DIESEL EXHAUST FLUID DOSING ANALYSIS IN BHARAT STAGE VI COMMERCIAL VEHICLE ENGINE

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF REQUIREMENTS FOR THE DEGREE OF

MASTER OF ENGINEERING

IN THERMAL ENGINEERING

BY

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CERTIFICATE

I hereby declare that the dissertation entitled "**Diesel Exhaust Fluid dosing analysis in Bharat Stage VI commercial vehicle engine**" is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering** in **Thermal Engineering** at **Thapar Institute of Engineering and Technology, Patiala** under the supervision of **Dr. Vikrant Khullar (Assistant Professor, Mechanical Engineering Department) and Vinita V. Iyer (Group Lead, Combustion, Performance & Emissions – Aftertreatment Integration Team, Cummins India Ltd.)**. No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

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ABSTRACT

Ammonia reacts with nitrogen oxides in the exhaust flue gases to produce nitrogen and water vapours. This reaction occurs inside the catalyst convertor and is very much temperature dependent. The present work predicts the catalyst temperature profiles different engine start-up conditions. This has been studied theoretically and experimentally and the results have been compared to draw conclusions.

Further, experiments have been carried out to assess how the ammonia dosing rates at fixed engine performance parameters impact the conversion efficiency. Finally, ammonia dosing map has been presented which may be used in catalyst performance tuning.

Key words- Emissions, catalyst, heavy duty engines, honeycomb reactor, oxides of nitrogen.

ACKNOWLEDGEMENTS

Firstly, I would acknowledge my professor **Dr. Vikrant Khullar** (Assistant Professor, Mechanical Engineering Department) for his continuous support and guidance all throughout the year. The research work was a part of the internship program sponsored by Cummins Technological Center, India. **Cummins** provided me the equipment and facilities to do my research. I have been lucky to have **Mrs. Vinita V. Iyer** (CPE-ATI Team) as my industry supervisor and **Mr. Utkarsh Verma** as my manager. They always listened patiently to my queries and settled them with their technical abilities. I would also recognize that **Mrs. Masum R. Page** (CPE-ATI Team) helped me to navigate my way to proceed smoothly to achieve my objectives.

Finally, I would like to express my sincere gratitude to my family for the moral support and the lord almighty for providing me with the strength and determination to complete the project work.

TABLE OF CONTENTS

CERTIFICATE 2

ABSTRACT 3

ACKNOWLEDGEMENTS 4

TABLE OF CONTENTS 5

LIST OF FIGURES 6

LIST OF TABLES 7

NOMENCLATURE 8

CHAPTER 1 INTRODUCTION 10

1.1 Motivation 10

1.2 Emission norms 10

1.3 Introduction to After-Treatment System 13

1.4 Basic terms associated with catalyst 15

CHAPTER 2 LITERATURE REVIEW 18

2.1 Organisations working on the After-treatment systems 18

2.2 Literature review 18

2.4 Objectives 24

2.5 Research Methodology 25

CHAPTER 3 DETAILS OF WORK 26

3.1 Mathematical model 26

3.2 Experimental set-up 28

CHAPTER 4 RESULTS 39

CHAPTER 5 CONCLUSIONS 44

5.1 Conclusions 44

5.2 Scope of work 44

5.3 Future work 44

REFERENCES 45

LIST OF FIGURES

Fig. No.	Description	Page No.
1	WHTC (World Harmonized Transient Cycle) standard speed and load combinations	13
2	Pictorial description of catalyst conversion reactions	15
3	Catalyst inner view to explain honeycomb channels	17
4	DEF (Deisel Exhaust Fluid) density - temperature profile curve	19
5	Modelled the catalyst bed temperature for all the speed and load combinations	27
6	Fuel conditioning unit picture	29
7	(a) Smoke meter working principle, and (b) Smoke meter unit	29
8	HC (Hydrocarbon) detector working principle pictorial description	30
9	Chemiluminescence Detector (working principle)	30
10	NDIR (Non Dispersive Infrared detector) working principle	31
11	FTIR (Fourier Transform Infrared detector) unit picture	32
12	Oxygen detector working principle	33
13	SPC working principle pictorial description	34
14	Repeat point plots for charge air-cooler depression, fuel inlet pressure, ambient pressure and compressor inlet pressure	36
15	Repeat point plots for fuel inlet temperature, relative humidity, temperature of air after charge air cooler and delta air-fuel ratio	36
16	Repeat point plot for fuel outlet pressure	37
17	Repeat point plot for ambient temperature	37
18	Engine torque and power curve	37
19	Engine Part Throttle Performance points	38
20	CAD representation of the catalyst set up	38
21	Pictorial description of thermocouple inside catalyst channel	39
22	Cold WHTC (World Harmonized Transient Cycle) comparison plot along with the error percent	40
23	Cold WHTC (World Harmonized Transient Cycle) lag explanation	41
24	Warm WHTC (World Harmonized Transient Cycle) comparison plot along with the error percent	41
25	Soaking period comparison plot along with the error percent	42
26	WHSC (World Harmonized Stationary Cycle) comparison plot along with the error percent	43
27	Varying ammonia dosing plot	43
28	Final mapped NH_3: NOx surface plot	44

LIST OF TABLES

Table. No.	Description	Page No.
1	Vehicular emission norms for India and global level	11
2	WHSC (World Harmonized Stationary Cycle) standard speed and load combinations	12
3	Organisations and researchers working in same field	18
4	Details of the engine used for the experimental work	28
5	Details of the dynamometer used for the experimental work	28
6	Air Conditioning unit specifications	28
7	Fuel conditioning unit specifications	29
8	Flame Ionization Detector specifications	30
9	Chemiluminescence Detector specifications	31
10	Non Dispersive Infrared radiations Detector specifications	32
11	FTIR (Fourier Transform Infrared detector) specifications	33
12	Oxygen detector specifications	34

NOMENCLATURE

English symbols:

p_s Dry inlet air absolute pressure (kPa)

f_a Constant of proportionality

t_a Ambient air temperature (K)

C_d Coefficient of discharge for the orifice meter (value lies between 0.6 to 0.85)

β Diameter ratio [orifice diameter (d) to pipe diameter (D)]

ε Expansibility factor

ρ_l Fluid density in the upstream of the tapping (kgm^{-3})

$\frac{d(NO)}{dt}$ Rate of formation of NOx

$[N_2]_e$ Nitrogen fraction in exhaust gas

$[O_2]_e$ Oxygen fraction in exhaust gas

T_{CAT1} Catalyst inlet temperature (K)

T_{CAT2} Catalyst outlet temperature (K)

Abbreviations:

Br. Brake

CAT1 Catalyst inlet

CAT2 Catalyst outlet

ATI After-treatment Integration

EBU Engine Business Unit

CPE	Combustions, Performance and Emissions
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DEF	Diesel Exhaust Fluid
CTCI	Cummins Technological Centre India
DCU	Dosing Control Unit
ECU	Engine Control Unit
BSVI	Bharat Stage VI
ARAI	Automotive Research Association of India
ATS	After-treatment System

CHAPTER 1 INTRODUCTION

1.1 MOTIVATION

1.1.1 Factors affecting emissions formations: The major pollutants released from vehicles are oxides of nitrogen, oxides of sulfur, particulate matter and hydrocarbons. The nitrogen oxides are produced at high combustion temperatures [1]. During lean operation the air to fuel ratio is high this causes more oxygen to take part in combustion reaction in the chamber. Fuel droplet has a coating of water around it. When this droplet is introduced into the chamber the water evaporates resulting in dry hydrocarbon. When the volumetric efficiency of the engine reduces, the combustion that occurs at that time is called partial combustion. The partial combustion results in un-burnt hydrocarbons in the engine exhaust. The exhaust gas temperature drops when the exhaust is released into the atmosphere. The hydrocarbons in the exhaust gas (at this moment) agglomerate and this result in formation of particulates.

1.1.2 Health hazards: Nitrogen oxides react with the water vapors present in the atmosphere to form acid vapors. These acid vapors can pass through the nasal cavity to reach lungs and cause diseases like bronchitis, emphysema etc. These vapors can also respond to skin and trigger skin diseases. In the form of acid rains, the acid vapors can descend to earth which can cause a huge impact on eco-system [2]. Exposure to ammonia rich environment can cause certain other diseases like frost bites. It may cause respiratory suffocation, caustic burns, cardio vascular illness etc.

1.2 Emission norms

Indian government has been making continuous efforts to minimize the pollution levels. In the year 2000, the first emission norms 'India 2000' were launched. These emission norms were inspired from Euro I emission norms. The test cycle that was used in this norm was ECE - R49 (Economic Commission for Europe - Regulation 49). It was an urban duty cycle. This emission norm limited the carbon monoxide, hydrocarbons, nitrogen oxides and particulate matter that could be released by the engine in the environment. Next revision made was BS II. This was inspired by Euro II legislation limits. It was launched in April 2005 and used ECE R49 for validation purpose. Five years thereafter another emission legislation BS III was introduced. This emission legislation mainly focused on dropping the hydrocarbon limit by around 40% and carbon monoxide limit by around 50%. It was inspired by Euro III emission norm which used ESC (European Stationary Cycle) and ETC (European Transient Cycle) cycles for validation. ESC (European Stationary Cycle) was a 13 – modes test cycle. And ETC (European Transient Cycle) was a transient test cycle. BS III remained in use for 7 years until a fresh emission standard BS IV was implemented. These norms were inspired by Euro IV emission norms. Major focus in these norms was on particulate matter reduction. Approximately 80% decrease was seen in permissible PM emissions. After BS IV, Government of India decided to skip the BS V phase and jump straight to BS VI emission standards. Such that there was around 70% to 73% drop in allowable hydrocarbon limits and about 87% to 88.5% drop in nitrogen oxides emissions. Also, particulate numbers were also limited to $8*10^{11}$ parts/kWh for transient and $6*10^{11}$ parts/kWh for steady state cycles. The cycles used for this emission legislation are world harmonized transient cycle (WHTC) and world harmonized stationary cycle (WHSC). WHTC was required to check the emissions under transient response i.e., when the speed and torque were changed frequently for the engine. WHSC was required to check the steady state response of the engine and to see the emissions produced whenever there was a mode change in the cycle.

Table 1: Vehicular emission norms for India and global level [3]

Indian Standards	Global Reference	Year	Test	CO (g/kWh)	HC (g/kWh)	NO_x (g/kWh)	PM (g/kWh)	PN (Parts/kWh)
India 2000	Euro I	June, 2000	ECE R49	4.5	1.1	8	0.36	-
BS II	Euro II	April, 2005	ECE R49	4	1.1	7	0.15	-
BS III	Euro III	April, 2010	ESC	2.1	0.66	5	0.1	-
			ETC	5.45	0.78	5	0.16	-
BS IV	Euro IV	April, 2017	ESC	1.5	0.46	3.5	0.02	-
			ETC	4	0.55	3.5	0.03	-
BS V	Euro V	Skipped	-	-	-	-	-	-
BS VI	Euro VI	April, 2020	WHTC	1.5	0.13	0.4	0.01	$8*10^{11}$
			WHSC	4	0.16	0.46	0.01	$6*10^{11}$

In the last decade, air pollution has risen to significant heights. Automobile emissions are suggested to be the most responsible ones for degrading air quality. To curb this issue, on 16 September 2019, the Ministry of Road Transport and Highways (MoRTH) introduced its fresh and strict emission regulations. With just engine tuning work, the strict legislative limits cannot be fully accomplished. This introduces the idea of having an after-treatment system for exhaust gas. This after-treatment system consists of a diesel oxidation catalyst (doc). It has precious metal (Pt) which serves as a three-way catalyst for the oxidation of carbon monoxide (co), un-burnt hydrocarbon (HC) and nitrogen oxides (NO_x). Diesel particulate filter (DPF) is responsible for the clean-up of the particulate matter (PM) from the exhaust gas. It is a non-flow component in the after-treatment system. Selective catalytic reactor (SCR) is responsible for the conversion of NO and NO_2 in the exhaust gas to N_2 and H_2O using urea-water solution (UWS) also known as aqueous urea solution (AUS32) or diesel exhaust fluid (DEF) [4]. DEF is stored in a separate tank from where it is drawn into the system. Table 2 shows the modes of WHSC while Fig. 1 shows the WHTC that is run. WHTC is shown in a graphical manner because it cannot be shown in tabular format as its speed and load percent changes every second. The combinations shown here are standard combinations published in United Nations, Global Technical Regulation No. 4.

Table 2: WHSC (World Harmonized Stationary Cycle) standard speed and load combinations [5]

Mode	**Speed**	**Load**	**Weighing factor**	**Mode length**
-	***%***	***%***	**-**	***s***
0	Motoring	-	0.24	-
1	0	0	0.17/2	210
2	55	100	0.02	50
3	55	25	0.1	250
4	55	70	0.03	75
5	35	100	0.02	50
6	25	25	0.08	200
7	45	70	0.03	75
8	45	25	0.06	150
9	55	50	0.05	125
10	75	100	0.02	50
11	35	50	0.08	200
12	35	25	0.1	250
13	0	0	0.17/2	210

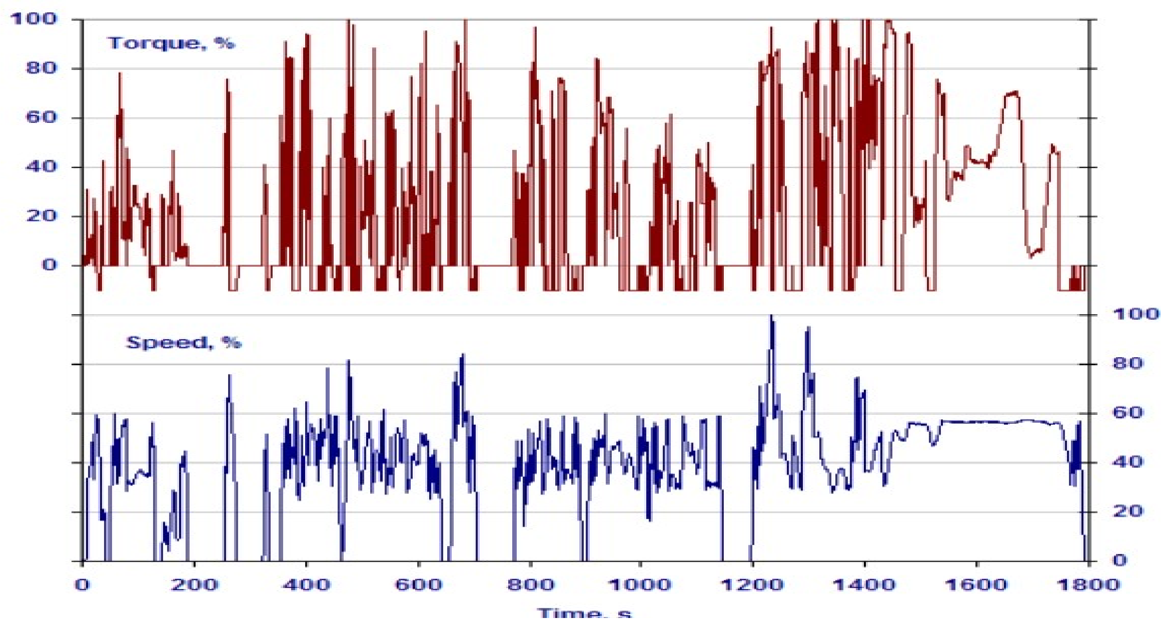


Figure 1: WHTC (World Harmonized Transient Cycle) standard speed and load combinations [5]

1.3 Introduction to After-treatment System

Tuning of the engine itself is not adequate to accomplish the limits of emission legislation. This calls for a distinct unit called the after-treatment system. Some basic reactions associated with different after-treatment components are discussed here. Here, Eqs. 1, 2 and 3 are for DOC.

$$C_{12}H_{23} + 7\frac{1}{2}O_2 \rightarrow 12CO_2 + \frac{23}{2}H_2O \quad (1)$$

Equation 1 represents the hydrocarbon oxidation reaction. $C_{12}H_{23}$ is a common formula for diesel particulates.

$$NO + \frac{1}{2}O_2 \rightarrow NO_2 \quad (2)$$

Equation 2 represents the nitric oxide oxidation to nitrogen dioxide. Here, it is to be noted that DOC changes the NO:NO_2 ratio from the engine but doesn't alter the overall nitrogen oxides.

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \quad (3)$$

Equation 3 represents the carbon monoxide oxidation to carbon dioxide. DPF traps the soot particles in its channels. The soot particles are a form of Carbon. These get burnt during the running engine which is called cleaning the filter and it followed by the Eqs. 4 and 5 as

$$C + NO_2 \rightarrow CO + NO \quad (4)$$

$$CO + NO_2 \rightarrow CO_2 + NO \quad (5)$$

Equations 4 and 5 explain us that the soot is burnt and carbon dioxide and nitric oxide are released into the emission gases. Thus, the total sum of NO_2 and NO in the emission gasses after DOC and DPF remains the same as that produced by the engine. Equations 6 and 7 represent the second process for cleaning the trapped soot particles inside the DPF channel. For this purpose, an active method is used. In this method, an extra quantity of fuel is introduced into the oxidation catalyst where it gets oxidized to produce heat. This heat is used to burn the soot accumulated in the DPF.

$$C + \frac{1}{2}O_2 \rightarrow CO \quad (6)$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \quad (7)$$

The emissions from DPF enter mixer where urea is dozed in the form of urea-water solution. Here, the water around urea droplet gets evaporated to produce dry urea as shown in equation 8.

$$(NH_2)_2CO + xH_2O \xrightarrow{\text{Evaporation}} (NH_2)_2CO \quad (8)$$

After the formation of urea molecule, thermolysis of the molecule occurs. During thermolysis, the urea droplet disintegrates into one ammonia molecule and one isocyanic molecule as shown by Eq. 9. This reaction takes the heat from the hot flue gases.

$$(NH_2)_2CO \xrightarrow{\text{Thermolysis}} NH_3 + HCNO \quad (9)$$

After thermolysis of urea, hydrolysis of isocyanic molecule occurs. In this, the isocyanic molecule furthermore breaks up to give one molecule of ammonia and one molecule of carbon dioxide. The hydrolysis is shown in Eq. 10 as

$$HCNO \xrightarrow{\text{Hydrolysis}} NH_3 + CO_2 \tag{10}$$

Thus, one urea molecule releases two ammonia molecules. Next to mixer is selective catalytic reactor. The reactor contains catalyst substrate which is why it can be referred to as catalyst in further chapters. The catalyst was introduced to the world by Engelhard Corporation, USA in the year 1957. It is the catalyst responsible for reducing nitrogen oxides below the standards of legislation. The basic reactions are illustrated in Eqs. 11-13 as

$$4NH_3{+}4NO + O_2 \rightarrow 4N_2 + 6H_2O \tag{11}$$

$$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O \tag{12}$$

$$4NH_3 + 3NO_2 \rightarrow \frac{7}{6} N_2 + 6H_2O \tag{13}$$

Equation 11 is called standard reaction that occurs at a higher temperature whereas, Eqs. 12 and 13 are termed as fast and slow reactions respectively. When the bed temperature is low, the nitrogen dioxide in the exhaust helps to initiate the conversion reaction. Typically, a catalyst follows Eq. 13, for most operating zones are within mid bed temperatures.

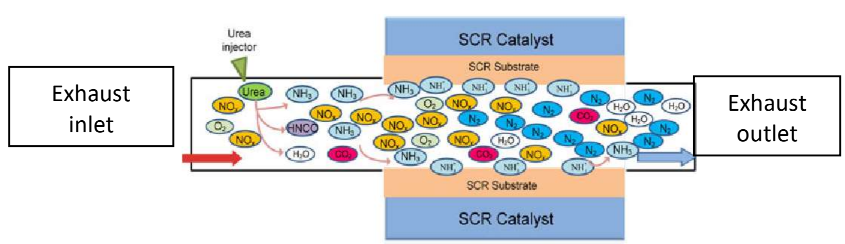


Figure 2: Pictorial description of catalyst conversion reactions [6]

1.4 BASIC TERMS ASSOCIATED WITH CATALYST

- **Doser** – Doser is attached to the mixer and it takes the command to dose the required quantity from the engine controlling module.

- **Injector** – It comes next to the doser. It is pintle type.

- **Dosing pump** – Supplies high pressurized urea-water solution into the supply line connected to doser.

- **Urea tank** – There is a separate storage tank in BSVI vehicles to store urea in it.

- **Deposits** – The sulfates and carbonate salts that get formed inside the catalyst and mixer respectively are referred to as deposits.

$$SO_{3(g)} + H_2O_g \leftrightarrow H_2SO_{2(g)} \tag{14}$$

$$NH_{3(g)} + H_2SO_{4(g)} \leftrightarrow NH_4SO_{4(g)} \tag{15}$$

$$NH_4SO_{4(g)} + NH_{3(g)} \leftrightarrow (NH_4)_2SO_{4(s)} \tag{16}$$

- Reactions that occur at high temperatures to decompose the deposits –

$$(NH_4)_2SO_{4(g)} \leftrightarrow NH_4HSO_{4(s)} + NH_{3(g)} \tag{17}$$

$$NH_4HSO_{4(s)} \leftrightarrow NH_{3(g)} + SO_{2(g)} + \frac{1}{2}O_{2(g)} + H_2O_{(g)} \tag{18}$$

- **Catalyst** – The selective catalytic reactor is a flow – through component in the after – treatment system. It provides the surface for conversion reaction to occur. The conversion reactions are endothermic in nature.

- **DEF** – It is an abbreviation for diesel exhaust fluid which is 32.5% wt./vol. of urea in water. Also known as, Adblue or urea-water solution. The density of this solution is 1.09 kg/m^3.

- **ANR** – It is an abbreviation for Ammonia to NO_x Ratio.

- **NO_x** – Nitrogen Oxides are collectively termed as NO_x

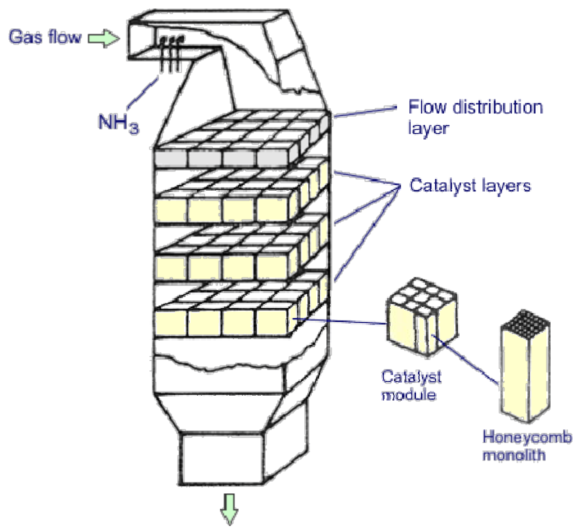


Figure 3: Catalyst inner view to explain honeycomb channels [7]

CHAPTER 2 LITERATURE REVIEW

2.1 ORGANISATIONS WORKING ON THE AFTER -TREATMENT SYSTEMS

There are countless researchers worldwide engaged in research related to the after-treatment system. Some of those researchers and the organization they are associated with have been listed in Table 3.

Table 3: Organisations and researchers working in same field

Sr. No.	Institute/University/Laboratory	Location	Researcher
1	Institute for Chemical Technology and Polymer Chemistry, University of Karlsruhe	Germany	Olaf Deutschmann
2	Hokkaido University	Japan	Yuta Nakasaka
3	Mendel University	Czech Republic	Adam Polcar
4	Automotive Research & Development Institute	Poland	Rafal Sala
5	Jiangsu University	China	Wei Tang
6	Lulea University of Technology	Sweden	Cornelia Lantto
7	Emitec Emission Control Technologies	India	Manjunath Fathepurkar
8	Presidency University	India	Sadashiva Prabhu S
9	Tata Technologies Limited	India	Swapnil Shelke
10	Sri Venkateshwara College of Engineering	India	G. Nagarajan
11	Argonne National Laboratory	USA	S.M. Aithal
12	Christ University	India	Gurumoorthy S Hebbar
13	University of Michigan-Dearborn	USA	Adnan Shaout
14	Chon Buk National University	Republic of Korea	Tae Hyun An

2.2 LITERATURE REVIEW

The literature review has been conducted by dividing it according to the work conducted in different catalyst-related areas. These areas of work are presented as below.

a) DEF (diesel exhaust fluid)
b) DEF storage tank
c) DEF injector
d) Mixer
e) DEF pump
f) DEF dosing controller

g) Reduction catalyst

h) Ammonia Oxidation Catalyst

i) NO_x sensor

j) NO_x formation

2.2.1 International Status:

a) DEF (diesel exhaust fluid): Optimum operating temperature range is 23°C to 27°C. A concentration lower than 32.5% is not desirable as it will lead to the formation of limescale at the injector surface [4]. DEF solution when dosed into the after-treatment system; it undergoes evaporation, thermolysis and hydrolysis. [8]

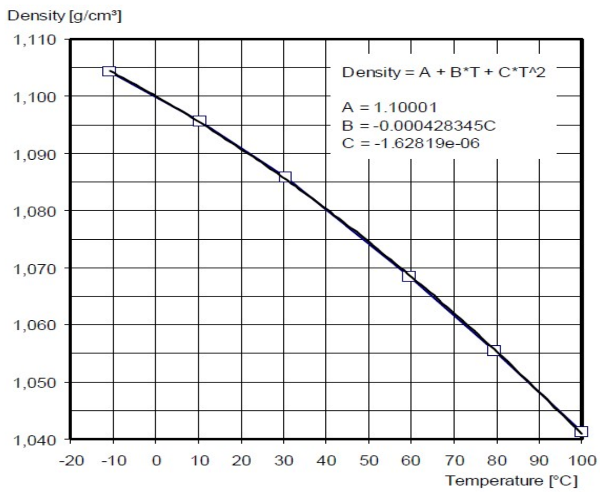


Figure 4: DEF density - temperature profile curve [9]

Figure 4 tells the basic relationship of urea density and temperature of the environment in which the solution is kept. Thus, it is understood that the hot tropical climates could be having a low-density DEF solution and the cold climate zones would be having higher density DEF solution [9].

b) DEF storage tank: The temperature sensor installed in the DEF storage tank indicates the temperature of the stored DEF in the tank at the dash board [10]. The coolant outlet from the engine is fed into the DEF storage tank thereby heating up the DEF in the tank to optimum operating temperatures. This is done in the colder regions [4].

c) DEF injector: Droplet size, half cone angle and angle of injection are the affecting parameters that fall under this category. A lower sized droplet shows a nearly same axial velocity at 30 mm and 50 mm from the nozzle exit [8]. A smaller nozzle size is preferred because a smaller sized droplet disintegrates much easily but a much smaller size would invite clogging of the nozzle opening. To overcome this, a feed pump must be provided [11]. An injection pressure above 5 bars is recommended [12]. A pintle nozzle can supply upto 50 bar pressure and has an added benefit that it is freeze proof. Therefore, we will not need to purge it [10].

d) Mixer: A mixer does the work of evaporation, thermolysis and hydrolysis of DEF. By thermolysis we can separate ammonia and Isocyanic acid from dry urea molecule. By hydrolysis of isocyanic acid we can have ammonia and CO_2 as products of hydrolysis. Also, a mixer ensures a proper mixing of ammonia with the exhaust gases thereby we reduce the catalyst length [10]. The need of a mixer can be eliminated by having a supply module and a dosing module. Here, the supply module mixes the DEF with air and is located just below the tank and the doser module houses a metering valve and an injector [13]. A heated line can also be provided in the path of the DEF supply line. This would provide us with the decomposed urea in the exhaust line. After the evaporation of water content at 100°C, the decomposition of dry urea begins at 160°C [11].

e) DEF pump: The pump can generate a very high pressure of upto 50 bar. Also, a solenoid drives the pump and the frequency of the solenoid valve determines the amount of DEF which will be dosed in the system [10].

f) DEF dosing controller: It is responsible for the amount of DEF that is dosed in the system. After - treatment sensors, CAN cable from engine provide the necessary information and the actuators that are connected to the dosing control unit are commanded accordingly [10]. Exhaust gas can have a temperature of about 673K and the mass flow rate of 400 g/s. Exit pressures can be about 3 atm. [12]. The controller must take values from double NO_x sensor also i.e. the NO_x sensor which is placed at engine out position and the other one which is placed at the system out position. At low temperatures there should be lesser quantity of urea dosed to prevent the deposits being formed and when the deposits are to be decomposed at that time the temperatures are to be increased [10].

g) Reduction catalyst: This part of after - treatment is responsible for conversion of NO_x into N_2 and H_2O using NH_3. There are three sets of reactions that undergo in the reduction catalyst namely – standard, fast and slow reactions. In the fast reaction phase NO_2 in the exhaust also participates and it occurs at a temperature range of 160°C to 190°C. This reaction helps us to use DOC as now more NO can be oxidized to raise the temperatures of the exhaust and passive soot cleanup of the DPF (diesel particulate filter) can be achieved which in turn would be eliminating the need of active regeneration. This eventually saves the fuel. The standard reactions start to occur at around 210°C [14]. The best operating range has been found to be 250°C – 350°C [10]. Only 36% of the available diffusion site in the catalyst is utilized for reaction. This is so because NO and NH_3 have to compete for diffusion sites in the catalyst [15]. Urea injection will be started at 200°C and will reach nominal state when the temperature reaches 250°C [10]. Maximum SCR poisoning is shown by Potassium Chloride. Thus, we need to provide a clean DEF into the mixer [16]. As the temperature increases, the surface area exposed, increases and the maximum exposed surface area is at 280°C. Sulfur dioxide in engine exhaust gets oxidized at DOC to produce SO_3. This reacts with water content in the exhaust to produce H_2SO_4 which further reacts with Ammonia to for Ammonium Bisulfate at 190°C. This goes on to react with NH_3 to form Ammonium Sulfate salts which settle down in the catalyst. The temperature to decompose this is about 300°C [17].

h) Ammonia Oxidation Catalyst: The ammonia that slips from the catalyst and go unreacted gets trapped in the ammonia oxidation catalyst. Here, we have two layers in which bottom layer is the oxidation layer and top layer is SCR porous layer. Ammonia which slips from the catalyst goes in the oxidation layer to form NO this passes to the SCR layer to react with ammonia and release nitrogen. This way the limit to achieve 10 ppm ammonia slip can be achieved [10]. The ammonia slip peaks that occur after the catalyst are not just because of over dosing of urea. These peaks may a resultant of ammonia deposits too that get formed inside the catalyst [18].

i) NO_x sensor: A NO_x sensor has two cells in it. In the first cell, O_2 is separated from the gaseous emissions by a pump. The rest of the emissions are passed to second cell where NO is decomposed into N_2 and O_2. This O_2 is again pumped out of the cell through a biasing voltage oxygen pump. The biasing voltage is proportional to the amount of NO dissociated thus amount of NO is detected. Now, when ammonia which goes unreacted from the AOC comes to the NO_x sensor then it gets oxidized into NO in first cell and this is read by the second cell as NO_x. This is the reason why even after dosing more ammonia in the system we see more NO_x being produced [19].

j) **NO_x formation:** The rate of NO_x production was modeled and it was found that it could put in a relation as shown below. [20]

$$\frac{d(NO)}{dt} = \left(\frac{6 \times 10^6}{\sqrt{T}}\right) \times e^{\frac{-69090}{T}} \times [N_2]_e \times \sqrt{[O_2]_e} \tag{19}$$

T= Flame temperature (K)

2.2.2 National Status

a) DEF (Diesel Exhaust Fluid): Ammonia is not safe to carry in a vehicle therefore we must use it in 32.5% by volume of water. Moreover, the DEF is cheaper and easier to handle [21].

b) DEF storage tank: DEF has a freezing point of -11℃ which is why we have a heating arrangement in the DEF storage tank. This integrated heated system is in the uptake area of the tank [22]. The positive temperature coefficient based elements which are a good conductor at lower temperatures and a bad conductor at a higher temperature are to be used. This way we can directly eliminate the need of any additional temperature sensing elements [22].

c) DEF injector: The dosing is purposely made asymmetric so that the DEF which is dosed in the mixer gets mixed with the exhaust on its own because the hot exhaust will flow and make a void which gets filled by the entering DEF [21].

d) Mixer: 8.65 L capacity mixer is to be used against 26.2 L capacity SCR. The static mixer increases the turbulence of the exhaust gas along with the urea droplets to increase its rate of evaporation [22].

e) DEF pump: There is supply line from DEF storage tank to the pump, a return line from pump back to the tank and a supply line from pump to the doser [22].

f) DEF dosing controller: There can be two dosing control modes, first is called the standalone working mode while the other is called the smart doser mode. In standalone working mode, the SCR doser calculates the right amount of DEF which is to be dosed based upon the integrated algorithm in the DCU (dosing control unit) and there is a minimum amount of engine information from the ECU (engine control unit). In smart doser mode, engine ECU computes the required DEF amount to be dosed based upon the sensor information [23]. There are two sets of information that go into the control unit, external and internal information. Air and exhaust gas mass flow, NO_x level before SCR, temperature of oxidation catalyst and temperature of SCR catalyst are the external information that the doser control unit will collect. Internal information includes the tank level, quality of the reducing agent, system pressure and system temperature. The decision of the amount of DEF is taken after realizing the two sets of information [22].

g) Reduction catalyst: Maximum NO_x conversion efficiency that can be achieved is 95% at 1 ANR [23].

h) NO_x formation: Various engine parameters such as flame temperature, injection timings and others have an impact on the NO_x formation [1]. Molecular oxygen concentration, ignition delay and density of the fuel influence the rate of NO_x formation. The effect of these factors on the rate of thermal formation can be established as NO_x emission index (NEI) of the engine fuelled with diesel. Fuel properties (cetane number, density) and engine design factors (bore, stroke, compression ratio) can be considered as influencing factors on NO_x formation [24].

Air temperature after compression in the cylinder:

$$\frac{T_{ia}}{T_{ia1}} = \left(\frac{V_{ia1}}{V_{ia}}\right)^{n-1} = (compression\_ratio)^{1.3-1} \tag{20}$$

T_{ia1}= Intake manifold temperature (K)

T_{ia} = final temperature after compression (K)

V_{ia1} = Swept volume of a cylinder

V_{ia}= Clearance volume of the cylinder

Reaction rate constant: This was calculated using Arrhenius equation i.e. $Exp\left(-E_a/RT\right)$ where;

E_a = Activation energy (38,465.61 J/mol)

R = Gas constant (8.3134 J mol^{-1} k^{-1})

Rate constant=exp (-4626.4399/T_{ia})

Load Percent = (Torque applied/peak torque) *100

Oxygen Concentration = $1 + C\left(-1.1860O_2^2 + 2.7960O_2 + 2.057\right)$ (21)

O_2 = 3.09 – 0.022 * Load Percent and, C = 1 for loaded condition. This forms the equation as Oxygen conc. $\left(-\left(1+\left(\left(-5.74\times10^{-3}\times Load\_percent^2+\left(0.0995\times Load\_percent\right)-0.603\right)\right)\right)\right)$

O_2 here is the ratio of moles of oxygen in exhaust gas therefore it is unitless.

Engine out NO_x produced in ppm = 20,956.69 * Density of fuel * oxygen concentration * ignition delay * rate constant (20,956.69 = Conversion constant to convert kg/m3 into ppm) [24]. A finite rate chemical model based upon various engine parameters can estimate the temporal variation in NO_x more accurately then Zeldovich mechanism alone [25].

2.4 OBJECTIVES

- Document engine architecture.
- Develop catalyst bed temperature and engine out NOx estimation model.
- Analyze Diesel Exhaust Fluid dosing.

2.5 Research Methodology

The methodology adopted was primarily experimental based. It was selected because it provides autonomy to research using the cause – effect relationship. Wherein, one could see the effect and the cause of that effect and act accordingly to achieve the desired objectives.

- ❑ Selecting the research area
    - ❑ Past work done for BSVI engines using the literature available
    - ❑ Present work done to achieve BSVI emission norms in the industry
- ❑ Gaps identification
- ❑ Formulating research objectives based on the research gaps
- ❑ Theoretical modelling
- ❑ Design of experiments to conduct test cell
- ❑ Data collection
    - ❑ Primary data
        - ❑ About the engine, aftertreatment systems and model
    - ❑ Secondary data
        - ❑ Data generated by test cell equipment
- ❑ Data analysis
- ❑ Reaching conclusions through comparisons
- ❑ Implementing the outcomes
- ❑ Final report

CHAPTER 3 DETAILS OF WORK

3.1 MATHEMATICAL MODEL

3.1.1 Introduction

Before starting with the model, engine part throttle performance must be known to the researcher. This helps in identifying the zones that are to be worked upon and the speed and load combinations to be chosen. The catalyst bed temperature model identifies coefficients between the temperatures before the catalyst and the temperatures after the catalyst and thus establishes a linear relationship between the two to generate the temperature of the catalyst bed. The temperatures are not growing exponentially or logarithmically rather their value would be a unique value and the final bed temperature value can be obtained by knowing the coefficients itself. Therefore, a linear relationship is chosen.

3.1.2 Governing equations

$$Catalyst\_bed\_temperature = [T_{CAT1} \times coefficient(say, x)] \times [T_{CAT2} \times coefficient(say, (1-x))]$$

3.1.3 Algorithm to model bed temperatures

Speed – Torque combination chosen from Part Throttle Performance plots

↓

Each Speed – Torque combination logged for 35 minutes 1 Hz and 5 minutes average log

↓

X coefficient matrix value ranging from 0.01 to 1

↓

Calculating the bed temperature values for each coefficient value in the matrix.

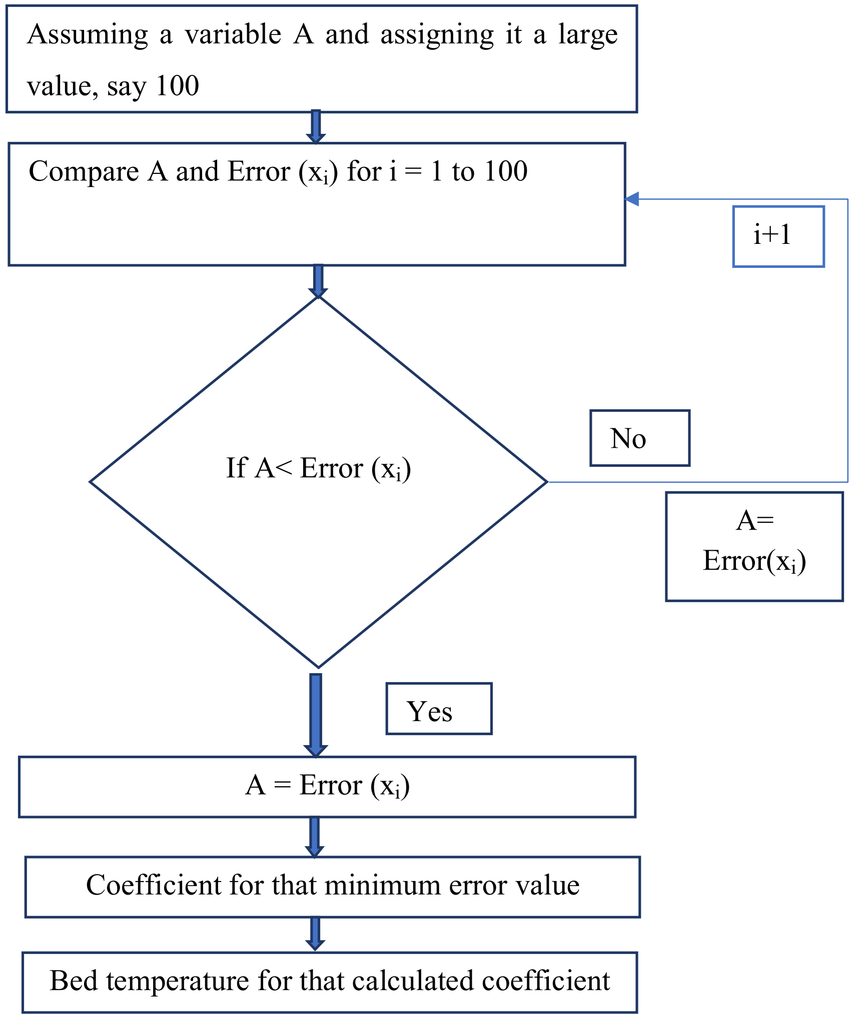
↓

Comparing these values with real values

↓

Error 1-D matrix formed by using the formula

↓



The same methodology was followed for other two temperature ranges. This approach considers the worst-case scenario in which three separate coefficients would be generated for the three ranges. The average of the three coefficient values gives us the final coefficient, x.

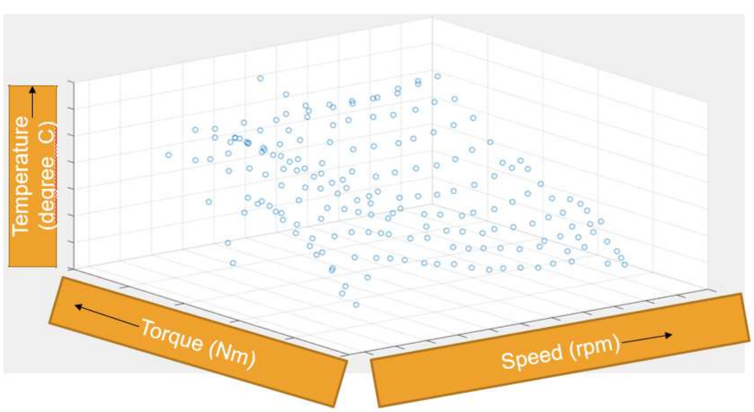


Figure 5: Modelled the catalyst bed temperature for all the speed and load combinations

3.2 EXPERIMENTAL SET-UP

The engine used was commercial vehicle engine manufactured by Cummins India Ltd. (Pune-Maharashtra). This test facility used was external test facility. The details are mentioned in Tables 4 and 5.

Table 4: Details of the engine used for the experimental work

Specifications	Details
Make	Cummins India Ltd.
Type	4-stroke
Installation	Trolley Installation

Table 5: Details of the dynamometer used for the experimental work

Specifications	Details
Make	Scorch
Type	Transient response

Test cell equipment: The test analyzers, test cell manager and test cell environment manager are collectively called test cell equipment.

(i) Air conditioning unit: This device takes in the ambient air and then filters it out. The filtered air passes through the heat exchanger to remove any water content. Now the dry clean air moves through the steam generation unit to get the required quantity of moisture. Table 6 elaborates its specification.

Table 6: Air Conditioning unit specifications [26]

Parameter	Range	Units
Temperature	$15\text{-}70 \pm 0.5$	°C
Pressure	1000 ± 1	Mbar
Humidity	8 to 20	g/kg of air

(ii) Fuel conditioning unit: The fuel conditioning unit takes in fuel from tank. Fuel is cleaned of any deposits by passing it through a fuel filter. Then the fuel passes through heating and cooling unit to attain the desired fuel temperatures.

Figure 6: Fuel conditioning unit picture [27]

Table 7: Fuel conditioning unit specifications [27]

Specifications	**Range**	**Units**
Temperature	20 – 45	℃
Maximum supply pressure to the engine	8	Bars
Cooling capacity	5	kW
Heating capacity	6	kW
Fuel circulation flow	12	l/min

(iii) Smoke meter: This device measures the smoke value in the emissions. A filter paper takes a smoke blot from the emissions and that blot is kept above the light source. Light source comes from lower end and the detector is placed on top of the cylinder. The smoke particles cause obstruction in the path which lowers the light intensity. This is intensity reduction is detected and is function of how dense the smoke is in the emissions. This is further expressed in FSN (Filter Smoke Number). Fig. 7(a) shows a smoke meter working in diagrammatical manner.

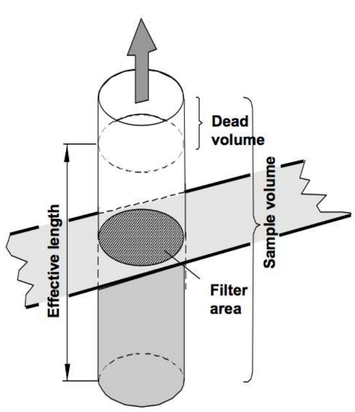


Figure 7(a): Smoke meter working principle [28]   Figure 7(b): Smoke meter unit [28]

(iv) Flame ionization detector: This instrument measures the un-burnt hydrocarbons in the exhaust. A hydrogen flame (with steady air and hydrogen / helium blend) is burning within an electrical field and a very tiny steady exhaust gas flow is introduced into this flame. If the sample gas includes hydrocarbons, the hydrocarbon molecules are cracked and ionized. The generated ions boost the ionic current between the FID anode and cathode. The Fig. 8 shows the working principle of FID in cartoon form. And the table 8 shows its specifications.

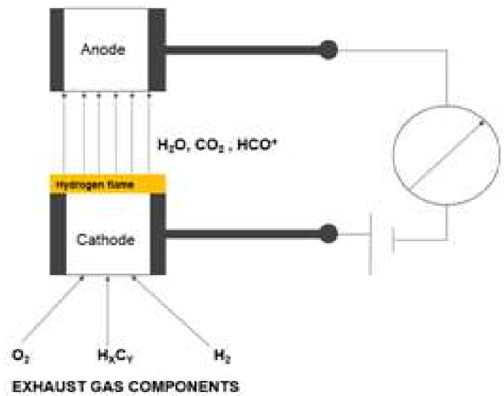


Figure 8: HC detector working principle pictorial description [29]

Table 8: Flame Ionization Detector specifications [30]

Title	Description
Zero gas	Synthetic gas
Span gas	C_3H_8

The zero gas is synthetic gas such that the zero measurement can be checked for the detector. The span gas is propane gas to check if the HC measurement is correct or to correct any drift in its value.

(v) Chemiluminescence detector: This device measures NO_x in the exhaust gas.

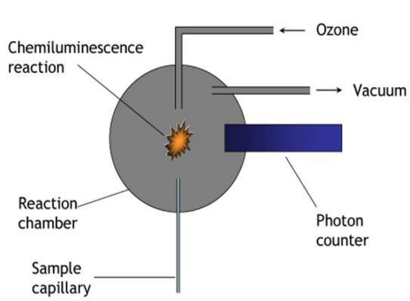


Figure 9: Chemiluminescence Detector (working principle) [31]

The Fig. 9 shows the working principle of a chemiluminescence detector. The ozone gas and exhaust gas are introduced in a chamber where they react to produce NO_2 and O_2 as

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{22}$$

Approximately 10% of the NO_2 is produced in excited state NO_2*. This excited state NO_2* comes back to the ground state and while doing so it emits light called chemiluminescence. This measured light intensity is directly proportional to the NO concentration in sample gas at constant flow rates.

Table 9: Chemiluminescence Detector specifications [32]

Title	**Description**
Zero gas	N_2
Span gas	NO
Operating gas	O_2

(vi) NDIR (Non- Dispersive Infrared): This device measures the CO and greenhouse gas within the exhaust gas. Fig. 10 shows the working of the NDIR. The infrared beam passes from the sample chamber. This then strikes the detector unbroken at the opposite finish. In parallel, there's another chamber with a reference gas. The IR signal from the supply is modulated so thermal background signals are offset from the specified signal.

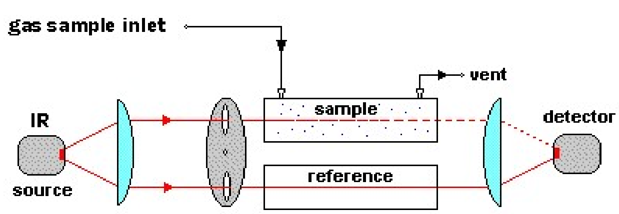


Figure 10: NDIR working principle [33]

The gas in the sample chamber causes absorption of specific wavelengths and the attenuation of these wavelengths is measured by the detector to determine the gas concentration. CO_2 and CO have the absorbing range in infrared region i.e. around 2.7 µm to about 13 µm. Table 10 shows the specifications for NDIR.

Table 10: Non Dispersive Infrared radiations Detector specifications [34]

Title	**Description**
Zero gas	N_2
Span gas	CO, CO_2

(vii) FTIR: It is an abbreviation for Fourier-Transform Infrared Spectroscopy. It basically creates an infrared broadband spectrum that can be used to detect all spectrum information of the exhaust gas sample at the same time. This absorption spectrum (intensity/wavelength) is calculated from measured interferograms (intensity/time) by means of Fourier Transformation. The Fig. 11 shows an FTIR instrument and Table 11 shows its specifications.

Figure 11: FTIR unit picture [35]

Table 11: FTIR specifications [35]

Title	**Description**
Zero Gas	N_2
Detector Cooling	Liquid Nitrogen (50 mL/h)
Sampling Flow Rate	10 L/min.
Measurement Cell Temperature	191℃

(viii) Paramagnetic detector: This instrument is used to detect the oxygen concentrations in the exhaust gas. The Fig. 12 illustrates the working principle.

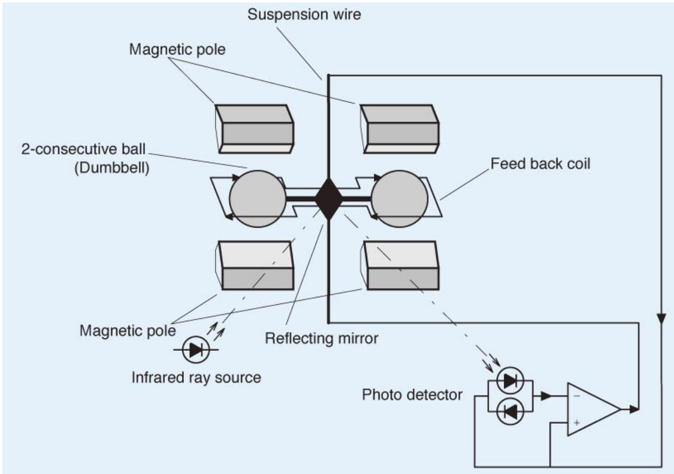


Figure 12: Oxygen detector working principle [36]

Two dumbbells shaped attached with a reflecting mirror are kept in magnetic field. The light from an infrared ray source falls in the mirror which reflects it onto a photo detector. This generates electricity and completed the circuit. When it introduced in exhaust gas, the oxygen atoms being paramagnetic try to get into the magnetic field and displace nitrogen filled dumbbells. This causes the movement of reflecting mirror which in turn decreases the infrared intensity at the photo detector. This causes decrease in output of the photo diode and this can be measured. Table 12 shows the specifications.

Table 12: Oxygen detector specifications [37]

Title	**Description**
Zero gas	N_2
Span gas	O_2

(ix) SPC (AVL smart sampler): This instrument is used to measure the particulate mass and particulate number in the emissions. Exhaust gas is diluted with clean air (25% ± 5) and the diluted gas shouldn’t be more than 52%. This partial flow system takes a suitable partial flow from the exhaust gas and samples it on the two Teflon coated glass fiber filters (primary and secondary filters). The total mass deposited on the filters is called particulate mass. It measures the gravimetric mass of entire particulate (carbon soot, sulfates, metal and fuel HC).

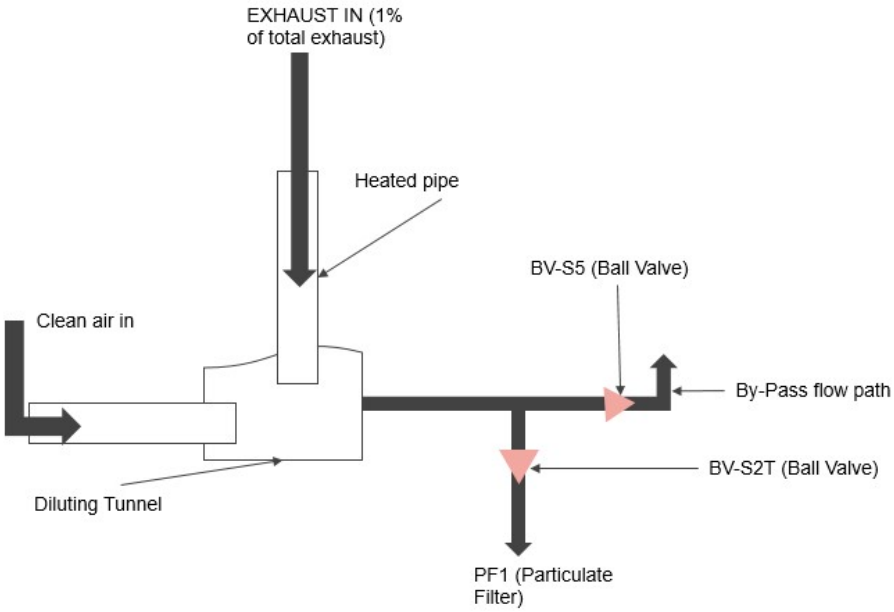


Figure 13: SPC working principle pictorial description [38]

(x) Orifice meter: The basic operational principle is based upon Bernoulli's theorem. The pressure is measured at the upstream of the vena-contracta and at the downstream of vena-contracta. Then with the help of Bernoulli's theorem the equation used is mentioned here.

$$\dot{q} = \left(\frac{C_d}{\sqrt{1-\beta^4}} \right) \times \in \times d^2 \times \sqrt{2 \times \rho_1 \times \Delta p} \tag{23}$$

Δp = differential pressure measured across the orifice, Pa

$\dot{q}$ = mass flow rate, kg⁄s

$$\text{Volume flow rate} = \dot{q} \times \rho_1 \times 10^6 \, \text{mL/s} \tag{24}$$

After getting familiar with the engine and the test cell equipment, it's important to check the health of the engine and test cell equipment early in the morning. To do this a set of repeat points were taken every morning before beginning with any trial. A repeat point set is a collection of distinct combinations of speed-torque that were repeated daily before any experiment in a test cell was started. It is important to take one set when the conditions were good and engine was new and use this set for further comparisons. The basic purpose is to check if any parameter has drifted from its original value. The tool is independent of the parameter arrangement and uses Microsoft Visual Basics for Applications to arrange the parameters and plot them for analysis. A long-term advantage of the tool would be to know whether the drift was transient or it occurred over some undefined time frame and the reason can be redressed and corrected before beginning with any further trial. For inlet air temperature and pressure AIS_137_Draft_ chapter_3_Paragraph _6.1(a) was used according to which $f_a = \left(99/p_s\right) \times \left(T_a/298\right)^{0.7}$ where; T_a = Inlet air temperature (K) and p_s = Dry inlet air absolute pressure (kPa). Also, value of f_a is a constant and is given by $0.96 \leq f_a \leq 1.06$. This gives T_a = 300K and p_s = 100kPa. The fuel inlet temperature was maintained within 38 ± 5.

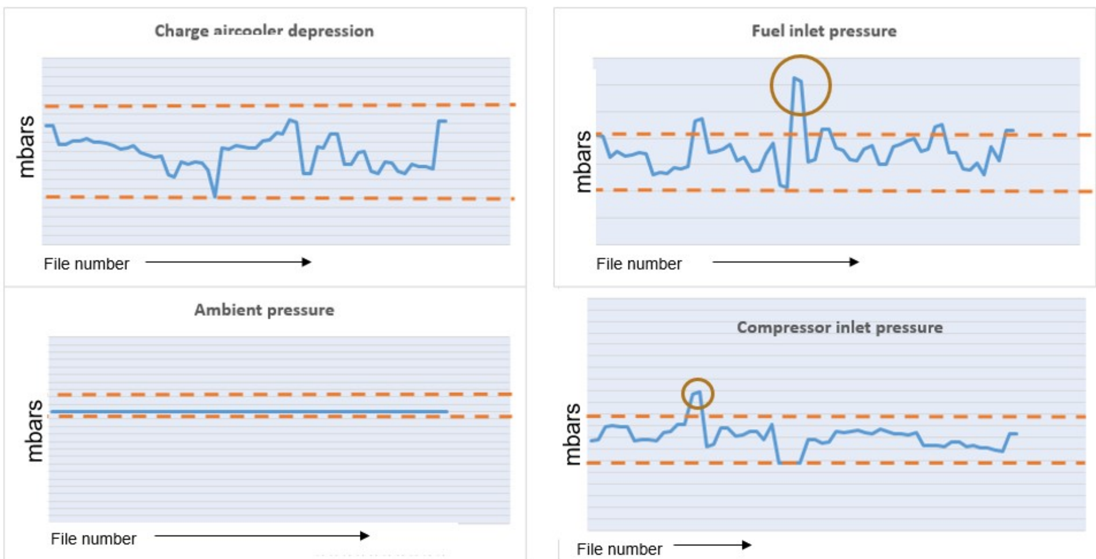


Figure 14: Repeat point plots for charge air-cooler depression, fuel inlet pressure, ambient pressure and compressor inlet pressure

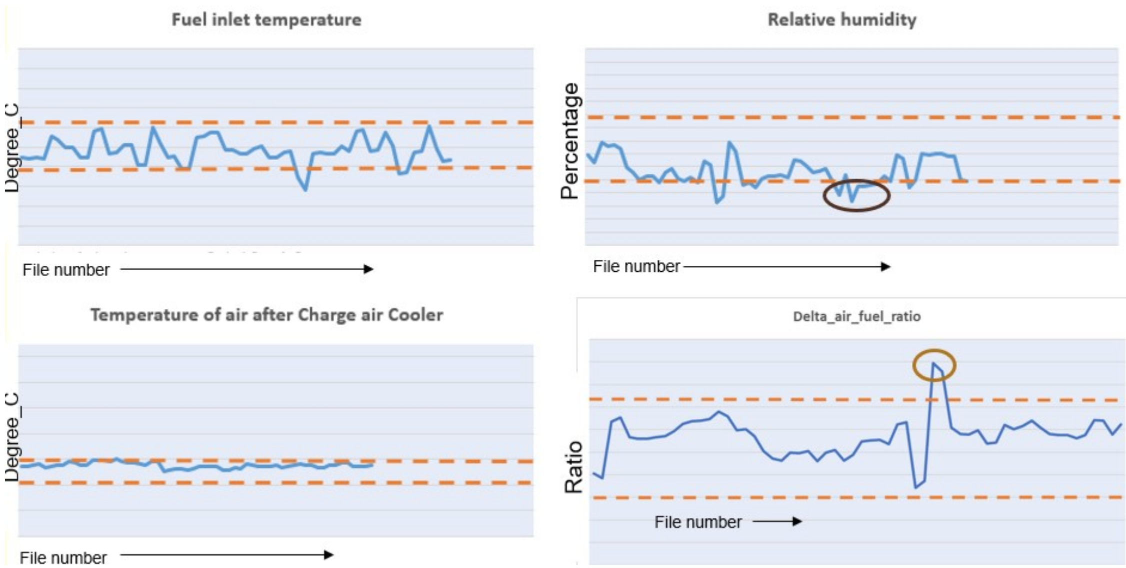


Figure 15: Repeat point plots for fuel inlet temperature, relative humidity, temperature of air after charge air cooler and delta air-fuel ratio

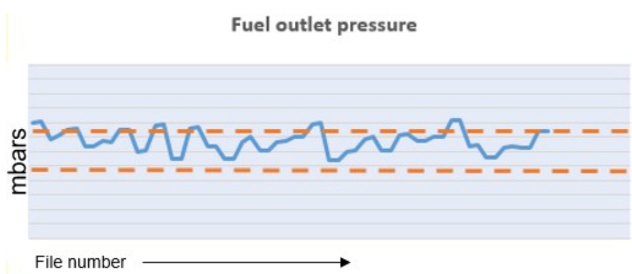


Figure 16: Repeat point plot for fuel outlet pressure

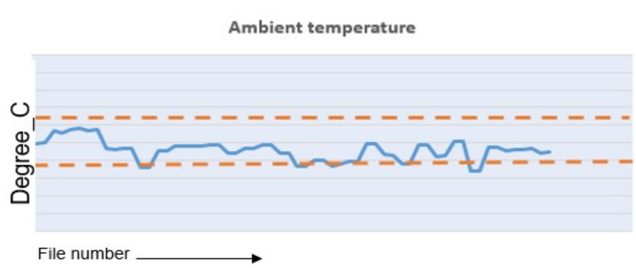


Figure 17: Repeat point plot for ambient temperature

In the repeat point plots shown above, the x-axis is common that is the file number while y-axis is parameter dependent. The dotted lines show the limits for that parameter. It was observed that the fuel inlet pressure was above the upper limit and upon examining it was revealed that its fuel conditioning unit membrane was damaged. Upon replacing it repeat points set was taken again and fuel inlet and outlet pressure was found to be within limits.

Similar processes were performed when compressor inlet pressure, relative humidity and air-fuel delta ratio were discovered to be off the boundaries.

Engine torque and power curve: After knowing that the health of the equipment and engine were good next step is to know about engine torque and power curve. These are shown in below plots.

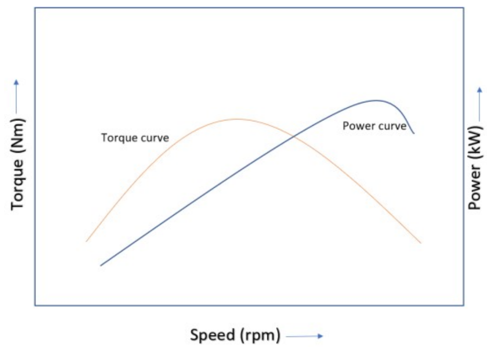


Figure 18: Engine torque and power curve [39]

The torque curve tells the engine operating area. The torque curve is at full throttle and 100% load. For part throttle performance the load is reduced by some percent such that, if torque is 500 Nm at full throttle then it is full throttle point. Then, 450 Nm will be part throttle point and so on. This is referred to as a 10% Part Throttle Performance. It is shown in Fig. 19.

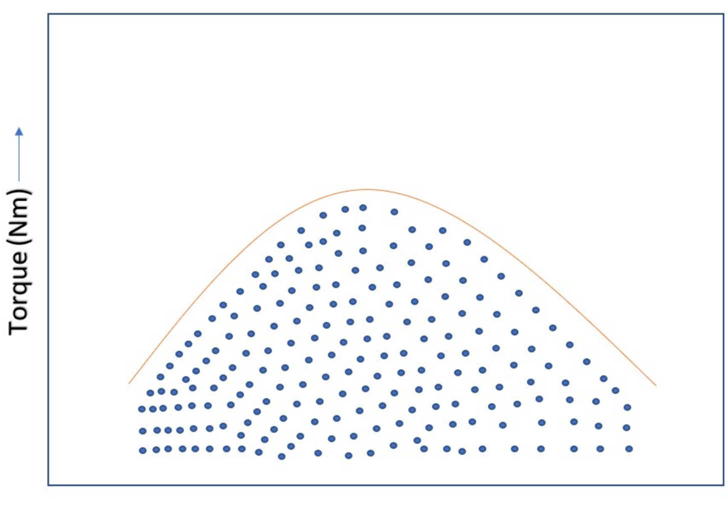


Figure 19: Engine Part Throttle Performance points [Courtesy: stack.imgur.com]

Catalyst bed temperature measurement: The modelled bed temperature had to be validated by a physical sensor reading. For this a catalyst was instrumented with a thermocouple going inside the catalyst. This is depicted in the fig. 20 below.

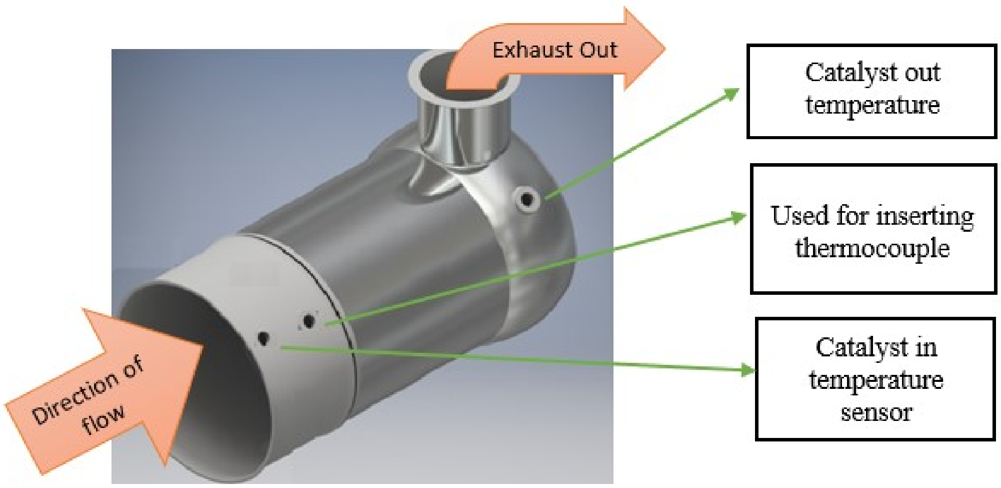


Figure 20: CAD representation of the catalyst set up

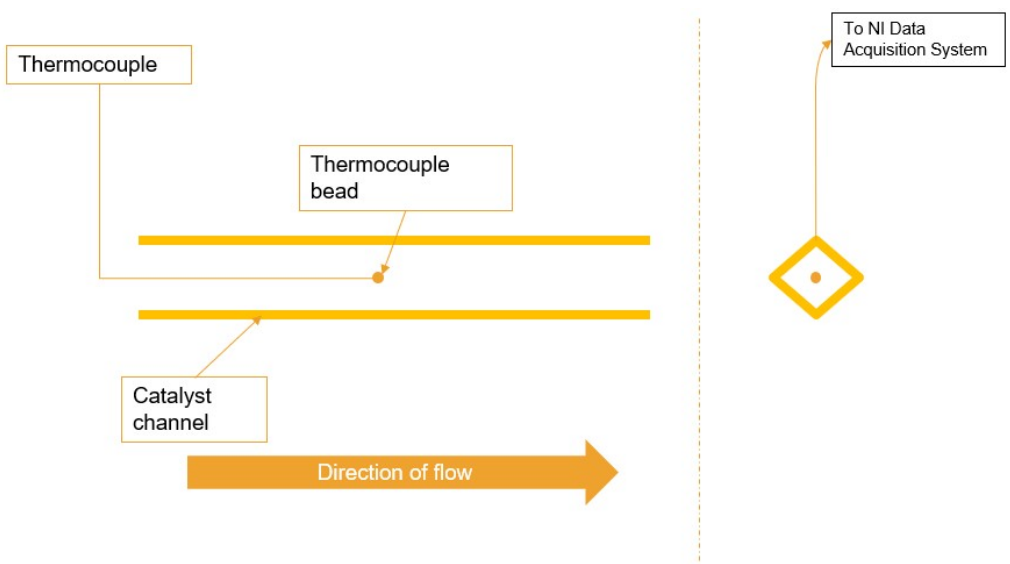


Figure 21: Pictorial description of thermocouple inside catalyst channel

The Fig. 21 shows the thermocouple instrumentation in the catalyst. A K-Type thermocouple was inserted through the adaptation ahead of the catalyst. The diameter of the thermocouple was 0.1 mm in diameter. It measured the readings from the bead and transfers them to the National Instruments data acquisition system as shown in Fig. 21.

CHAPTER 4 RESULTS AND DISCUSSION

It was discussed how the model operates and how the experimental set-up works in the previous chapters. It was also discussed how the outcomes can be affected by engine parameters and engine start and operating conditions. Its impact would be analysed in this portion. The results shown are for various BS VI emissions test cycles that are run in test cell.

4.1 Bed temperature model:

4.1.1 Cold World Harmonized Transient Cycle (WHTC): A set of WHTCs were run and the engine was left to cool - down to room temperature then cranked the engine. Thus, it's called cold WHTC.

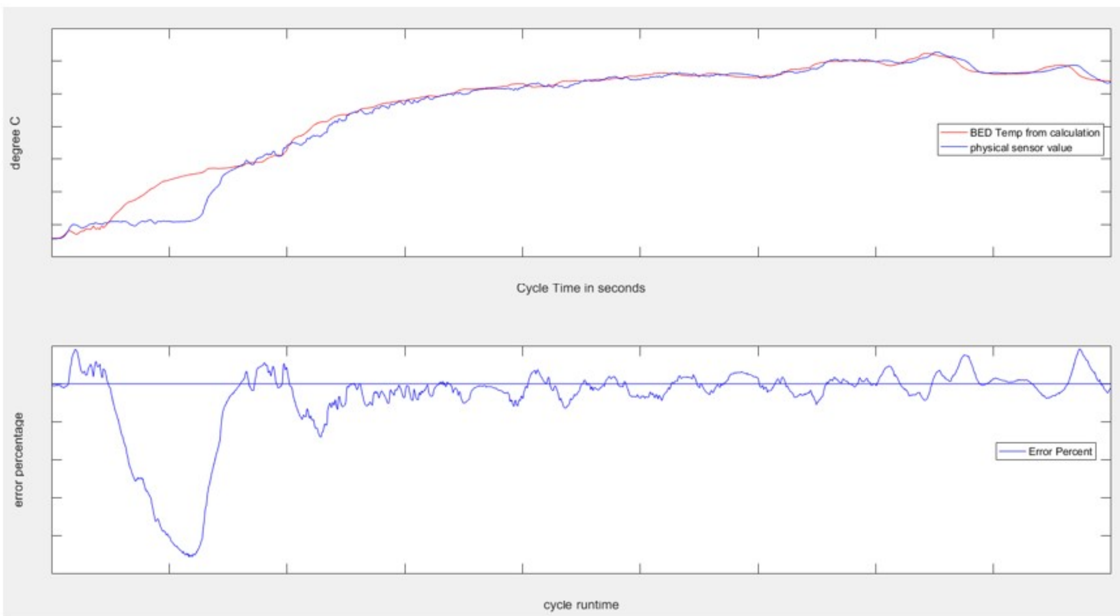


Figure 22: Cold WHTC comparison plot along with the error percent

The range of error percent for this was -21.1 % to 5.07 %. A higher negative value in the beginning is further explained using Fig. 23. The flow rates are low so probably thermocouple touches the channel wall. Once the flow rates increase, the thermocouple bead again rises from the wall and starts to read the gas temperature. Another probable reason could be the trapped cold gases inside the channel. The thermocouple reads the cold gas temperature till the time it gets flushed out of the catalyst. To support this declaration, the catalyst out temperature is also low for quite a long time before it starts to rise.

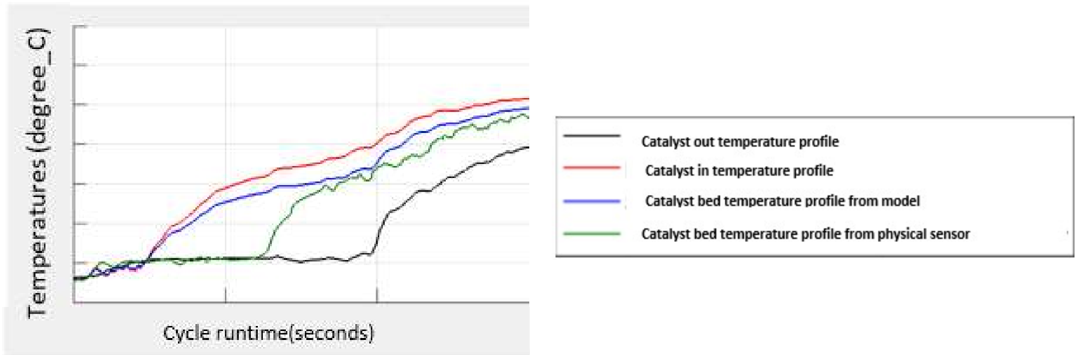


Figure 23: Cold WHTC lag explanation

4.1.2 <u>Warm World Harmonized Transient Cycle (WHTC):</u> The engine was held on a 10-minute soak period after cold WHTC, and then it was cranked for WHTC. Because the engine is warm, it's called warm WHTC. The catalyst channel was in hot condition but the aftertreatment line temperatures are not that high. This explains the positive error percentage (around 22%) and after that error percent was within 5% band.

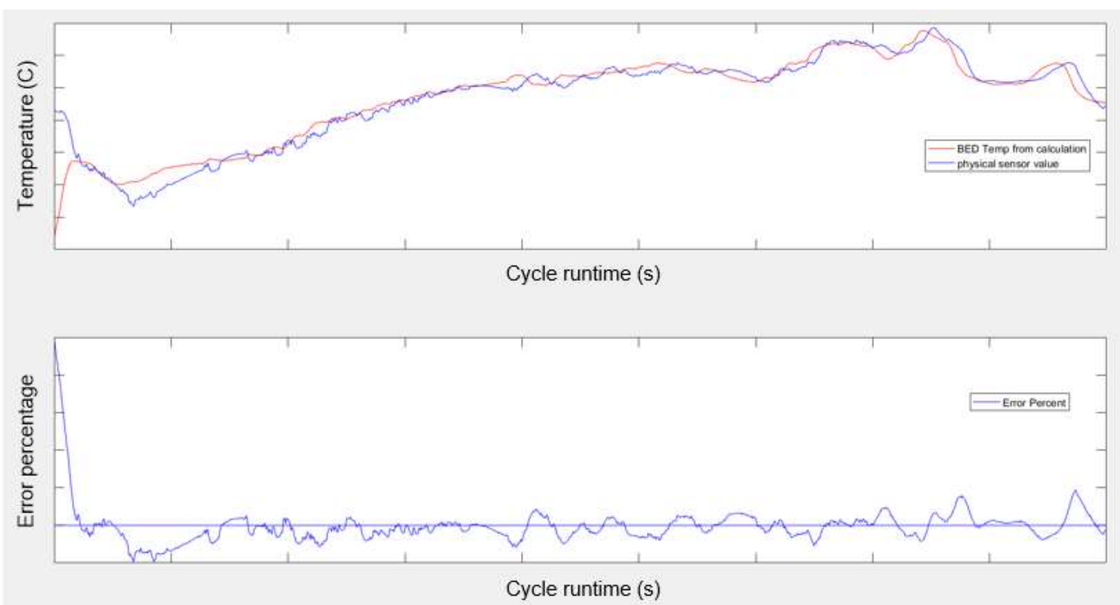


Figure 24: Warm WHTC comparison plot along with the error percent

The calculated temperature value takes catalyst in and catalyst out temperatures as inputs and physical sensor takes values from the catalyst channel. Due to this reason, the calculated value changes rapidly and the physical sensor value takes a while to update the value. This studied more effectively from the long soak period plot shown in the Fig. 25.

4.1.3 Long soak period: After running three WHTCs with 10 minutes soak in between every cycle, the system was left on a long soak period till the temperatures dropped to room temperature. The plot shows that for first 3.5 hours the catalyst is hot and physical temperature value is more than the calculated value. This is so because the calculated value comes from a linear relationship between catalyst in temperature and catalyst out temperature values. The thermocouple measurements of the catalyst generate a cooling curve that initially produces a greater percentage of error.

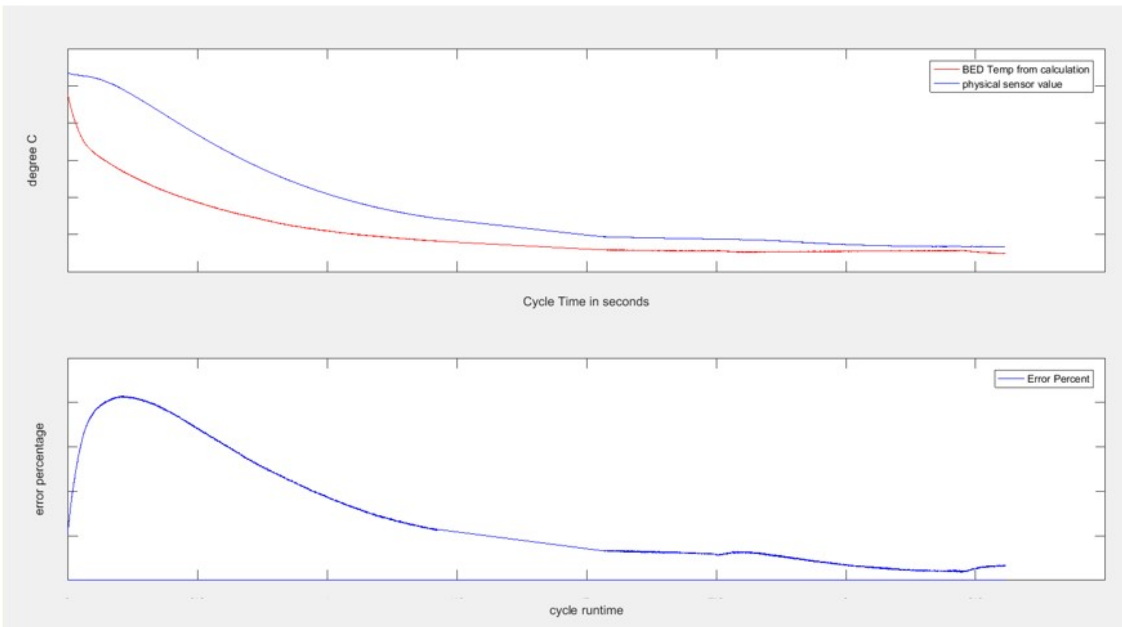


Figure 25: Soaking period comparison plot along with the error percent

4.1.4 World Harmonized Stationary Cycle (WHSC): Fig. 26 shows the result for stationary test cycle or WHSC. It's a standard test cycle for stage 6 on highway heavy duty engines. WHSC is a thirteen-mode test cycle. Each mode is a speed-load combination which runs for a specific period. The plot below shows that whenever there was transition from one mode to another mode, the physical sensor lagged the modeled value by around 0.5 seconds. Therefore, when the cycle moves from mode 1 to mode 2, the lag becomes prominent as the plot error percentage peaks to -9.5%. Similarly, when the cycle transits from 8th to 9th mode, which is the higher temperature mode in the cycle, the error percentage peak occurs again in cycle but for around 6% this time. The error percentage for rest of the cycle was within the band of 4%.

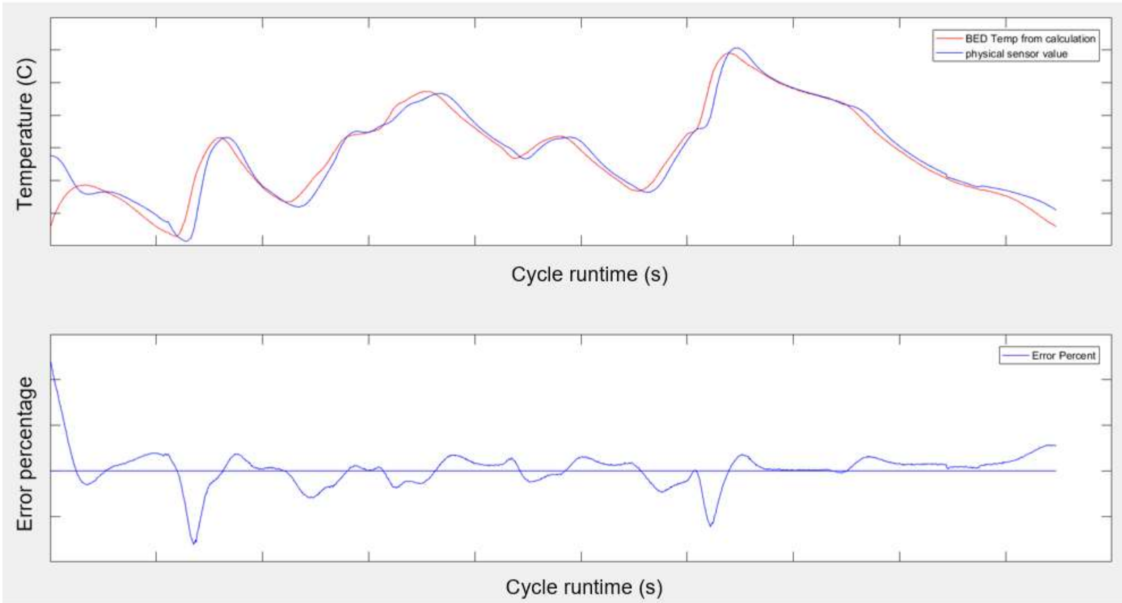
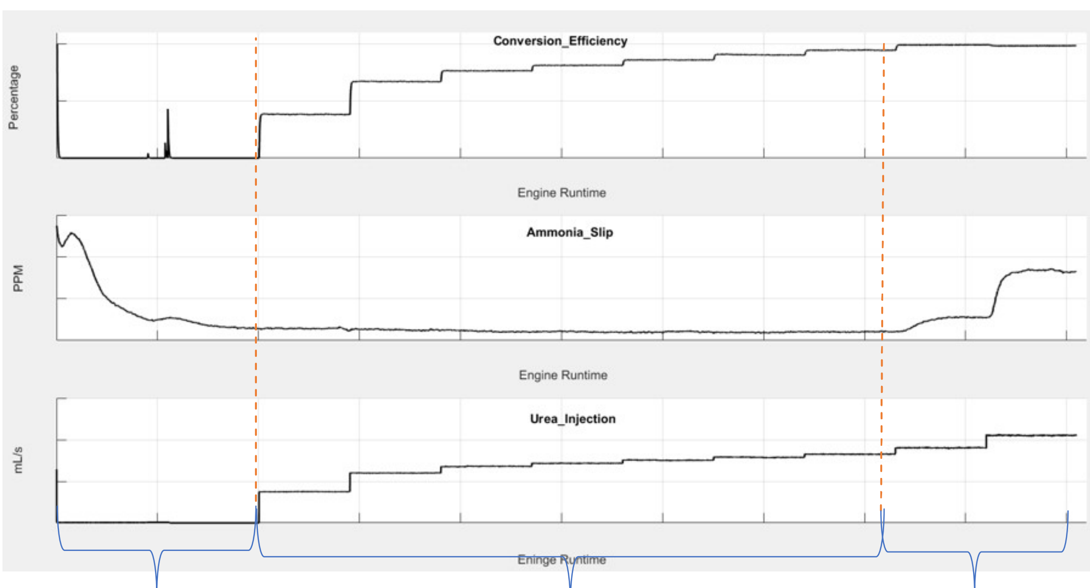


Figure 26: WHSC comparison plot along with the error percent

4.2 Varying ammonia dosing at fixed bed temperature:

Till now we know the nitrogen oxides coming from the engine and bed temperatures at a specific speed and torque combination. In this trial, the ammonia dosing rate was increased from zero to a very high value.



High temperature zone to clean catalyst	Conversion efficiency increases with increasing urea dosing.	Zone of high ammonia slip.

Figure 27: Varying ammonia dosing plot

The basic intent to conduct the trial was to map the ammonia dosing rate and conversion efficiency obtained at fixed engine performance parameters depicted by Fig. 27. This was repeated for specific speed and load combinations to come up with a final ammonia dosing values for specific speed and torque combination. Furthermore, as per the industry requirements a formula was used to convert the dosing in terms of ammonia to nitrogen oxide ratio. A surface plot is shown in succeeding Fig. 28.

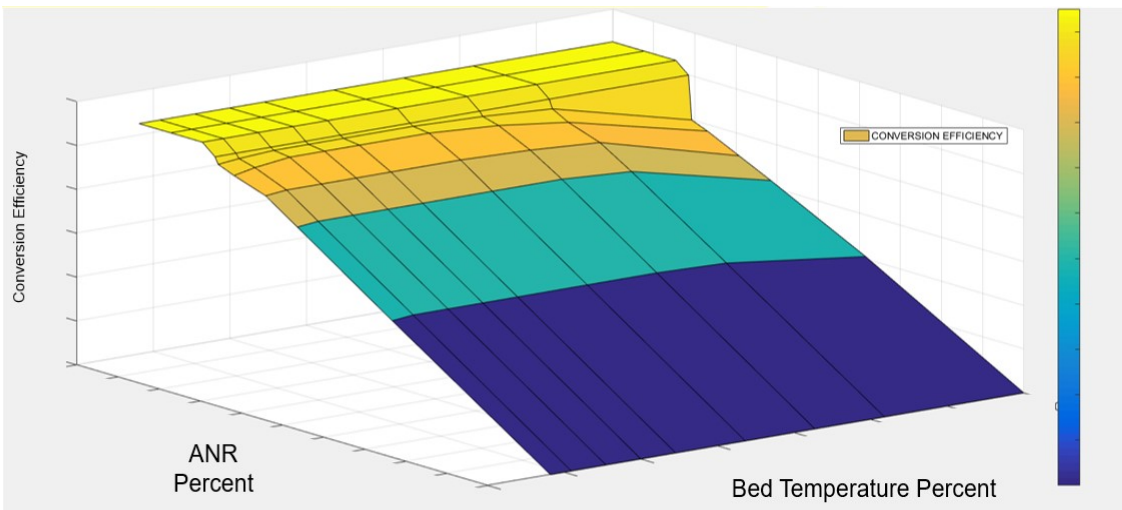


Figure 38: Final mapped NH_3: NO_X surface plot

This is very much useful is catalyst performance tuning.

CHAPTER 5 CONCLUSIONS

5.1 CONCLUSIONS

The research comprised of both experimental and theoretical modelling. This gives an advantage of exploring the cause and effect relationship in depth. The work helps in establishing a linear relationship between catalyst in temperatures and catalyst out temperatures to calculate the catalyst bed temperature. Then ammonia dosing and associated conversion efficiencies upon fixing the engine performance parameters was mapped. This research work also helps explain why, even after increasing ammonia dosage, the conversion efficiency starts to fall after a while.

5.2 SCOPE OF WORK

The research finds its scope in understanding the catalyst conversion reaction rates. The findings can be used in catalyst performance tuning. The engine health check tool that was part of the thesis finds its use wherever the performance tuning of the engine and after - treatment system occurs. This explains the wide applicability of the project work.

5.3 FUTURE WORK

The mode transitions in a cycle impact the catalyst bed temperature profile a lot. Therefore, the catalyst behaviour during the mode changes can be researched more in future. It is known that the catalyst conversion reaction is endothermic in nature. This can be explored experimentally in future.

References

Sr. No.	Reference
1	Hebbar, G.S., 2014. NOx from Diesel Engine Emission and Control Strategies-A Review. International Journal of Mechanical Engineering and Robotics Research, 3(4), p.471.
2	Baukal, C., 2005. Everything you need to know about NOx. Metal finishing, 103(11), pp.18-24.
3	EU Commission, 2011. Commission Regulation (EU) No 582/2011 of 25 May 2011. Off J Eur Union L, 167(1).
4	Polcar, A., Čupera, J., Kumbár, V., Dostál, P. and Votava, J., 2016. Influence of Urea Concentration on Refractive Index of AdBlue fluid Evaluated by Regression Analysis. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 64(2), pp.509-516.
5	U.N., Test procedure for compression-ignition (c.i.) Engines and positive ignition (p.i.) Engines fuelled with natural gas (ng) or liquefied petroleum gas (lpg) with regard to the emission of pollutants. ECE/TRANS/180/Add.4 January 25, 2007. http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29wgs/wp29gen/wp29registry/ECE-TRANS-180a4e.pdf.
6	Zhang, H., Wang, J. and Wang, Y.Y., 2014. Sensor reduction in diesel engine two-cell selective catalytic reduction (SCR) systems for automotive applications. IEEE/ASME Transactions on Mechatronics, 20(5), pp.2222-2233.
7	Majewski, W. Addy. DeiselNet Technology Guide. [Online] May 2005. https://www.dieselnet.com/tech/cat_scr.php.
8	Birkhold, F., Meingast, U., Wassermann, P. and Deutschmann, O., 2006. Analysis of the injection of urea-water-solution for automotive SCR DeNOx-systems: modeling of two-phase flow and spray/wall-interaction (No. 2006-01-0643). SAE Technical Paper.
9	Technical Leaflet BASF, the chemical Company (2005), “AdBlue,” ECAL/L, Rev. 1, pp 16
10	Majewski, W.A., 2015. Urea Dosing and Injection Systems. DieselNet. com, Retrieved May, 2, p.2016.
11	Sala, R., Bielaczyc, P. and Brzezanski, M., 2017. Concept of vaporized urea dosing in selective catalytic reduction. Catalysts, 7(10), p.307.
12	Ahn, T.H., Lee, G.W. and Kim, M.Y., 2014. Numerical Investigation of the Evaporation and Mixing of UWS in a Diesel Exhaust Pipe. International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering, 8(10), pp.1080-1084.
13	Tang, W., Cai, Y. and Wang, J., 2015. Experimental studies on the diesel engine urea-SCR system using a double NOx sensor system. Environmental Engineering Research, 20(4), pp.397-402.
14	Gall, M., 2015. Study of SCR using Cu-Zeolite catalysts on a light-duty diesel engine under steady state and transient conditions (Doctoral dissertation, Coventry University).
15	Nakasaka, Y., Kanda, T., Shimizu, K.I., Kon, K., Shibata, G. and Masuda, T., 2019. Micropore diffusivities of NO and NH3 in Cu-ZSM-5 and their effect on NH3-SCR. Catalysis Today, 332, pp.64-68.
16	Johansson, S., 2006. Evaluation of alkali-impregnated honeycomb catalysts for NOx reduction in the SCR-process.

17	Lantto, C., 2017. Sulfur tolerance of SCR catalysts: Development of a lab testing method.
18	Czerwinski, J., Zimmerli, Y., Mayer, A., D'Urbano, G. and Zürcher, D., 2015. Emission reduction with diesel particle filter with SCR coating (SDPF). Emission Control Science and Technology, 1(2), pp.152-166.
19	Tang, W., Cai, Y. and Wang, J., 2015. Experimental studies on the diesel engine urea-SCR system using a double NOx sensor system. Environmental Engineering Research, 20(4), pp.397-402.
20	Heywood, J.B., 1988. Internal combustion engine fundamentals.
21	Sadashiva P., 2018. A review on selective catalytic reduction (SCR) - A promising technology to mitigate NOx of Modern Automobiles. International Journal of Applied Engineering ISSN 0973-4562, 1(13), pp. 5-9.
22	Jayat, F., Reck, A. and Babu, K.V.R., 2011. SCR and SCRi® as After-treatment Systems for Low CO_2 and Low NOx Vehicles (No. 2011-26-0038). SAE Technical Paper.
23	Manjunath F., Jean B. C., 2013. Compact SCR dosing. Symposium in International Automotive Technology. pp. 77 - 79.
24	Saravanan, S., Nagarajan, G., Anand, S. and Sampath, S., 2012. Correlation for thermal NOx formation in compression ignition (CI) engine fuelled with diesel and biodiesel. Energy, 42(1), pp.401-410.
25	Aithal, S.M., 2010. Modeling of NOx formation in diesel engines using finite-rate chemical kinetics. Applied Energy, 87(7), pp.2256-2265.
26	AVL. Air Conditioning unit. [Online] 2007. http://https/www.avl.com/media-conditioning1/-/asset_publisher/gYjUpY19vEA8/content/intake-air-conditioning?_com_liferay_asset_publisher_web_portlet_AssetPublisherPortlet_INSTANCE_gYjUpY19vEA8_redirect=https://www.avl.com:443/media-conditioning1?p_p_id%3D.
27	FEV-sts. Fuel conditioning unit. [Online] 2017. http://https/www.fev-sts.com/fileadmin/user_upload/FUELCON_DE_EN_web.pdf.
28	AVL. Smokemeter. [Online] 2007. https://www.avl.com/-/avl-smoke-meter.
29	Cambustion. HFID. [Online] Cambustion. https://www.cambustion.com/sites/default/files/products/gas/hfr500/fidstd.png.
30	Horiba. Mexa1170HFID. [Online] 2007. http://www.horiba.com/uk/automotive-test-systems/products/emission-measurement-systems/analytical-systems/standard-emissions/details/mexa-1170hfid-851/.
31	Cambustion. CLD 500. [Online] Cambustion. http://https/www.cambustion.com/sites/default/files/products/gas/cld500/cldop.png.
32	Horiba. Mexa 1170HCLD. [Online] 2007. http://www.horiba.com/uk/automotive-test-systems/products/emission-measurement-systems/analytical-systems/standard-emissions/details/mexa-1170hcld-852/.
33	Instrumetnation tools. CO2-ANALYSER-WORKING-PRINCIPLE. [Online] http://https/instrumentationtools.com/wp-content/uploads/2015/08/CO2-Analyzer-Working-Principle.gif.
34	Horiba. Mexa-One. [Online] 2007. http://www.horiba.com/uk/automotive-test-systems/products/emission-measurement-systems/analytical-systems/standard-emissions/details/mexa-one-16671/.
35	AVL. Sesam-i60-ft. [Online] 2007. http://https/www.avl.com/web/guest/-/avl-sesam-i60-ft-multi-component-exhaust-measurement-system.
36	Fuji electric. Gas analyser. [Online] Fuji electric.

	http://https/www.fujielectric.com/products/instruments/products/anlz_gas/box/img/genri/g_ZKG.jpg.
37	Horiba. EMGA-930. [Online] 2007. http://www.horiba.com/uk/scientific/products/elemental-analyzers/oxygennitrogenhydrogen/details/emga-930-3473/.
38	Khan, M.Y., Shimpi, S.A. and Martin, W.T., 2015. The repeatability and reproducibility of particle number measurements from a heavy duty diesel engine. Emission Control Science and Technology, 1(4), pp.298-307.
39	Ghosh, Shibashis. Mechguru. [Online] September 07, 2011. https://mechguru.com/machine-design/understanding-torque-curve/.

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