중 첫 번째 가속구간에 대한 배기결과는 다음과 같았다. 과도 상태일 때의 일산화질소가 정상상태 때보다 적게 배출되었으며 이는 가변 형상 터보차져의 터보랙으로 인해 발생한 가압의 상승으로 인하여 과잉 공급된 EGR 때문이다. 따라서, 정상상태의 EGR 혹은 가압을 과도상태와 일치시킬 시 NO 배출량이 같아지는 것을 확인할 수 있었다. PM의 경우 NOx-PM trade-off에 따라 NO와 상충되는 결과를 나타내었다. 또한, PM의 경우 피크값이 발생하였으며, 이는 터보랙으로 인해 발생한

느린 공기량의 추종으로 순간적으로 생성된 농후한 혼합기 때문이다. 감속 시에는 가속과는 반대되는 결과가 도출되었다.

EURO-6 이후의 배기규제에서는 더욱 더 가혹한 조건의 과도운전 조건이 포함될 예정이므로, 추월 시 빈번하게 발생하는 급가속 운전조건에서의 배기 배출물 수준을 파악하는 것이 중요하다. NEDC 실험 결과와 마찬가지로 급가속시에도 정상상태의 NO가 과도상태보다 많은 것을 확인할 수 있었다. 하지만, NEDC와는 달리 NO 피크값이 발생하였으며, 이는 VGT의 터보랙으로 인해 실제 공기량이 목표 공기량을 추종하지 못했기 때문이다. PM 피크값도 발생하였으나 NEDC와 비교하여 값의 수준이 현저하게 작았다.

마지막으로, 실제 차량들이 여러 온도조건에서 운행된다는 사실을 고려하였을 때 상온뿐만이 아닌 저온 및 고온에서의 배기 배출물 수준을 파악하는 것 또한 중요하다. 저온 및 고온조건에서는 EGR 공급이 차단되어 NO 값이 3배 증가하는 것을 확인할 수 있었으며, 이 때에 PM은 거의 배출되지 않았다. 또한, 상온에서와는 달리 저온 및 고온에서는 NO와 PM의 피크값이 발생하지 않았다.

주요어 : 승용 디젤 엔진, 질소산화물, 입자상 물질, 정상상태, 과도상태,

NEDC, 급가속, 온도

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