Studies on Emission Reduction Techniques in Automobiles

by

PRADEEP KUMAR GUPTA

(2011RME7147)

Department of Mechanical Engineering

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY, JAIPUR

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Submitted in fulfillment of the requirements for the degree of

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I dedicate this Thesis to my beloved parents who sacrificed their comforts for the education of their children. They so dearly wanted to see me complete my doctorate, but unfortunately left for their heavenly abode.

DEPARTMENT OF MECHANICAL ENGINEERING

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY, JAIPUR

CERTIFICATE

This is to certify that the thesis entitled **'Studies on Emission Reduction Techniques in Automobiles'** submitted by **Mr. Pradeep Kumar Gupta (2011RME7147)**, to the Malaviya National Institute of Technology, Jaipur for the award for the degree of **Doctor of Philosophy** is a bonafide record of original research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirement for the submission of this thesis.

The results contained in this thesis have not been submitted in part or full, to any other University or Institute for the award of any degree or diploma.

(Prof. Dilip Sharma)
Professor
Department of Mechanical Engineering
Malaviya National Institute of Technology
Jaipur

(Prof. S.L.Soni)
Professor
Department of Mechanical Engineering
Malaviya National Institute of Technology
Jaipur

Date: March 04, 2018

DECLARATION

I, **Pradeep Kumar Gupta**, declare that this thesis titled, "**Studies on Emission Reduction Techniques in Automobiles**" and the work presented in it, are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this institute.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this institute or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself, jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Date: March 04, 2018

Pradeep Kumar Gupta
(Student ID: 2011RME7147)

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Place: Jaipur

Date: March 04, 2018 **(Pradeep Kumar Gupta)**

ABSTRACT

There is a serious need for controlling exhaust emissions in transportation sector. Though strict automotive emission norms are being implemented by all countries, still the road worthiness of vehicles is tested as per the year of manufacture. Hence, old vehicles (Euro III and earlier), which produce more emissions, will continue to ply on roads, fulfilling the emission norms of their respective year of manufacture, especially in developing nations. Hence, it is desired that appropriate emission reduction technologies are tested on such engines to analyze their feasibility. Nitrogen oxides (NOx) and particulate matter (PM) emissions from diesel engines require more attention. While studies have been conducted on constant speed stationary engines and modern engines, this study tried to analyze the effectiveness of an uncoated (uncatalyzed) wall-flow type ceramic diesel particulate filter and an electronic control unit (ECU) controlled exhaust gas recirculation valve on a Euro-1, 4-cylinder, water-cooled, direct injection, variable speed, automotive compression ignition engine in a laboratory set-up in India. Also, this study focused on diesel particulate filter regeneration by two methods: active regeneration by diesel injection in the particulate filter using an electronic control unit; and off-board regeneration by taking out and heating the diesel particulate filter in an electrical resistance furnace at 650^{o}C for 10 hours. The results, in the form of smoke emission, NOx emission and engine performance, obtained using both the regeneration methods were analyzed and conclusions were drawn. It was found that using diesel particulate filter, particulate matter emissions (smoke) were almost entirely eliminated. It was also found that off-board regeneration had numerous advantages compared to active regeneration. Since a furnace would be needed for off-board regeneration, an exchange process for diesel particulate filter is suggested. Reduction of NOx was achieved by testing an Exhaust Gas Recirculation (EGR) valve running the engine on different speeds; with different torques, as also with varying EGR percentages. It was found that using EGR, NOx emissions were substantially reduced (average 45% reduction), however slightly impacting the engine performance. Also, smoke emission increased with EGR. In order to counter the adverse effects, additional emission reduction technologies should be used in tandem with EGR like Diesel Particulate Filter (DPF). Next, DPF and EGR were used in tandem on the same engine giving the desired results of substantial reduction in NOx as well as smoke compared to base case. Effect of vehicle weight on emission was also studied and conclusions were drawn. Various

researchers have come out with different empirical formulae for CO_2 emission with vehicle weight which shows a linear relationship between the two. i.e. CO_2 emissions increase proportionally with increase in vehicle weight keeping other parameters constant. However, no straight relationship could be found between vehicle weight and other emissions though it is certain that other emissions also reduce on reduction in vehicle weight. Various Emission Reduction Techniques (ERTs) were studied and relative importance of ERTs w.r.t. future Bharat Stage (BS) norms was predicted concluding that DPF / Gasoline Particulate Filter (GPF) will be a must post BS IV (BS VI onwards).

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APPENDIX

NOMENCLATURE

2W	2 wheeler (vehicle)
3W	3 wheeler (vehicle)
AFT	After treatment
AQI	Air quality index
BS	Bharat stage (emission standards)
BSFC	Break specific fuel consumption (kg/kWh)
BTE	Break thermal efficiency (%)
CAFE	Corporate average fuel economy
CARB	California (CA) air resources board, USA
CCV	Closed crankcase ventilation
CE	Construction equipment
CEV	Construction equipment and vehicles
CI	Compression ignition
CNG	Compressed natural gas
CO	Carbon monoxide
COP	Conformity of production
CPCB	Central pollution control board, India
CSF	Catalyzed soot filter
CV	Construction vehicle
DG	Diesel generator
DMF	Diesel Multi-Stage Filter
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
ECT	Emission control technology
EPA	Environmental protection agency, USA
ERT	Emission reduction technology
EV	Electric vehicle
FE	Fuel economy
GBD	Global burden of disease
GPF	Gasoline particulate filter

GWP	Global warming potential
HC	Hydrocarbons
HD	Heavy duty
HEV	Hybrid electric vehicle
HSD	High speed diesel
IARC	International agency for research on cancer
IC	Internal combustion
I/M (I&M)	Inspection and maintenance
IUPR	In use performance ratio
LDD	Light duty diesel
LDG	Light duty gasoline
LDV	Light duty vehicles
LNT	Lean NO_X traps
LPG	Liquefied petroleum gas
MoPNG	The Ministry of Petroleum and Natural Gas, India
MPFI	Multipoint fuel injection
MS	Motor spirit (gasoline)
MToE	Million tons of oil equivalent
MUV	Multi utility vehicle
MY	Model year
NMHC	Non-methane hydrocarbons
NO_x	Oxides of nitrogen
NRMM	Non-road mobile machinery
NSC	NOx storage catalyst
OBD	On-board diagnostics
OEM	Original equipment manufacturer
ORVR	Onboard refueling vapor recovery
pDPF	Partial diesel particulate filter
PEMS	Portable emissions measurement system
PEV	Plug-in electric vehicle
PGM	Platinum group metal
PHEV	Plug-in hybrid electric vehicle

PM	Particulate matter
PN	Particle number
POC	Particle oxidation catalyst
ppm	Parts per million
PUC	Pollution under control
RDE	Real driving emissions
SCR	Selective catalytic reduction
SFTP	Supplemental federal test procedure
SI	Spark ignition
SOF	Soluble organic fraction
SUV	Sports utility vehicle
TBI	Throttle body injection
TWC	Three-way catalytic converter
UHC	Unburned hydrocarbons
ULSD	Ultra low sulfur diesel
VOC	Volatile organic compounds
WHO	World health organization

CHAPTER 1

INTRODUCTION

1.1 Research background

Quicker than expected advent of effects of global warming and ill-effects of poor air quality on the health of human and other living creatures have raised serious concerns on greenhouse gas emissions and there is an all-out effort all over the globe to find newer, more economical and feasible emission reduction techniques.

1.1.1 Health status – India and World – attributed to poor air quality

Fig. 1.1 shows the major risk factors for deaths in India in 2015 and ambient particulate matter (PM) proves to be the 3rd largest cause of deaths in India. The figure shows that air pollution (ambient particulate matter + household air pollution) is the cause for maximum deaths in India in 2015 and this trend is repeating itself year after year.

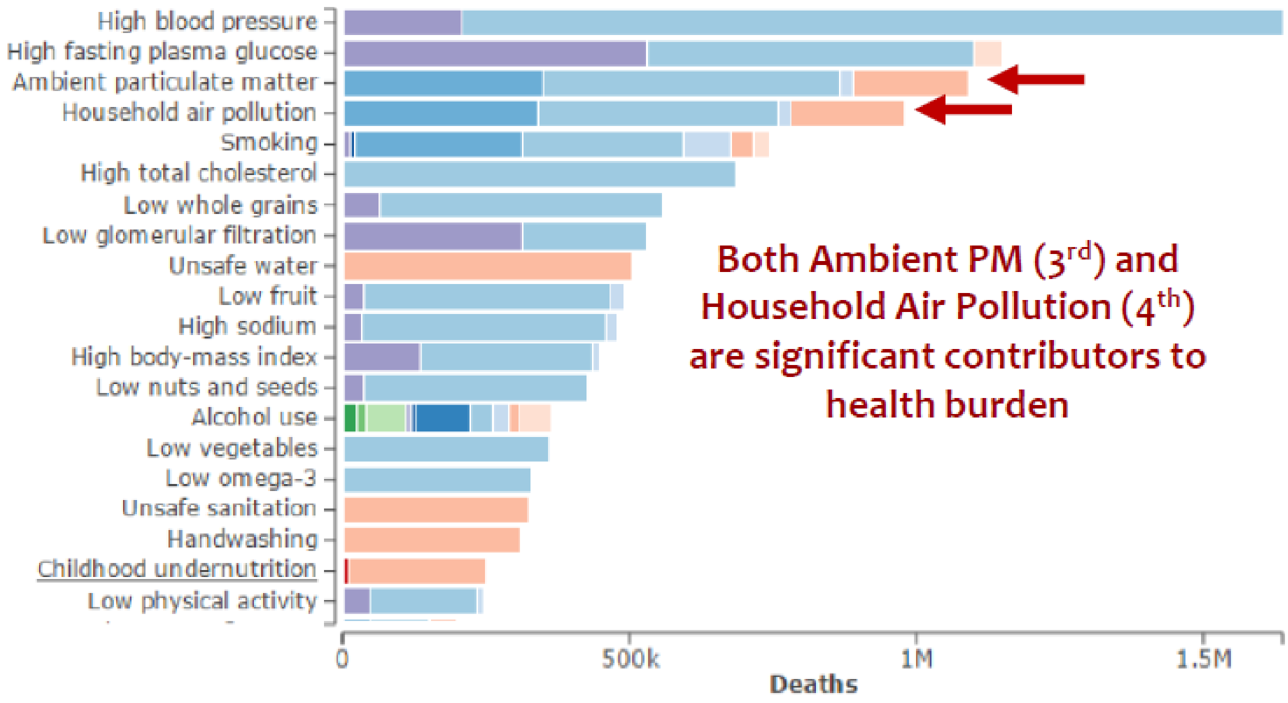


Fig. 1.1 Leading risk factors for deaths in India in 2015 [1, 2]

The major diseases related to PM are [3]:

- Premature death
- Lung cancer
- Exacerbation of COPD (Chronic Obstructive Pulmonary Disease)
- Development of chronic lung disease

- Heart attacks / stroke
- Hospital admissions and ER (Emergency Room) visits for heart and lung disease
- Respiratory symptoms and medication use in people with chronic lung disease and asthma
- Decreased lung function
- Low birth weight

In addition to PM, NOx also has quite serious impact on human health and environment. The adverse effects of various air pollutants are shown graphically in Fig. A.1 of appendices, which is quite complicated and hence often neglected. Table 1.1 shows the global warming potential of various pollutants comparing their intensity with that of CO_2 with the value of CO_2 taken as 1.

Table 1.1: Global warming potential of different pollutants [4]

Pollutant	**GWP – 100 year**
Carbon dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous oxide (N_2O)	298
Carbon monoxide (CO)	1.9
Non-methane volatile organic compound (NMVOC)	3.4
Nitrogen oxide (NOx)*	NA

*GWP for NOx is highly uncertain and hence, it is not included here.

Black carbon (a PM constituent) has been recently identified as a significant contributor to global warming with a CO_2 equivalence estimated to be several hundred times that of carbon dioxide [5].

The major health and environment impacts of NOx are [6]:

- Poor visibility as nitrates and NO_2 block light
- NOx with VOCs create smog which damages lungs, vegetation and crops
- NOx reacts to form acid vapors and particles, which penetrate lungs to cause bronchitis and other respiratory diseases
- Acid rains damage forests, buildings and water sources
- Global warming – N_2O is 300 times more damaging than CO_2 as shown in table 1.1
- NOx travels long distances with wind resulting in damages to far-off places also

Table 1.2 shows the ill effects of various pollutants on health and ecosystem. The major health problems due to exhaust emissions (consisting primarily of PM, NOx and CO_2) are headache, fatigue, respiratory problems, wheezing, cough, cancer, chest pain, reduced reflexes, etc.

Table 1.2: Effect of various air pollutants on health and ecosystem [3]

Air Pollutant	Effects
Criteria pollutants (i.e., CO, SO_2, NO_2, O_3, PM2.5/PM10 and Pb)	Adverse health and ecosystem effects
Light scattering and absorbing PM and gases (e.g., NO_3-, NH_4+, OC, sea salt, soil and NO_2)	Adverse visibility, health and ecosystem effects
Hazardous Air Pollutants (HAPs, or toxics; e.g., persistent organic pollutants [POPs] and metals [e.g., As, Cd, Cr, Cu, Hg, Ni, Pb, Se and Zn])	Carcinogenic health effects (cancer, reproductive or birth defects) Adverse environmental effects (bio-accumulation of Hg in fish and lakes)
Oxidizing pollutants (e.g., H+, SO_4= and O_3)	Destruction of forests, crops and lakes
Depositing pollutants (e.g., SO_2, HNO_3, O_3, soot [BC] and soil dust)	Soiling and degradation of buildings, antiquities, vehicles and clothing
Reduced sulfur compounds and certain VOCs	Unpleasant odors
Climate forcers (e.g., BC, O_3, CO_2, CH_4, and halocarbons [Freon-122])	Alter earth's radiation balance (e.g., absorbing electromagnetic radiation, depleting stratospheric O_3 and changing cloud cover and water vapor)

1.1.2 Air quality in India

In India, 93 out of 670 cities under observation by Central Pollution Control Board (CPCB) could not meet the norms in 2016, and hence, were declared non-attainment cities. Out of these 43 were critically polluted [7]. Table 1.3 shows the city-wise air quality index for 21 major cities of India as of January 2016 as provided by CPCB, India on their website. The data shown that the AQI of none of the Indian cities is in green zone (0-50), only 1 city is in satisfactory range (51-100) and 8 cities including the national capital, Delhi in red zone i.e. very poor (301-400) or severe (>400).

Table 1.3: City-wise Air Quality Index values in Jan 2016 for various cities of India [7]

S.No	Cities	Max	Min	Average
1	Agra	449	262	372
2	Bengaluru	210	55	122
3	Chandrapur	237	84	141
4	Chennai	314	63	140
5	Delhi	434	269	362
6	Faridabad	453	276	399
7	Gaya	348	123	278
8	Haldia	113	51	90
9	Hyderabad	230	82	142
10	Jaipur	344	247	294
11	Jodhpur	394	147	284
12	Kanpur	455	60	359
13	Lucknow	408	183	339
14	Muzzaffarpur	474	300	409
15	Navi Mumbai	116	79	103
16	Panchkula	283	27	125
17	Patna	488	112	388
18	Pune	320	92	195
19	Rohtak	300	82	191
20	Solapur	196	94	133
21	Varanasi	487	266	409

Good (0–50)	Satisfactory (51–100)	Moderate (101–200)	Poor (201–300)	Very Poor (301–400)	Severe (>401)

1.1.3 Causes of poor air quality

The Global Burden of Disease (GBD), a systematic scientific effort to quantify the magnitude of health loss from disease and injuries (e.g. cardiovascular disease, respiratory disease, HIV-AIDS, cancer, road traffic injuries, etc.) in 195 countries around the world from 1990 to 2015 and risks factors (e.g. smoking, diet, high blood pressure, air pollution, obesity, etc.) associated with those diseases shows the following as major sources for air-pollution [2]:

- Transportation (on-road, non-road)
- Household Biomass
- Brick Kilns, stone crusher, hot mix plants etc.)
- Coal: Power, Industry, Domestic
- Non-coal Industrial (large number of DG sets)
- Agriculture
- Open Burning

Transportation forms to be the most major source of air pollution especially NOx in India. As is seen from Fig. 1.2, transportation contributes for 18% of PM and 53% of NOx in India. Key emissions from vehicles include carbon monoxide (CO), unburned hydrocarbons (HC) and volatile organic compounds (VOC), nitrogen oxides (NOx), and particulate matter (PM).

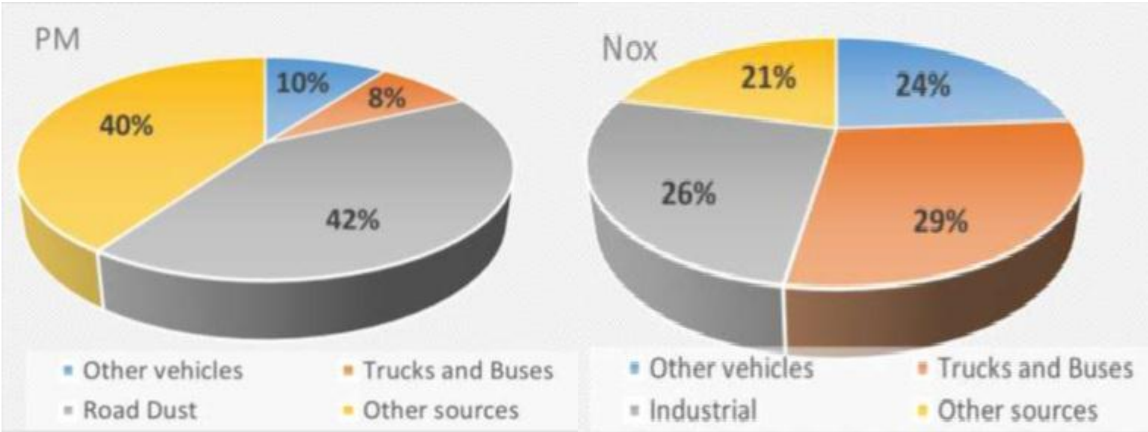


Fig. 1.2 Source of PM and NOx in India [6, 8]

The primary reasons for automotive pollution are [3]:

- Uncontrolled growth of vehicular population
- Type of vehicles on road (predominant old vehicles, 2W/3W)
- Fuel quality issues
- Fuel adulteration issues
- Emission from Off Road Engine (Tractor, Construction Vehicles, Earth moving Equipment, etc.)

1.1.4 Prediction for future air quality

Global CO_2 emissions are expected to increase by 1.9% annually between 2001 & 2025 which may result in more than 5ºC global temperature rise. Developing countries' emissions are expected to grow above the world average at 2.7%. IC engines consume nearly 75% of petroleum oils, of which more than half is consumed by transport sector followed by construction equipment and vehicles (CEV), tractors, generators, etc. Each gallon of fuel burnt adds 20 pounds of CO_2 in the environment. This means we are adding ~ 4 tons of CO_2/vehicle/year [9, 10].

According to the World Business Council for Sustainable Development, global personal and goods transport is expected to grow rapidly through 2050, which will drive the worldwide demand for fuel, expected to double by 2050 from present levels of demand. In industrialized countries, even as cleaner vehicles are replacing older and dirtier ones and total transportation emissions are beginning to decline due to stringent emission regulations, vehicles are still a significant source of air pollution. Whereas, in developing and transition countries, vehicle numbers are growing exponentially and, without strict controls in place, emissions from transportation sources are becoming an increasingly urgent concern [5].

Transport sector is the major consumer of petroleum. In India, the current demand in transport sector is 75 MToE (i.e. 14 % of total energy consumed in India) and it is expected to reach 240 MToE by 2040. Passenger cars' population is expected to rise from 28 million in 2013 to 280 million by 2040 and an additional 30 million more trucks will be on road by 2040 as compared to 2013. 2/3 wheeler population is expected to double by 2040 [11, 12].

Fig. 1.3 shows the expected increase in vehicle population in India and it looks clear that IC engines (gasoline and diesel) will be the main technology in the foreseeable future [13].

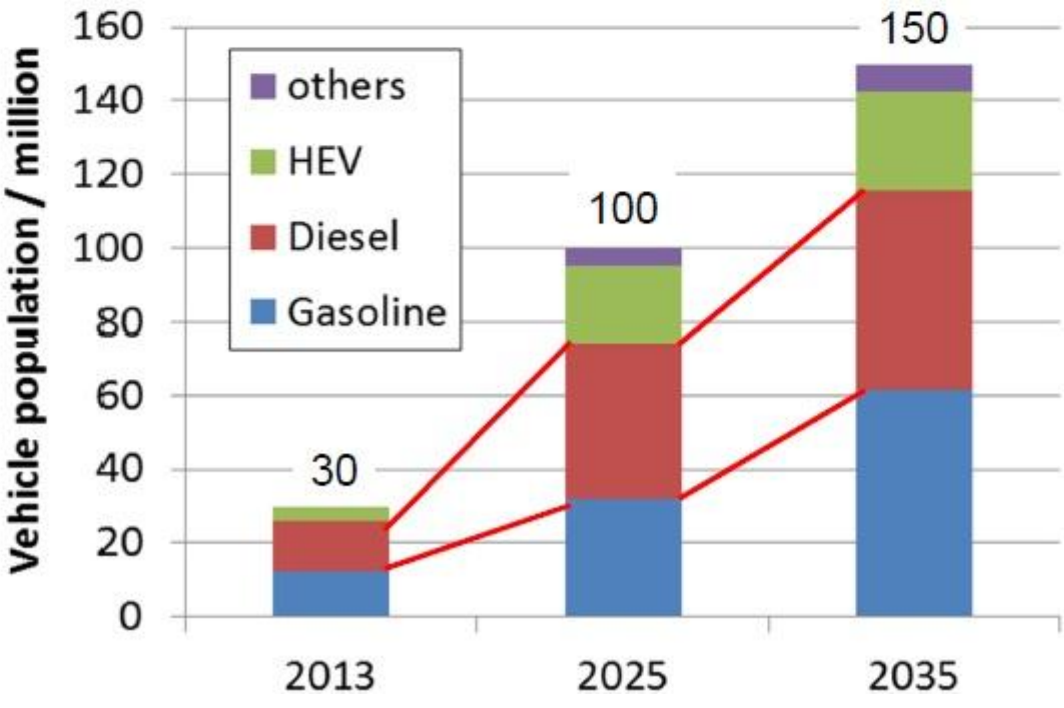


Fig. 1.3 Expected increase of vehicle population in India between 2013 and 2035 [13]

India wide vehicular NOx and PM10 emission is predicted to increase by 260% between 2015 and 2035. HD vehicles in India are predicted to account for 50% of total vehicular PM10 emissions and 38% of NOx emissions by 2035. Currently, up to 40% PM10 and 90% NOx emissions in certain cities of India come from HD vehicles [14, 15].

The above scenario presents demanding challenges for all involved in the transportation sector to reduce both harmful exhaust emissions and fuel consumption.

1.1.5 Ways to improve air quality by reduction in automotive emissions

A combination of regulatory tools and incentives is necessary to reduce transport emissions. Various options for urban air quality improvement focusing primarily on automotive pollution control are [3, 16]:

- Fuel quality improvement pan India (BS-VI quality fuel): High fuel quality (especially low sulfur levels) enables advanced emission control technologies (using catalysts) to be deployed in the fleet.
- Strict check on fuel adulteration / removal of kerosene from market: Fuel quality compliance programs are critical to prevent damage to engines.
- Improved inspection and maintenance (I&M) system for in-use vehicles:
  - Catching gross-emitters
  - Scrappage / replacement programs
  - Retrofit programs
- Stringent mass emission standards for new vehicles (BS-VI norms):
  - Must consider emissions from all mobile sources: on-road, off-road, marine, locomotives, aviation, etc.
  - Real-world performance (RDE testing)
- Improvement in mass transport infrastructure (buses, metro-rail, monorail, etc.) – this will reduce number of personal vehicles on road.
- Improvement in road conditions – While good roads directly improve fuel economy, they also improve fuel economy indirectly by facilitating vehicle weight reduction.
- Restrictions on personal vehicles during strong inversion/calm atmospheric conditions.

1.2 Automotive emissions in the world

Automotive emissions are one of the major causes for poor air quality and global warming as is seen from the data produced above.

1.2.1 The key challenge: Old diesel engines

Particles emitted from diesel engines are small – in most cases less than 2.5 microns in diameter, and thus have raised many health concerns. Diesel exhaust contributes to respiratory and cardiovascular diseases, including lung cancer. Toxic emissions from diesel school bus tailpipes and crankcases pollute bus interiors, as well as outdoor air. Children, with their developing lungs and higher respiratory rates, are especially vulnerable. Diesel exhaust is also classified as a known human carcinogen [1, 17]. Exposure to older diesel is pervasive in much of the world.

The carbonaceous component of PM (black carbon) has been found to be a significant contributor to the atmospheric warming effect by enhancing the absorption of sunlight. The global warming potential of black carbon has been estimated to be several times higher than that of CO_2 on unit emission basis. Black carbon particles remain airborne for few weeks; therefore, removing black carbon from diesel exhaust has an immediate benefit to both global warming and public health.

The NOx emissions also pose a number of health concerns. Once in the atmosphere, NOx react with volatile organic compounds (VOCs) in the presence of sunlight to form Ozone. Ozone is a reactive and corrosive gas that contributes many respiratory problems. Ozone is particularly harmful to children and the elders.

NOx emissions are also a major contributor to PM2.5 inventory when they react in the atmosphere with ammonia and other gases to form nitrate particles as secondary PM2.5.

PM, black carbon and NOx are the major emissions from diesel. Normally, CO and HC are well controlled emissions from diesel engine combustion. Older diesel vehicles, including buses, are said to be a major source of carbon dioxide (CO_2) and black carbon emissions. With the aging of engine, CO and HC emissions may exceed and become an issue in addition to NOx, PM and black carbon issues. Old / tampered / unmaintained diesels emit higher emissions. Depending on the type and age of the vehicle, bus emissions may make their way into the bus cabin. The pollution comes from two sources (a) the tailpipe and the (b) engine crankcase. Even though children may spend only a small portion of their day on buses, the high exposures they receive inside the bus can add considerably to their daily and annual exposures [5].

1.2.2 Indispensability of diesel vehicles

Despite health and environmental concerns, diesel engine remains a popular means of powering world's heavy-duty trucks, buses, construction vehicles (CV) and other heavy equipment / off-road vehicles because they are quite reliable, extremely durable, fuel efficient, easy to repair, relatively inexpensive to operate, high-torque (at low speeds) engines. In heavy-duty trucks, some engines have achieved operating lives of a million miles; some engines power city buses for up to 15 to 20 years.

From the standpoint of greenhouse gas emissions, diesel engines can compete with other advanced technologies, like hybrid electric vehicles, due to a diesel engine's inherent fuel economy relative to conventional spark-ignited, gasoline engines. Diesel-powered vehicles have demonstrated a 30-40% fuel economy advantage over their gasoline counterparts. This translates to about a 20% reduction in CO_2 emissions [5].

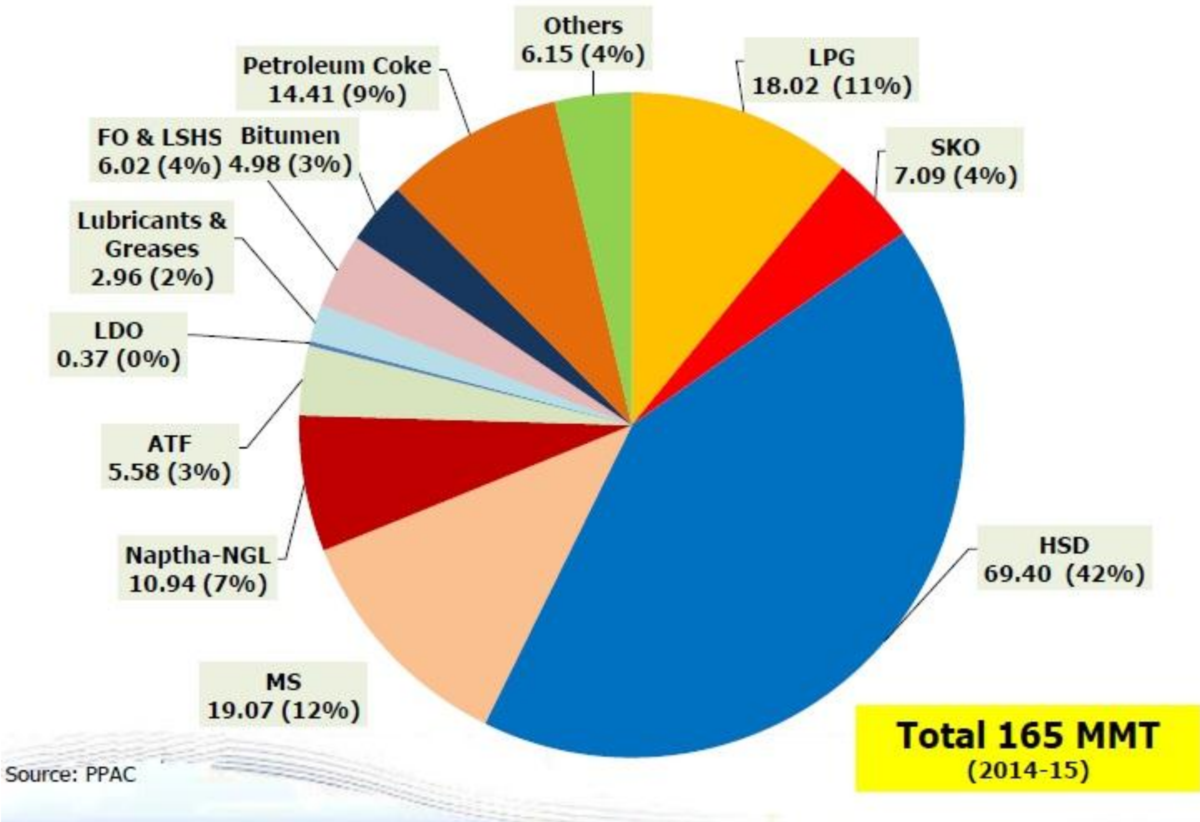


Fig. 1.4 India's consumption pattern of petroleum products in 2014-15 [18].

Because of the above attributes, better fuel economy and lower CO_2 emissions, diesel engines are popular and significant powertrain for several applications and shall continue to be in popular use for decades to come. Fig. 1.4 shows the consumption pattern of various petroleum products in India for 2014-15, with diesel having 42% share (more than double of motor spirit, i.e. petrol/gasoline and LPG), and it is quite evident from it that despite all the negatives of diesel, it might take at least couple of decades to find a suitable replacement for diesel as source of energy.

1.2.3 Automotive emission norms (BS, Euro, US, China, etc.)

A number of countries worldwide, including India, have established significantly lower exhaust emission limits for new diesel engines. India will be leap-frogging to BS VI in 2020 from BS IV pan India in 2017 as per their revised aggressive plan. According to the original plan, BS V was to be implemented in 2019 and BS VI in 2024 [5]. Fig. 1.5 shows the changed timelines for implementation of BS VI with BS V completely skipped.

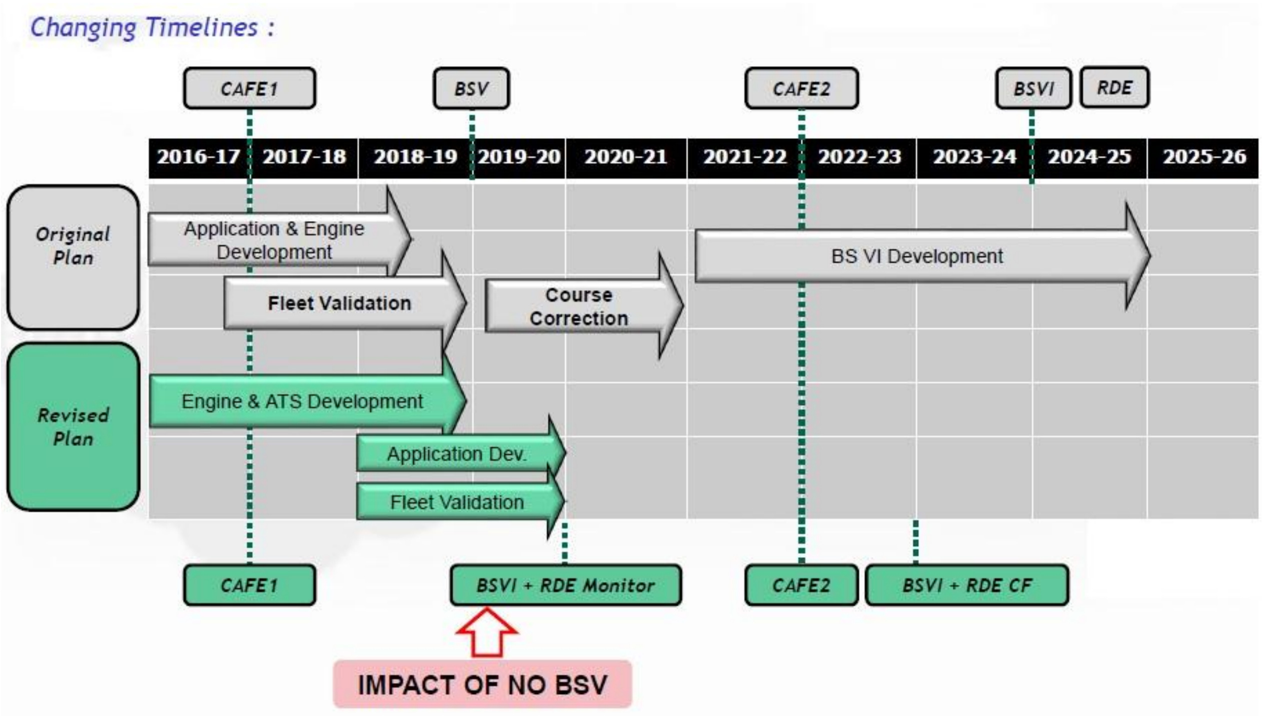


Fig. 1.5 Change in implementation plan of BS V and BS VI norms (No BS V now) [19]

As per Government of India notification number GSR 889(E) dated 16th September, 2016, on BS6, during type approval and conformity of production (COP) applicable from 1st April, 2020, real world driving cycle emission measurement using PEMS shall be carried out for data collection and from 1st April, 2023 real world driving cycle emission conformity shall be applicable [19], to all models (four wheelers), whereas two wheelers will have to follow Euro 5 norms. As per the new administrative procedures:

– In-service compliance of 160,000 km is required
– PEMS based RDE clearance is required (data collection is already underway)
– On-board diagnostics (OBD) is introduced for 2 and 3 wheelers also.

And the new fuel economy (FE) regulations for passenger cars are:

- Phase 1: 2017-18 to 2021-22, manufacturers to meet 129.8 g/km CO_2 (fuel consumption standard of 5.5 liters per 100 km) at industry weight of 1037 kg
- Phase 2: 2022-23 onwards, manufacturers to meet 113 g/km CO_2 (fuel consumption standard of 4.78 liters per 100 km) at industry weight of 1145 kg

It is an open secret that cars have higher emissions on roads than in the laboratory. That's how manufacturers like Volkswagen were able to 'cheat' the tests. Hence, real world emission testing is a welcome regulation [19].

The major developments globally in terms of automotive emission norms are [16]:
- US implementation of Tier III light-duty emission standards from MY 2017 onwards
- EU adopting real-driving emissions (RDE) test requirements
- EU and Japan adopted World Harmonized Light-duty Vehicles Testing Procedure (WLTP).
- Beijing proposed perhaps the most stringent emission standards in the world
- China proposed China 6/VI emission standards
- EU adopted Stage V emission standards for non-road vehicles

China 6 emission standards are an ambitious step forward, in which:
- Emission limits are fuel neutral and more stringent than those in Euro 6
- N_2O emission limits are specified
- Stringent evaporation limits, innovative 48-hr test procedure, OBD and Onboard refueling vapor recovery (ORVR) requirements are added.
- OBD provisions are largely based on CA OBD II with a few modification
- Modified RDE boundary conditions are applied

Key aspects of Euro VI emission standards are as follows (Courtesy: FEV GmbH) [6]:

- Challenging emission limits for NOx, PM, PN, CO and HC
- On-board diagnostics
- NOx control monitoring (driver warning and inducement)
- World harmonized test cycles
- In-service conformity / In-use emissions
- Certification, conformity and enforcement
- Useful life requirements
- Repair and maintenance information

There is a drastic reduction in NOx emission limits from BS IV to BS VI as shown in Fig. 1.6 in a very small time span. This will certainly bring about a very positive change in Indian environment, but obviously this will cost some extra money. Hence, it is not wrong to say that though BS VI is bad for pocket, but it is good for lungs.

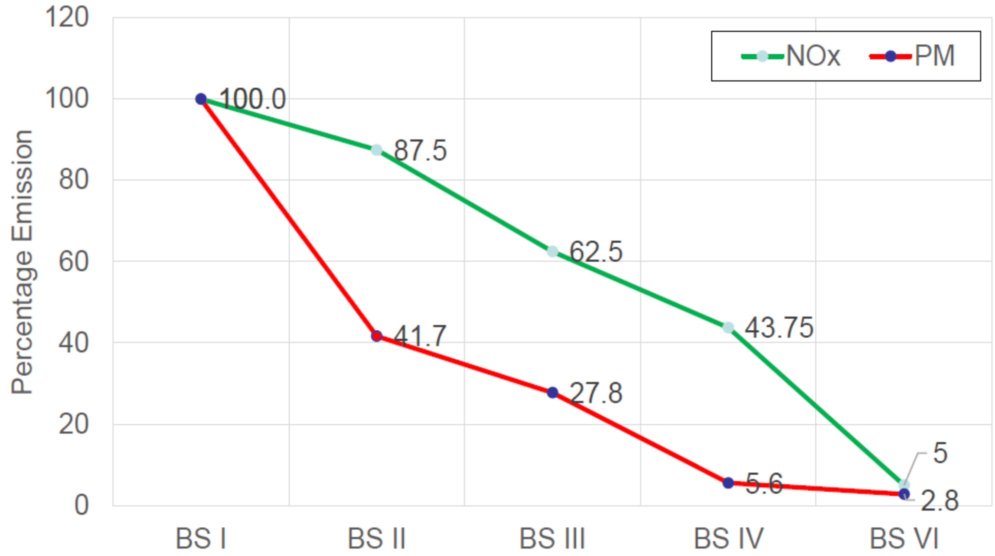
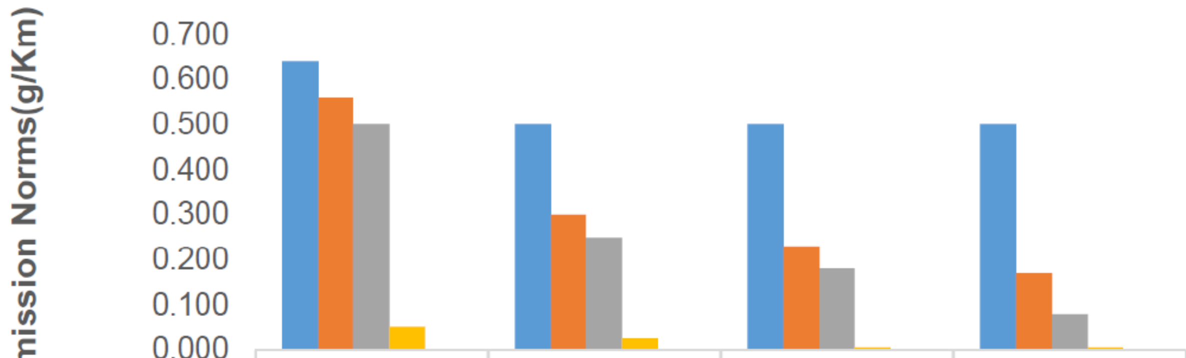


Fig. 1.6 % reduction in PM and NOx limits from BS I to BS VI for HDD vehicles [6]

Fig. 1.7 shows the emission limits from BS III to BS VI for diesel cars and Fig. 1.8 shows the emission limits for BS I to BS VI for HDD vehicles. PM and NOx limits for various Euro and US emission standards for LDVs are shown in Fig. A.2 in appendices.



	BS3	BS4	BS5	BS6
CO(g/km)	0.640	0.500	0.500	0.500
HC+NOx(g/km)	0.560	0.300	0.230	0.170
NOx(g/km)	0.500	0.250	0.180	0.080
PM(g/km)	0.050	0.025	0.0045	0.0045
PN	0	0	6.00E-11	6.00E-11

Fig. 1.7 BS III to BS VI emission limits for passenger cars (diesel) [20]

Norm	Year	NOx	CO	HC	PM	PN	Test Cycle
Bharat Stage I	2000	8.0	4.5	1.1	0.36	-	R 49
Bharat Stage II	2001/2005 (*)	7.0	4.0	1.1	0.15	-	R 49
Bharat Stage III	2005/2010	5.0	2.1	0.66	0.10	-	ESC
Bharat Stage IV	2010/2017	3.5	1.5	0.46	0.02		ESC
Bharat Stage VI	2020 -	0.40	1.5	0.13	0.01	6×10^{11}	WHSC

NOx 90% redn.   PM 50% redn.

Fig. 1.8 BS I to BS VI emission limits in g/kWh for HDD vehicles [6]

1.2.4 Challenges / Opportunities to achieve future emission norms in India

While the Indian Government has decided to leapfrog to BSVI pan India in 2020, there are concerns all over (amongst automobile manufacturers and sellers, fuel refiners, fleet owners, etc.) about the successful implementation and cost impact of the same due to many constraints which are discussed below as noises.

Noise # 1: Quite an aggressive implementation timeline

BS VI implementation requires significant changes to engine and after treatment systems. Also, extensive calibration effort is required for latest OBD and in-use performance ratio (IUPR) standards [6]. While Europe, with much superior infrastructure, law enforcement and discipline, took 9 years (2005 to 2014) to move from Euro 4 to Euro 6, it is a big question of India can achieve the same in 3 years (2017 to 2020), especially when it took 7 years to move from BS III to BS IV pan India (2010 to 2017), skipping BS V, compared to Europe’s 5 years (2000 to 2005) for the same work [21, 22]. Comparison of implementation schedule of various Euro and BS norms is shown in Fig. A.3 of appendices. It is worth mentioning here that BS VI is almost same as Euro 6. Also, BS VI is being implemented in 2020 pan India whereas BS IV was implemented in phases and there are many Indian cities on BS III even today [14]. Schuckert has commented that while Euro 6 requires by far the most complex technology, India today is mainly on Euro 0 to Euro III [23].

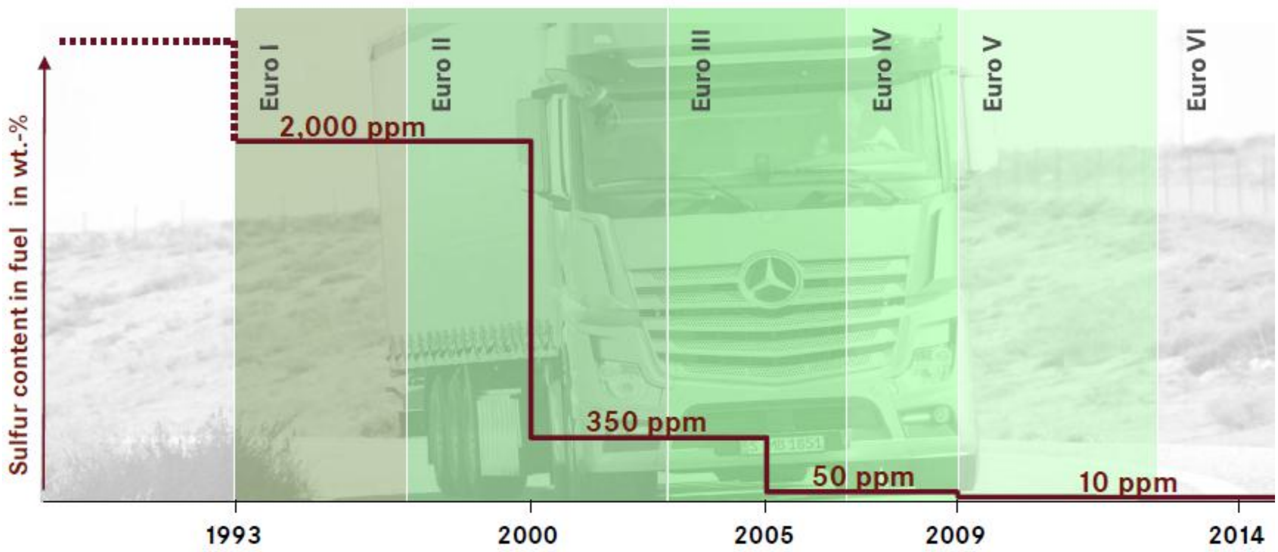


Fig. 1.9 Sulfur (ppm) limits (max) for Euro I to Euro VI diesel [23]

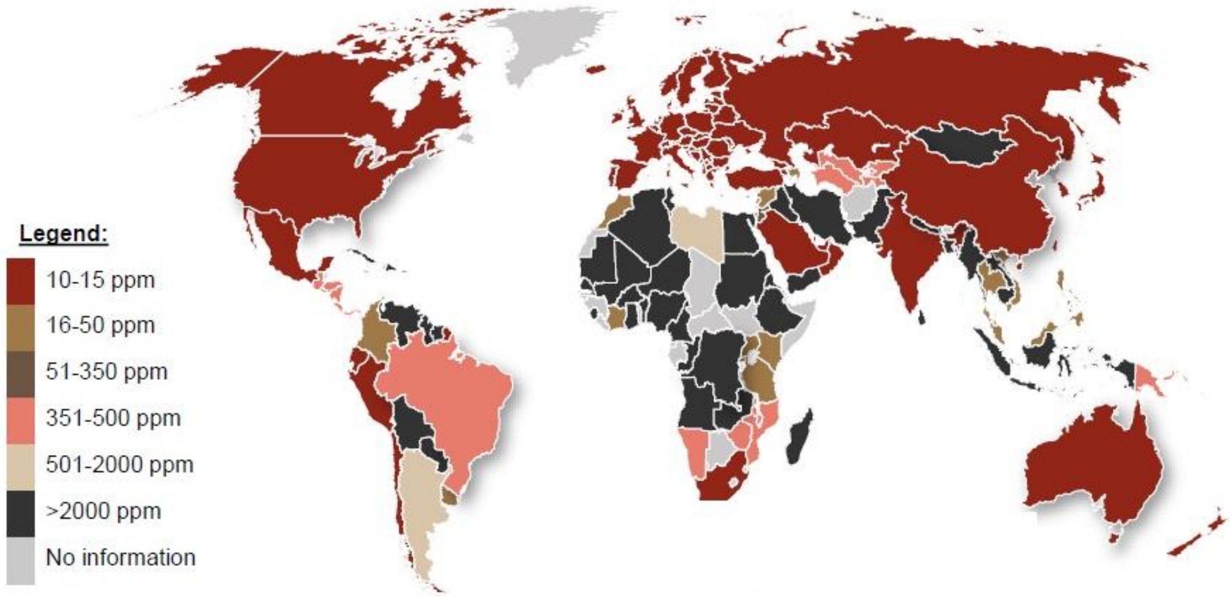


Fig. 1.10 Maximum Sulfur limits in on-road diesel in 2020 (planned) [26, 27]

Noise # 2: Availability of unadulterated ultralow sulfur fuel pan India

Fig. 1.9 shows the maximum sulfur allowed in diesel for Euro I to Euro VI. Fig. 1.10 shows the maximum sulfur norms in various countries in 2020. Countries like India, China, South Africa and Ukraine are moving to 10 ppm by 2020, which is quite encouraging but at the same time challenging. Fig. A.4 in appendices shows sulfur (ppm) and aromatics limits for BS III, IV and VI fuels.

The Ministry of Petroleum and Natural Gas, India (MoPNG) announced nationwide supply of BS VI fuel in conjunction with the proposed BS VI emission standard implementation date of

1st April, 2020. However, a transition phase of one year is expected before the 10 ppm S diesel fuel is fully available nationwide. How to bridge this one year phase is still not clear. The fuel companies have stated that they will be able to supply 10 ppm S fuel to all the vehicle manufacturers in the quantities required for testing by April 2019 and will be able to start full scale supply of 10 ppm S fuel (both petrol and diesel) pan India by April 2020. Hence, to deliver on the fuel road map for 50 and 10 ppm fuels pan India by 2017 and 2019 is a challenge [22, 24-25].

Adulterated fuel; the misuse of kerosene - Kerosene in India is subsidized with the intention of providing poor households with sufficient fuel for cooking and lighting, however, this is subjected to widespread abuse in the form of mixing the same with diesel / petrol. Kerosene can contain up to 2500 ppm S and hence, even a small quantity of kerosene can have disastrous effect on engine, after-treatment devices and emissions. While OEMs are expected to develop and utilize sulfur tolerance technologies and better DeSOx strategies / technologies, there is no solution for kerosene adulteration - it simply kills the catalyst and catalyst is very expensive [24].

Noise # 3: Economic power to bear the additional cost

The economic power has essential impact on the fleet emission standard distribution as is evident from Fig. 1.11, which shows that majority of Indian vehicles are still on Euro 0/I/II levels. Only with costly measures in engine and after-treatment systems Euro VI (or BS VI) can be attained. Will the Indian heavy duty vehicle market be ready for a costly and complex technology so soon, is a big question [23]. Make in India initiatives on all new technologies are needed to have less impact on cost and availability [6].

Noise # 4: CO_2, fuel economy standards and costs associated

Due to 90% reduction in NOx limits, there will be significant loss in fuel efficiency, but norms are being made with stricter fuel efficiency at the same time [21]. To meet the strict NOx levels, fuel economy will suffer, however, to meet the fuel economy standards, expensive NOx control technologies will have to be used like LNT, SCR in addition to EGR. But to keep the cost impact minimal, catalyst should be downsized and PGM loading is to be minimized. And with chances of high sulfur in fuel, DOC, SCR, LNT, cDPF, etc. will be futile [24]. Indian 2 wheelers’ engines are lean burn hence most fuel efficient in the world, but BS-VI norms will have major impact on FE as NOx limit is very low, hence, engines have to be calibrated to stoichiometric ratio. Also, BS-VI gasoline octane number continues

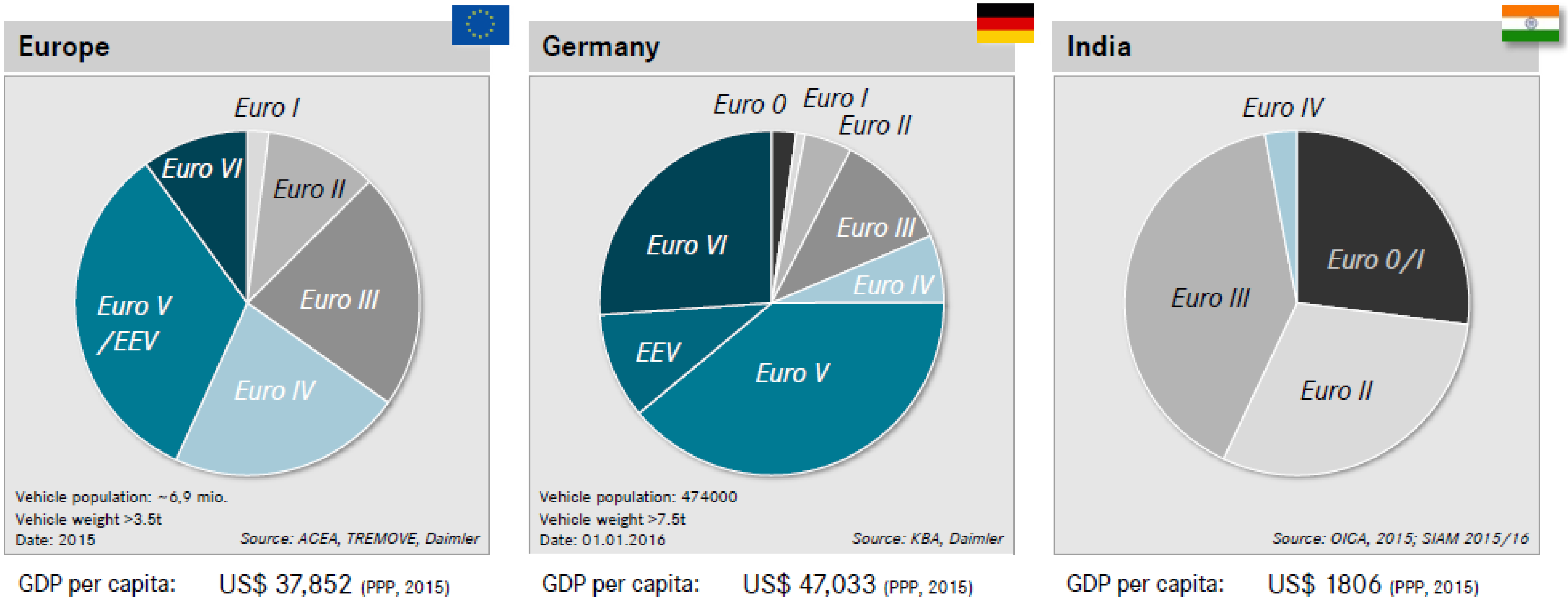


Fig. 1.11 Vehicle population distribution in Europe, Germany and India by respective emission norms [23]

to be 91, whereas Euro-6 fuel has octane rating of 95 [21]. Fig. A.5 shows the maximum sulfur content and minimum octane no. for gasoline for various BS norms. Here, it is important to mention that high octane fuel is need of the hour. With change in octane from 91 to 95, CR can be enhanced by 10% resulting in FE improvement of 2% [11].

Noise # 5: Indian driving pattern and cycles, Indian market demographics

- Road and infrastructure conditions are challenging – due to poor road conditions, rolling resistance is 30% higher which results in adverse impact of 2.5% on fuel economy. Also, due to uneven roads and unregulated speed breakers, 30 – 60 mm extra ground clearance is provided which results in poor aerodynamics resulting in further reduction of 1% FE.
- Maintenance / service practices are still fairly basic. Also vehicle are often seen clocking 1 million km. This will pose challenge to the durability of after-treatment devices.
- Heavy traffic and road conditions results in slow speeds and low exhaust temperatures – this restricts usage of SCR and passive regeneration of DPF becomes impossible.
- Also poor road conditions warrant for heavier vehicles, and this addition in vehicle weight results in reduction of 1% FE.
- Challenging environmental conditions: vibrations, poor air quality, doubtful fuel / lube / AdBlue quality, very low to very high torque zones, large temperature gradient (sub-zero temperatures in Himalayas to around 50^{o}C in Rajasthan, huge humidity difference (near 0 to near 100 RH), etc. [24, 28].

Noise # 6: Indian hot climate resulting in high VOC emissions

- India's hot climate results in high year-round evaporative VOC emissions. While significant reductions in exhaust emissions are expected with BS VI implementation, the evaporative VOC inventory will continue rising above the current 100,000 mt/yr. India should work towards an accurate evaporative and refueling emissions inventory and consider a more effective control program like those in the US, Canada, S. Korea, and China [29].

Noise # 7: Indian Powertrains

In India, the trucks are smaller and are often heavily overloaded. The engines used are smaller for the same category and engine power rating is low (Sub 1.0 L engines for LDD and LDG applications). India is operating at significantly lower power to weight ratios compared to the rest of the Euro emissionized world, as is clear from Fig. A.6 and Fig. A.7 in appendices [24]. From Fig. A.6, it is clear that while engine power (in HP) to vehicle weight (in tons) in Europe is of the tune of 12 to15, the same for India is 4.5 to 6.2 and China has more than double of that of India. Fig. A.7 shows that while almost 100% of Indian vehicles, weighing more than 15 mt, have less than 9 L engines, Europe and USA have almost 100% vehicles with more than 9 L engines.

Noise # 8: Urea / AdBlue availability

Urea manufacturers in India have to necessarily sell urea only for fertilizer applications as per law. Hence, integrated AdBlue manufacturing at urea plants does not seem possible in the current situation and establishing a pan-India AdBlue infrastructure and AdBlue quality program is a great challenge [22, 25, 30].

Noise # 9: Compliance issues and Indian user mindset

- India might need to establish effective compliance programs (e.g. U.S. EPA/CARB Model) to ensure vehicles deliver needed emission reductions [25].
- Public awareness and strict implementation is required to ensure the practical success of BS VI norms pan India [6].
- Vehicles need to be redesigned for close coupled after-treatment avoiding pipes between engine and after-treatment of several meters. Robust after-treatment systems need to be developed which are tolerant for misuse [22].
- Huge interest of OEM is needed to have reliable systems and prevent customer failures along with customer’s own interest to avoid false handling [22].
- Service organizations have to be trained for electronic controls and operators have to be trained [22].

Noise # 10: Shortage of skilled manpower for testing of vehicles

With approx. 10 auto manufacturers in India, each with approx. 35 models of vehicles, roughly 350 vehicles need to be tested by 2020. BS VI fuel, even for testing will be made available around April 2019. So to do all the testing each manufacturer will need around 250 engineers, whereas as on date, there are less than 300 skilled emission engineers in India. This is again going to be a big challenge [19].

1.2.5 Methods to reduce automotive emissions

Automotive emission reduction methods can be broadly classified in the following categories:

(i) **In-cylinder methods:** These methods include combustion system and fuel injection which comprise of the changes to cylinder design, injection method, injection timing, injection pressure, optimized nozzle spray pattern, re-entrant piston bowl, 4 valves per cylinder, hydraulic lash adjuster, better swirl ratio, common rail system, etc.

(ii) **Air management methods:** Air management methods include turbocharging (variable geometry turbocharging, two stage turbocharging, etc.) and exhaust gas recirculation (basic EGR, cooled EGR, high pressure/low pressure EGR, etc.).

(iii) **After treatment devices:** Unlike in-cylinder methods, after treatment devices reduce emissions by absorbing / adsorbing / oxidizing / reducing various pollutants. These include DOC, DPF, POC, SCR, LNT, NAC, etc.

(iv) **Alternate Fuels:** Not only due to emission reduction, but also for preservation of fossil fuels, there has been a great focus on alternate fuels which include alcohols (ethanol, methanol, etc.), bio-diesels, CNG, LPG, propane, hydrogen, etc. Using these alternate fuels the fuel efficiency goes up by up to 40% and carbon footprint comes down by up to 30% [10].

(v) **Alternate prime-movers:** Vehicles running without IC engines have great advantage in terms of emission reduction. These include HEVs (dual prime movers), EVs, fuel cell operated vehicles, etc.

(vi) **Weight reduction:** Emissions increase with increase in fuel consumption, which increases with vehicle weight. Hence, vehicle weight reduction, change in aerodynamic design, etc. are also important methods to reduce automotive emissions.

CHAPTER 2

LITERATURE REVIEW

2.1 Automotive emission reduction norms and techniques – an overview

Automotive exhaust emissions are of major concern all over world in current scenario. Though strict automotive emission norms are being implemented by almost all countries, still the road worthiness of vehicles is tested as per the year of manufacture. Hence, old vehicles (Euro III and earlier) will continue to ply on roads, fulfilling the emission norms of their respective year of manufacture, especially in developing nations [31, 32].

In India, CO_2 emissions from the consumption of fossil fuels have increased from 293 MMT (million metric tons) to 1293 MMT between 1980 and 2006. ADB projects the CO_2 emission from on-road transport in India will increase about 600% from 2005 to 2035 [4, 33].

Nesamani (2010) observed that PM is a major concern in Indian cities since 60 out of 62 metropolitan cities have already exceeded WHO standards (24-h average ambient air quality standards) and that one of the leading causes of death in India is air pollution [4]. Pundir (2001) stated that the increase in this PM concentration is primarily due to automotive emissions which according to him have increased at a faster rate than any other sector and that 60% of vehicular pollution in India is from the 20% poorly maintained / old vehicles [34].

Pachauri et al. (1998) claimed that NOx has 30% share in total 10.3 million tons of pollution from transport sector in India in 1997 [35]. Wang et al. (2012) and Yi et al. (2007) observed that in large Chinese cities, NOx from automotive emissions accounted for up to 70% of total urban NOx pollution [36, 37]. They also mentioned that NOx is a precursor to photochemical formation of ozone (O_3) which causes many lung related diseases. According to them, NOx is one of the causes of secondary formation of $PM_{2.5}$ and its exposure results in serious health issues including death [35-37]. Baikerikar and Chaudhari (2003) opined that diesel vehicles will essentially have continuous importance in transportation, in spite of high NOx and PM emissions that they produce, because of their economical superiority and reliability [38]. Diesels are needed for low CO_2 emissions and low fuel consumption [39].

There are great opportunities around the globe to reduce conventional pollutant emissions from light-duty vehicles (LDVs), with positive effects on air quality and public health. Even though the benefits of more stringent standards have been demonstrated and the technologies to achieve those benefits are readily available, there are still large differences in the implementation schedules for increasing emission stringency. Among the reasons for delaying the implementation of stricter emission levels is the extra cost added to the vehicle by the emission control system [40].

Emissions control technologies can be divided into two groups: in-cylinder control and after-treatment control. Table A.1 and Table A.2 in appendices show some in-cylinder and after-treatment techniques respectively for emission reduction in automobiles. Almost all gasoline, spark-ignited (SI) engines run at stoichiometric condition, which is the point where available oxygen from the air is completely consumed, oxidizing the fuel delivered to the engine. Stoichiometric SI engines use a homogenous air-fuel mixture with early fuel introduction for good fuel vaporization. Gasoline fuel delivery systems have evolved from carbureted systems to throttle body injection (TBI), multipoint fuel injection (MPFI), and sequential MPFI. The latest evolutionary step, stoichiometric direct injection, represents a significant improvement for spark-ignited engines and when combined with turbocharging and engine downsizing makes them competitive with diesel engines in terms of fuel economy and performance. Air-fuel control has a major impact on the formation of hydrocarbons (HC), or unburned fuel, and carbon monoxide (CO), which is partially oxidized fuel. In contrast, NO_X is a byproduct of combustion, created when nitrogen and oxygen in the air combine during the combustion process. The higher the cylinder temperature, the more NO_X is formed. Thus, the primary strategy to reduce the formation of NO_X in the engine is to reduce combustion temperatures, using faster burn combustion chamber design and exhaust gas recirculation (EGR) [40].

After-treatment emission control for stoichiometric engines is based on three-way catalytic converter (TWC). The TWC is capable of oxidizing HC and CO, and simultaneously reducing NO_X if the air-fuel ratio is controlled very precisely at stoichiometry. Improvements in SI emission control have focused on extreme precision in air-fuel control, maintenance of stoichiometric conditions at all times, and catalyst improvements. The latest systems can simultaneously reduce all three pollutants by more than 99% after the catalyst has reached normal operating temperature. Catalyst improvements have focused on ways to quickly bring the catalyst to operating temperature and minimize emissions following cold starts, while significantly reducing the amount of precious metals required for proper operation [40].

Unlike gasoline SI engines, which always control both the amount of air and the amount of fuel close to complete combustion conditions, the diesel engine runs un-throttled with an excess of air (lean operation). HC and CO emissions are not usually a concern with diesel engines, as the lean operation reduces engine-out HC and CO emissions and enables high oxidation efficiency in simple oxidation catalysts. PM and NO_X emissions are more challenging to control and are the main focus of diesel emissions control research, as well as the main source of technology costs [40]. Tzamkiozis et al. (2010) wrote that since combustion in diesel engine is featured by lean burning (high air-to-fuel ratio), it results in increased NOx emissions [41].

Engine-out PM emissions from diesel engines are also much higher than that from SI engines due to direct in-cylinder fuel injection. The timing of fuel combustion is controlled when fuel is injected and the fuel ignites almost immediately after injection. This allows little time for the fuel to vaporize and mix with air, creating flame plumes. During this combustion process, carbonaceous particulates grow by aggregating with other organic and inorganic particles. Thus, particulate matter (both mass and number) is also much more challenging to control in a CI diesel engine. In-cylinder emission control of NO_X and PM in CI diesel engines is associated with three systems: fuel injection, air handling, and EGR. Fuel injection system improvements involve the use of high-pressure fuel injection with variable injection fuel timing and metering, as well as redesigned nozzle and piston bowl. The fuel injection pressure and the rate of fuel injection are used to control both NO_X and PM. The high-pressure injection improves diesel fuel penetration and atomization, improving the mixing of air and fuel. Advancing fuel injection timing increases combustion pressures and temperatures, improving efficiency and reducing PM, but increasing NO_X emissions. Delaying the injection of fuel has the opposite effect. Multiple injections of fuel, including pilot, main and post injections, minimize the trade-off between NO_X and PM emissions. Multiple fuel injection strategies can only be performed with high-pressure unit injectors or common-rail fuel injectors. Electronically controlled fuel metering and timing are also required for after-treatment devices with active regeneration. Air handling is focused on the use of variable geometry turbochargers to provide the right amount of air under specific engine operational conditions. The availability of additional air reduces PM emissions, and has positive effects on power output. EGR is the most significant technology for in-cylinder NO_X reduction in diesel-powered engines [40]. Hence, implementation of EGR system seems to be essential in light of the regulatory changes and the increasing demand for environment friendly vehicles capable of complying with future regulations [42-47]. The EGR fraction is tailored for each engine operating condition and may vary vastly. The EGR system requires fuel sulfur level below 500 parts per million (ppm) to avoid pipe corrosion with sulfur compounds. Agarwal et al. (2011) elaborated on EGR, a widely used pre-treatment technique for reduction of NOx emissions from diesel engines by lowering oxygen concentration and flame temperature of the working fluid in the cylinder [48]. Broadly three effects alter the diesel combustion process with the help of EGR – (a) lowering of the temperature during the compression and combustion processes by increasing the specific heat capacity of the intake charge (thermal effect) by induction of the recirculated inert gases (in exhaust), mainly carbon dioxide (CO_2) and water vapor (H_2O), (b) the reduction of excess-air ratio (k) by dilution of the intake charge (dilution effect) due to the replacement of intake oxygen with the inert gases, and (c) increase in the ignition delay and slowing down of the fuel burning rate (chemical effect) because of the retardation of mixing of oxygen (O_2) and fuel [49-55]. Plee et al. (1982) documented that the main cause of NOx reduction with EGR is thermal effect rather than the dilution effect [56].

EGR is a well known technique for suppressing knock and reducing nitrous oxide (NOx) emissions in spark-ignition engines, and this technique is now receiving more attention because of the negative effect of EGR on engine particulate emissions [57]. Re-circulating part of the exhaust gas helps in reducing NOx, but appreciable particulate emissions are observed at high loads, hence there is a trade-off between NOx and smoke emission. Opacity of the exhaust gas increases as the rate of EGR is increased [58]. At low loads, the rate of increase in opacity is almost the same with increase in EGR but at higher loads and higher rates of EGR, opacity increases rapidly [58, 59]. A likely mechanism for engine-out particulate growth is the reintroduction of particle nuclei into the cylinder through EGR. These recirculated PM particles serve as sites for further condensation and accumulation promoting larger and greater number of particles [60].

After-treatment of NO_X can be accomplished using lean NO_X traps (LNT) or selective catalytic reduction (SCR) with ammonia. PM after-treatment control relies on diesel oxidation catalyst (DOC) and diesel particulate filters (DPF). LNT is based on materials that can adsorb NO_X during normal lean operation, and then releases them during periodic rich periods of operation. The NO_X adsorber requires a sophisticated air-fuel management system in order to create rich operation and regenerate the trap. NOx adsorbers are capable of 70-

90% NOx reduction, but require ultra-low-sulfur diesel fuel (< 15 ppm). SCR systems use a urea solution to provide ammonia to reduce the nitrogen oxides on a catalytic surface, even during normal lean operation. SCR systems can achieve high conversion efficiencies regardless of the engine-out NOx. This allows for the engine to be tuned at high engine-out NOx levels for higher engine efficiency and lower PM generation. However, the urea must be refilled periodically, which is both a consumer and an enforcement concern. The urea will also freeze at low ambient temperatures, generally requiring heating the urea tank and heating or draining the lines. The diesel oxidation catalyst (DOC) oxidizes HC, CO and the soluble organic fraction (SOF) of PM. In conventional heavy-duty vehicles, the conversion efficiency of these components is high, but the contribution to total PM reduction can be only around 20-25%. DOCs are not effective for PM control in high temperature cycles due to the low SOF in PM at high temperatures. DOCs require 500 ppm or lower sulfur in diesel fuel. Diesel particulate filter (DPF) substrates physically trap solid particulate matter, including soot. Wall flow filters achieve PM reduction efficiencies higher than 95% due to their ability to accumulate the solid fraction of PM, including ultra-fine particles. Catalyzed DPFs require a fuel sulfur level of 50 ppm or lower to be effective [40].

It is felt that implementation of diesel particulate filters seems to be essential in light of the stricter regulations and the increasing demand for environment friendly vehicles capable of complying with future standards. Installation of DPF systems is mandated in all diesel vehicles registered after 2011 in Europe due to the increasing evidence of the toxicity of diesel PM and the proven robustness of the DPF systems [61, 62]. However, since the DPF gets choked with accumulated soot, it needs to be cleaned regularly to keep up the performance. This process of cleaning the DPF is called 'regeneration'. DPF regeneration is done either by: (a) passive regeneration or (b) active regeneration. Passive regeneration burns the deposited material using NO_2 formed from NOx on an oxidation catalyst located upstream of the DPF, whereas active regeneration requires late fuel injections or fuel burners upstream of the DPF to regenerate the trap, increasing fuel consumption modestly [40, 63]. Both, active and passive methods are on-board regeneration techniques. Whereas, the DPF can also be taken out of the system and regenerated off-board by heating in a furnace.

An effective thermal management system is considered necessary to prevent the failure of a DPF system caused by the thermal runaway, which can occur during the oxidation of excess soot deposit in DPF regeneration. A detailed experimental information on heat release characteristics during the oxidation of diesel PM is important not only for devising an efficient thermal management system for DPF regeneration, but also for developing an accurate predictive tool. An experiment for the same was conducted by Chong et al. (2011) [64]. Chong et al. conducted an experimental investigation on the oxidation behavior of diesel PM collected from a DPF test system connected to the exhaust stream of a 1.9 L, 4-cylinder, light-duty diesel engine with a thermogravimetric analyzer (TGA) to measure the instantaneous sample mass and the rate of mass loss during its oxidation for a wide range of conditions. They found that the oxidation rate of diesel soot was nearly constant until about 80% of the sample mass was oxidized, and then decreased as the sample was completely oxidized. They also inferred that the oxidation behavior of diesel soot is strongly influenced by the heat treatment schemes used [65].

Fuel quality must align with advanced technology to meet stringent emission standards. Sulphur content in fuel is the most important factor and has a drastic impact on emission-control technologies. The required sulphur content to meet the different levels of stringent emission standards has already been discussed in previous chapter. Fuel injection technology with a two-way oxidation catalyst must be used to meet the current Bharat Stage Emission Standards in two- and three-wheeler segments [66].

Battery-powered cars and hydrogen-fuel-cell buses are alternative technologies to significantly reduce local and global pollutants. However, the cost of such technologies is beyond the affordability of most road users in India. In developed countries like the U.S., these technologies are at demonstration stages and mass production is not expected until beyond 2025–2030 due to performance limitations and safety requirements. In Chennai, the Department of Transport has introduced about 5000 liquefied petroleum gas (LPG)-based three-wheelers to promote alternative-fuel vehicles. Such technologies could be adopted at ecologically sensitive areas in a limited way [67].

At constant vehicle performance and size, a 30–50% reduction in the fuel consumption of new light-duty vehicles is feasible over the next 20–30 years. The greater uncertainty lies with the time necessary to achieve these changes, rather than the technological options available to realize them. In the near term, a combination of improved gasoline and diesel engines and transmissions, and gasoline hybrids, can achieve reductions on this trajectory. Vehicle weight and drag reductions can contribute in both the near and long term. The longer-term options for moving beyond such improvements currently appear to be plug-in electric hybrids and electricity, and fuel cells and hydrogen. Compelling visions of efficient low GHG-emitting ways for transportation to use these two energy carriers are yet to be developed [68].

Cost is a key factor in assessing the likelihood of technologies becoming widely adopted. Vehicles with turbocharged gasoline engines, diesel engines, and hybrids entering the fleet today are estimated to cost from 5–30% more than a baseline gasoline vehicle. Longer-term options such as plug-in hybrids and fuel cell vehicles would cost 25–35% more than a future gasoline vehicle. Battery electric vehicles are even more costly. Reducing weight by 20% in a future vehicle would cost an additional 5%; reducing weight by 35% would cost an additional 10% of today's baseline gasoline vehicle cost [68].

Vehicle air-conditioning can significantly impact fuel economy and tailpipe emissions of conventional and hybrid electric vehicles (HEV) and reduce electric vehicle (EV) range. In addition, a new U. S. emissions procedure, called the Supplemental Federal Test Procedure (SFTP), has provided the motivation for reducing the size of vehicle air-conditioning systems in the United States. The SFTP will measure tailpipe emissions with the air-conditioning system operating. Current air-conditioning systems can reduce the fuel economy of high fuel-economy vehicles by about 50% and reduce the fuel economy of today's mid-sized vehicles by more than 20% while increasing NOx by nearly 80% and CO by 70% [69].

No single technology development or alternative fuel can solve the problems of growing transportation fuel use and GHG emissions. Progress must come from a comprehensive, coordinated effort to develop and market more efficient vehicles and benign fuels, and to find more sustainable ways to satisfy transportation demands [68].

To control vehicular emissions central, state and local governments have implemented many policy measures such as improving vehicular technology, revising traffic-management schemes, implementing stricter emission controls, introducing cleaner fuels, and promoting alternative fuels (CNG and LPG). The effectiveness of such efforts has not been evaluated. Base emission rates depend on vehicle technology, air/fuel ratios, engine sizes, and fuel types [4].

India should reduce sales taxes and import duties through incentives to encourage faster penetration of advanced technologies such as hybrid vehicles, BOV, and fuel cells. It is necessary to improve the fuel quality to take advantage of after-treatment technologies such as particulate traps and catalytic converters. Since the Indian transportation sector consumes more than 90% of HSD, it is imperative to reduce the sulphur and benzene content in diesel fuel all over India. Recently it has been permitted to use ethanol blend up to 5% in gasoline [4, 70].

Gasoline vehicles alone contribute to about 88% of VOC emissions, reduction of which is another challenge esp. considering high ambient temperatures in India. This is also due to lower combustion efficiency in gasoline engines, more specifically in two-stroke engines. It has been estimated that 15–25% of two-stroke engine exhaust is unburned fuel [34].

While EGR was introduced in vehicles in 2004 to reduce NOx emission, DOC was used the same year for reduction in PM, NOx, CO and VOC, but it also increased NO_2. DPF was introduced in 2007 which removes PM by filtering and oxidation, but it needs to be regenerated and also, it increases NO_2. SCR was used in 2010 which reduces NO_2 using urea (NH_3) with Ammonia oxidation catalyst (AMOX) which removes any remaining ammonia SCR technology for mobile applications was developed from proven SCR technology in stationary applications. SCR has been used to reduce stationary source emissions since the 1980s. SCR is mainstream technology for NOx reduction for HDVs (trucks and buses) since Euro IV (from 2005). In addition, more than 100 marine vessels worldwide have been equipped with SCR technology, including cargo vessels, ferries and tugboats [39, 71].

2.2 Technologies needed for compliance of future automotive emission norms

From automotive emission control point of view, catalytic converters, particulate filters, traps & adsorbers, substrates, catalytic coatings, etc. are used based on different engine technologies, applications, operating conditions, precious materials, etc. The emission control technologies (for IC engines) are broadly divided into: Catalysts (DOC, LNT, SCR, etc.), EGR, Filters (DPF, GPF, etc.), Sensors and Thermal Management. However, another way of reducing emissions is increasing the usage of hybrid vehicles, electric vehicles, fuel cells, etc., which are discussed in a separate section in this chapter later.

2.2.1 HC / CO reduction techniques

DOCs reduce emissions of the organic fraction of particulate matter (PM), gas-phase hydrocarbons and carbon monoxide. It is usually a cylindrical ceramic honeycomb catalyst structure. DOCs are already in use in India in BS IV vehicles. DOC uses a catalytically (platinum or other metals based catalyst) induced reaction that converts PM, CO and

Hydrocarbons to CO_2 and H_2O. It does not use a filter. DOC can reduce total PM by over 50 percent. It can also reduce smoke emissions from older vehicles and virtually eliminate the obnoxious odors associated with diesel exhaust. It is often used in combination with other devices to achieve a higher PM reduction. Oxidation catalysts can reduce more than 90 percent of the CO and HC emissions and more than 70% of the toxic hydrocarbon emissions in diesel exhaust [71, 72]. DOCs can last upwards of 10 years, are low cost and require little to no maintenance once installed. DOCs help in additional transformation of NO to NO_2 and PM reduction with SOF oxidation. However, thermal and chemical stability of DOCs is a challenge due to formation of sulfuric acid [10]. However, HC and CO emission are not of much concern as far as diesel engines are considered. TWC and SCR both help in reduction of CO / HC along with reduction of NOx which is the primary purpose of their usage.

Most modern cars are equipped with three-way catalytic converters. ‘Three-way’ refers to the three regulated emissions it helps to reduce - Carbon Monoxide, Hydrocarbon and Nitrogen Oxides. The converter uses different types of catalysts, for reducing and oxidizing the pollutants within a single honeycomb monolith. It consists of a ceramic structure coated with a metal catalyst, usually Platinum, Rhodium and / or Palladium. The idea is to create a structure that exposes the maximum surface area of the catalyst to the exhaust stream, while also minimizing the amount of catalyst required as they are expensive. The conventional three-way catalyst technology used on petrol engines needs a 'richer' environment with less oxygen in the exhaust than is available on these engines to be able to reduce NOx. The oxidation catalyst minimizes the unburned Hydrocarbons and Carbon Monoxide (CO) by burning (oxidizing) them over a Platinum and Palladium catalyst. The third stage controls the fuel injection system. There is an oxygen sensor mounted upstream of the catalytic converter and hence, it is closer to the engine than the converter is. This sensor tells the ECU the amount oxygen in the exhaust. The ECU can increase or decrease the amount of oxygen in the exhaust by adjusting the air-to-fuel ratio. This control scheme allows the ECU to make sure that the engine is running at close to the stoichiometric point, and also to make sure that there is enough oxygen in the exhaust to allow the catalyst to oxidize the unburned hydrocarbons and CO [71, 72]. Hydrocarbon trap can be applied with advanced TWC technology [73]. The chemical reactions taking place in a TWC are shown in Fig. 2.1.

$$CO + 0.5O_2 \rightarrow CO_2$$
$$CO + H_2O \rightarrow CO_2 + H_2$$
$$HC + O_2 \rightarrow CO_2 + H_2O$$

Oxidation

$$NO + CO \rightarrow CO_2 + 0.5N_2$$
$$NO + H_2 \rightarrow 0.5N_2 + H_2O$$
$$NO + HC \rightarrow CO_2 + H_2O + 0.5N_2$$

Reduction

Fig. 2.1 Equations for typical chemical reactions on a TWC surface [74]

2.2.2 PM / PN reduction techniques

GPF (gasoline particulate filter) is required for EU and China from 2017 and for India from 2020 to meet the PN legislation. US market will follow because a stringent PM legislation will be implemented. With this technology, lower backpressure is the major aim. Euro VI (and BS VI) regulates particle number, forcing the automobile manufacturers to use high efficiency wall flow filters. As of now, nobody is sure as to which regeneration strategy (active or passive) is to be followed for GPF or DPF or catalyzed soot filters (CSF) [73]. Catalyzed DPFs are typically installed on new diesel passenger vehicles with Euro 5 standards and on heavy duty vehicles with Euro VI standards, but can be retrofitted to older diesel engines provided <50 ppm sulfur fuel is available [16]. Wall flow DPFs offer the highest PM filtration efficiency. Filters are extremely effective in controlling the carbon fraction of the particulate known as black carbon. DPFs are also the most effective devices to control emissions of ultrafine particles emitted from diesel engines. Particulate filters can be combined with a DOC or directly catalyzed to control up to 90 percent or more of the toxic HCs emitted by a diesel engine [71, 72]. Passively regenerated DPFs employ catalysts and available exhaust heat to burn soot and hence, require specified exhaust temperature range of 250^0C - 450^0C with the presence of NO_2. Due to presence of catalyst, the sulfur content in the fuel should be less than 50 ppm. Catalyzed DPFs are able to achieve large reduction in toxics and black carbon. Regeneration of DPF is the biggest challenge. Actively regenerated DPFs are suited for on-road and off-road applications with low exhaust temperatures. Active regeneration needs temperatures around 600^0C in the presence of O_2 and hence, usually these are with a fuel burner for regeneration [75, 76]. Electric regeneration is possible for uncatalyzed (uncoated) or catalyzed wall-flow filters. Catalyzed filter along with electrical element combines functions of active and passive regeneration, where regeneration is possible with vehicle on or off [75]. If appropriate regeneration is not applied, the following failures may occur: The deterioration of DPF catalyst advance rapidly at temperatures beyond 900^0C. Between 1000^0C and 1300^0C, face cracks and ring-off cracks may occur. Ring-off cracks depend on the shape of the DPF. Catalyst will start melting at temperatures beyond 1300^0C [13]. Coating of DPF is needed to ensure proper regeneration by platinum (Pt) or palladium (Pd) inside and in close contact to soot, to have longer intervals between regenerations and hence, to reduce fuel penalty [20]. The chemical reactions for active and passive regenerations are [76]:

$$C + O_2 \rightarrow CO_2 \qquad \text{(Active Regeneration)}$$

$$C + 2NO_2 \rightarrow CO_2 + 2NO \qquad \text{(Passive Regeneration)}$$

A DPF has a working life span between 7 and 15 years. Regeneration and chances of thermal failure are the biggest challenges of using DPF [10].

2.2.3 NOx reduction techniques

There are primarily 3 after-treatment technologies for NOx reduction – EGR, SCR and NSC.

NOx storage catalyst (NSC), Lean NOx trap (LNT), NOx storage/reduction (NSR) catalyst, NOx adsorber catalyst (NAC) and DeNOx trap (DNT) are different names of the same technology. However, SCR or Lean NOx catalyst (LNC) are names of another technology used for selective catalytic reduction of NOx using hydrocarbons, which is an entirely different technology than LNT which uses NOx adsorbers [77, 78].

NOx adsorber-catalyst systems have been developed to control NOx emissions from partial lean burn gasoline engines and from diesel engines. The adsorbers, which are incorporated into the catalyst washcoat, chemically bind nitrogen oxides during lean engine operation. After the adsorber capacity is saturated, the system is regenerated during a period of rich engine operation, and released NOx is catalytically reduced to nitrogen. NOx adsorbers also require periodic desulfation, to remove sulfur stored in their washcoat [77, 78]. The NOx adsorber was designed to avoid the problems that EGR and SCR experienced as NOx reduction technologies. The theory is that the zeolite will trap the NO and NO_2 molecules - in effect acting as a molecular sponge. Once the trap is full (like a sponge full of water) no more NOx can be absorbed and it is passed out of the exhaust system. Various schemes have been designed to "purge" or "regenerate" the adsorber. Injection of diesel (or other reactant) before the adsorber, can purge it. NO_2 in particular is unstable and will join with hydrocarbons to produce H_2O and N_2. Use of hydrogen has also been tried, with the same results, however hydrogen is difficult to store. Some experimental engines have mounted hydrogen reformers for on board hydrogen generation; however fuel reformers are not mature technology. Thin washcoat of Pt, Pd, zeolite and alumina acts as oxidation catalyst, which is widely used with diesel engines to oxidize carbon based emissions and process NO to NO_2 at downstream after-treatment devices [71, 72].

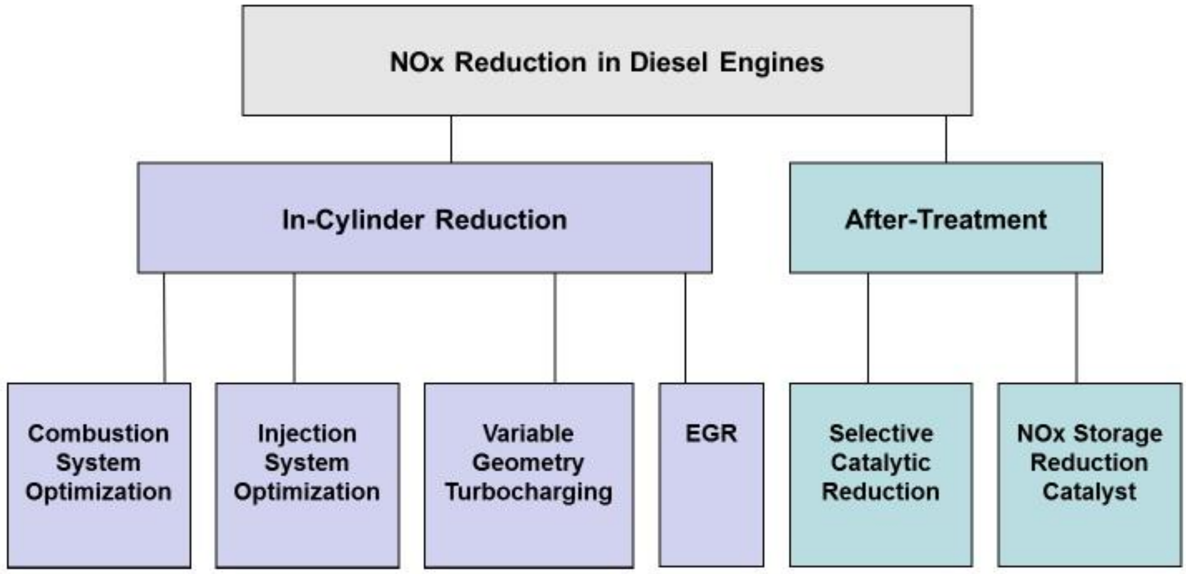


Fig. 2.2 Various technologies for NOx reduction in automobiles [79]

Fig. 2.2 shows various in-cylinder and after-treatment technologies for NOx reduction from automotive emissions. While EGR is the most desired in-cylinder technique, there is a tough competition between SCR and NSR (or LNT) for the after-treatment of NOx. One weakness for EGR is the maximum exhaust recirculation rate which is possible to reach with stable combustion decreases as a function of engine load [43].

Sumiya (2016) compared the performance and cost of two lean burn engines' after-treatment technologies viz., NSC and SCR. In case of NSC, PGM loading is high and so the PGM cost is high and it has calibration complexity as well. Also, reduction of N_2O emission and improvement of sulfur tolerance are challenging. NOx adsorbers will be poisoned from sulfur oxides and they require ultra-low sulfur content (< 15 ppm) in diesel fuel. LNTs need to run periodical desulfation regeneration cycles to remove SOx. It is ECU programmed and rich pulses are needed for regeneration. The regeneration imposes a fuel penalty resulting in an increase in fuel consumption with NSC and hence, reducing the brake thermal efficiency of the engine [20, 73, 74]. LNT have been successfully used on new light and medium-duty vehicles with over 80 percent NOx removal [71, 72]. However, the good part is, it does not require any accessory are so it is generally lighter and more compact than SCR, and it works best at 200-450^{0}C temperatures. LNTs do not require an external reducing agent like SCR [20, 74]. LNTs are easy to install and integrate but require ULSD to save from sulfur poisoning [10].

Whereas, since SCR uses metal-zeolite based catalyst, PGM loading is low (for slip catalyst only) [73, 80]. SCR allows for low fuel consumption engine design and, consequently, low CO_2 emissions as well as low engine-out particulate levels. Urea is used as an aqueous solution called 'AdBlue' or Diesel Exhaust Fluid (DEF), which is injected into the exhaust pipe for the supply of ammonia (NH_3) enabling fast chemical reactions for NOx reduction [22, 39]. This sets off a chemical reaction that converts nitrogen oxides into nitrogen and water in the catalyst, which is then expelled through the tailpipe. The chemical reactions are shown in Fig. 2.3 [71, 72].

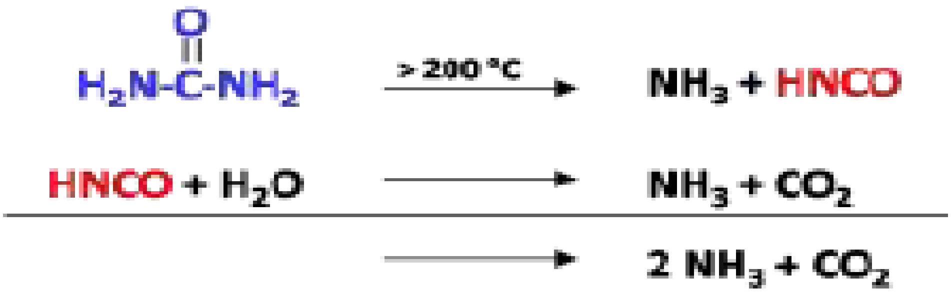


Fig. 2.3 Equations of chemical reaction for Urea decomposition [22]

Urea is an aqueous solution, freezing at -11^{0}C [10]. While urea is the primary operating fluid presently used in SCR systems, alternatives to the urea agent are currently being explored. One option involves the use of diesel to transform NOx into harmless gases [71, 72]. Hence, SCR requires urea injection system along with AdBlue tank, pump, mixer doser, ammonia slip measurement, ammonia slip catalyst, and injector systems, which has a space constraint as it is a bulky set-up and hence, favored on larger vehicles primarily. SCR has a non PGM catalyst and results in more than 90% conversion of NOx. It can be tuned for various operating conditions [74]. However, SCR is susceptible to sulfur poisoning and hence, requires ULSD as fuel [10]. From the economical comparison of SCR and NSC, it was inferred that while the cost of both the systems increase proportionally as a function of engine displacement, for engines less than 2.4 litres, NSC costs less, whereas for engines above 2.4 litres, SCR will be cheaper [73, 80]. Veluswamy (2015) tried to find the effectiveness of NSC and SCR based on vehicle weight and came out with a conclusion that sedans weighing less than 1500 kg should go for NSC whereas MUV and SUV/LD vehicles weighing more than 1500 kg should choose SCR instead [76].

Lean De-NOx Catalysts, also known as hydrocarbon-SCR systems use different catalyst to reduce NOx; Hydrocarbon like Ethanol or diesel is dosed in order to create a rich 'microclimate' due to which reduction of NOx happens, while the overall exhaust remains lean [71, 72]. Equations of chemical reactions for SCR DeNOx are shown in Fig. 2.4.

$$NO + NO_2 + 2\,NH_3 \longrightarrow 2\,N_2 + 3\,H_2O$$

$$4\,NO + O_2 + 4\,NH_3 \longrightarrow 4\,N_2 + 6\,H_2O$$

$$2\,NO_2 + O_2 + 4\,NH_3 \longrightarrow 3\,N_2 + 6\,H_2O$$

Fig. 2.4 Equations of chemical reactions for SCR DeNOx [22]

2.3 Alternate fuels, HEV, FEV, Fuel cells, etc.

Development of alternatively fueled engines has become vital in order to meet the increasingly stringent emissions norms being implemented globally. Furthermore, alternative fuels provide a cost benefit, due to the lower costs of production of these fuels. Compressed Natural Gas (CNG), Liquefied Petroleum Gas (LPG) and Hydrogen-CNG blended fuel (HCNG) are promising alternative fuels in India. Various sub-systems of the baseline SI/CI engine, such as the air-intake system, combustion bowl, CR, the exhaust system, after treatment device are reviewed and suitably modified to achieve the target specifications. Experience of developing CNG/LPG engines with carburetion and injection kit fuel technologies is available. Fuel system parts such as 1st stage reducer, 2nd stage reducer and mixer are also suitably modified & optimized to achieve target specifications [81].

The CNG engines & vehicles developed by ARAI, India have passed current emission norms with comfortable margins in CO & NMHC + NOx emissions. As exhibited by the results, closed loop control of CNG engines results in a large reduction in NOx and PM emissions as compared to diesel engines. CNG Injected engine can meet Euro-IV norms easily and have superior performance as compared to carbureted engines. The charge stratification in the

CNG combustion chamber permits extremely lean combustion without high cycle-by-cycle variations with high combustion efficiency [81].

Liquefied Petroleum Gas (LPG) is a prominent alternative fuel with well-developed distribution infrastructure and increasing number of gasoline engines are now being converted to run on LPG considering the fuel economy and low exhaust emissions. Several bi-fuel (LPG/Gasoline) and dedicated LPG engines ranging from single cylinder two wheeler engines to advanced 4 cylinder passenger car engines have been developed. Optimization with LPG kit includes emission optimization on to give equivalent mileage on gasoline.

Traditionally, CNG vehicles have been developed in India in variety of segments and have contributed to cleaning the ambient conditions of cities like Delhi. However, the persistent NOx levels are becoming a hotly debated issue. One of the solutions to this crisis is the addition of hydrogen to CNG. The hydrogen + CNG fuel referred to as HCNG has the potential to lower emissions including NOx as compared to CNG and is considered to be the first step towards promotion of a hydrogen economy. A 6-Cylinder HCNG naturally aspirated engine using the lean burn concept of combustion is being developed. The six cylinder engine was chosen due to its importance for urban bus transportation. In this study the lean burn combustion concept has been evaluated for varying HCNG blends. The HCNG engine has potential to meet Euro-IV and beyond norms with injection technology. It is also expected that HCNG fuel blends reduce NOx emissions by approximately 50%, non-methane hydrocarbons by 58%, and total hydrocarbons by 23% and CO_2 by 7% as compared to CNG. No PM emissions are observed in CNG or HCNG engines [81].

Fuel cell is another promising technology for emission reduction in future. After researching on many possible fuels and membranes, hydrogen seems to be the best fuel for fuel cell. However, carrying hydrogen on vehicle is difficult and dangerous. Hence, production of hydrogen from water by electrolysis on the running vehicle is tried but has certain limitations like the time and energy required for electrolysis process to produce the desired amount of hydrogen for fuel cell.

HEV and FEV, Solar cars are other good solutions for reducing emissions. However, these technologies are also in their early stage and commercial acceptance of these might take couple of decades. Some of the constraints are high cost to power ratio, maximum speed, etc.

2.4 Retrofitment

Reducing people's exposure to diesel exhaust is a public health goal that depends on controlling diesel emissions; the Retrofitment Technology is one of the Technology Solutions for the same. Diesel engines can last up to 20 to 30 years or longer. It will take many years before the existing diesel engines may be retired and be replaced with advance diesel engines that meet more stringent emissions standards. Putting new technologies to old vehicles / engines is called retrofitment. Diesel retrofit programs are successfully employed worldwide in USA, Hong Kong, Japan, South Korea, Mexico, Sweden, etc. China, Thailand, India and Chile are also considering the retrofit programs seriously [5].

2.4.1 Need for retrofitment

As emissions regulations become more and more stringent for new vehicles, the issue of pollution from the older vehicles becomes relevant for the overall improvement in the quality of ambient air. Globally, apart from the phase-out of old vehicles, retrofit of older vehicles with new engines or various after-treatment devices have been practiced with some success. These have almost always been implemented with financial incentives coupled with penalties for pollution to persuade in-use vehicle owners for the change. In India, while retrofit has often been talked about, this has not yet been implemented as a means to clean up the environment. While a lot of time, effort and finances are spent on improving new vehicles, the retrofit option has as yet, remained unexplored. In-use old vehicles have been subject to wear and tear, fuel injection parts and calibration may have been disturbed, and engine oil consumption (an important parameter in particulate emissions and control) may be high. This results in unpredictable emissions. The Indian automotive market is different as apart from PUC, there is no check on the condition of in-use vehicles and no I&M. This implies a large difference in the condition of the vehicles on the road making it difficult to make vehicles comply with a definite jump from one stage to another. The quickest and most easily implementable solution is the fitment of DOC on trucks and buses running on Diesel (prominent polluters). While this may only give an improvement of 20% to 30%, more efficient solutions such as open traps (filters) can be implemented. The use of SCR along with DOC would give the best conversion but is complex and expensive to implement and sustain on road [82].

Due to very long operating lives of many diesel engines, older uncontrolled diesel vehicles will continue to be used in particularly heavy-duty vehicle fleet (buses and trucks) for public and goods transportation. In spite of stricter regulations, on any day on the coming years, more than 75% older vehicles (BS2 and BS3) will co-exist on the road emitting higher emissions due to aging. This scenario completely dilutes the benefits of newly introduced low emitting vehicles. To achieve air quality control aligned with tighter regulations, there is increasing interest to retrofit older, 'dirtier' diesel engines while newer, 'cleaner' diesel engines enter the marketplace [5].

Large number of LCVs and HCVs would have been registered as BS III. Such LCVs, and heavy vehicles, buses and trucks will also get BS IV fuel from April 2017 without any benefits to environment. Retrofits on these vehicles and engines have potential to cut on PM and NOx emissions when BS IV fuel will be available [71].

Hence, retrofitment seems to be absolutely necessary for improving the AQI.

2.4.2 Methods to accomplish retrofitment

(i) Refuel the engine: Cleaner fuels and ultra-low sulfur diesel (ULSD) fuel will have a direct impact on emission levels. It will also enable the use of advance emission control technologies that will further reduce vehicle emissions. Some of the alternative fuels include emulsified diesel, biodiesel, natural gas, propane and ethanol. Some require little or no modification to the engine while others require engine conversion or replacement as discussed in section 2.3.

(ii) Retrofit the engine: Installing emission control technologies on older vehicles. The buses drive frequently in densely populated areas. Therefore, bus retrofit program will prove to be a cost effective strategy for reducing emissions in urban areas vis-à-vis the health benefits to the citizens.

(iii) Repower the engine: Replacing an older engine with a new one which has been certified to cleaner emission standards is another option for some equipment and vehicles. Repowering with a new engine may extend the life of the vehicle, reduce fuel consumption, and significantly reduce emissions.

(iv) Rebuild the engine: Diesel engines often can be rebuilt and continue to operate in the same capacity. An engine in need of rebuilding may have low power, increased emissions and increased fuel consumption. In some cases an engine can be rebuilt to comply with cleaner emission standards. Successful implementation and operation of a diesel retrofit program depends on suitability of vehicles for retro-fitment, desired emission reductions, engine size, backpressure specification, duty cycle, exhaust temperature profile, appropriate emission control technology, fuel quality needs (e.g., sulfur level; ideally, ULSD should be used), operational and maintenance requirements, vehicle integration and safety, training and education needs of vehicle operators, etc. For optimum results, the engine of a vehicle should be rebuilt to the manufacturer's specifications before a catalyst, filter system or other emission control device is installed.

(v) Replace the vehicle: Retire older vehicles and replace by substantially cleaner and more fuel efficient vehicles.

2.4.3 Retrofitment devices

Various devices used for retrofitment are DOCs, DPFs, DMFs, EGR, SCR, LNTs, POCs, CCV, etc. While some of these have already been discussed in earlier sections, some more discussions are presented below.

Wall-flow DPFs have been widely retrofitted on on-and off-road in-use diesel vehicles as they can remove 60-90% of PM.

Diesel Multi-Stage Filter (DMF) removes 71-75% of PM, HC and CO. The DMF is priced between $6000 and $8000 and requires minimal maintenance. This unit is considered to be an effective compromise between the less expensive DOC and the more efficient DPF.

Flow-through or partial filters (DoC+) are a relatively new method for reducing diesel PM emissions. Flow-through filters employ catalyzed metal wire mesh structures or tortuous flow, metal foil-based substrates with sintered metal sheets to reduce diesel PM. Flow-through filters are capable of achieving PM reduction of more than 50 percent, depending on the engine operating characteristics. Because of open structure, these devices are less prone to clogging and may be more suited to older diesel engines with higher engine-out PM levels. These create back-pressure much lesser than DPF and hence, provide better thermal efficiency.

EGR systems have been retrofitted on heavy-duty diesel vehicles. Low-pressure EGR is used for retrofit applications because it does not require engine modifications. However, capability of withstanding the reduction in fresh air should be examined; else there will be more power loss with increased fuel penalty, smoke and PM emissions. EGR and lean NOx catalysts combined with DPFs have been retrofitted on heavy-duty diesel vehicles in USA and few other countries.

Lean NOx Catalysts or HC-SCR have been installed on heavy-duty on-road and off-road vehicles in combination with a DPF and are capable of achieving up to 40 percent NOx reduction. These devices rely on the use of diesel from the vehicle as the reducing agent.

CCV technology can be retrofitted on turbocharged diesel engines to eliminate crankcase emissions. Crankcase gases impact children on school buses. Emissions from the engine compartment seep through cracks and openings in windows and doors to create conditions in which the particulate matter concentrations inside the bus may be many times that of ambient conditions. Crankcase filters reduce emissions of particulate matter to the cabin by nearly 100%. Priced near $400-$700 each, CCFs achieve the highest emission reductions to the cabin per dollar. The CCF must be maintained on a regular basis by replacing the internal filter at each oil change, at a cost of approximately $50. The CCF can be used in conjunction with DMFs, DOCs or DPFs [72].

POC (Particle oxidation catalyst) have filter efficiency of 60-80% (less than DPF) and use passive generation (typically). These are less sensitive to ash accumulation but are quite sensitive to sulfur and hence, require low sulfur diesel [10].

2.4.4 Impact of sulfur in diesel fuel on catalyst technologies

Catalysts can also oxidize sulfur dioxide to form sulfates, which is considered part of the particulate. Catalyst-based diesel particulate filter technology works best when fuel sulfur levels are less than 15 ppm. In general, the less sulfur in the fuel, the better the technology performs. Use of ultra-low sulfur diesel fuel (15 ppm sulfur maximum) greatly facilitates filter regeneration at lower temperatures in passive DPF devices. The performance of un-catalyzed filters, such as those used in many active regenerated devices, is not affected by fuel sulfur. Due to sulfur poisoning, the catalyst go bad fast and the catalysts (PGMs) are very expensive. Hence, for retrofit purposes, un-catalyzed DPFs would prove to be better and more acceptable solution, esp. when sulfur level in fuel is unpredictable.

2.4.5 Current challenges for retrofits in India

The following challenges are being faced for successful retrofitment of old vehicle in India [71]:

- Packaging constraints (integration of Retrofit package in existing vehicle configuration),
- Availability of clean fuel (Un-adulterated fuel with appropriate sulfur content for better emission and PM control),
- Need for good preventive maintenance practices (air filters, injectors and turbochargers),
- Basic inspection and maintenance of installations is a must and users must be mindful of not taking short-cuts to get equipment retrofitted quickly.

Further the additional issues, mentioned under, aggravated the retrofitment scenario in India:

- Who will carry out the Retrofitment?
- Design of catalytic converter – for old vehicles
- Assessment of efficiency of catalytic converters on in-use vehicles
- Should it be model based or engine capacity based or year of manufacture based
- Non-OEM catalytic converter evaluation procedure
- Economic incentives for fitment of catalytic converters

People going for retrofit of their old vehicle should be suitably incentivized properly esp. by partial funding of retrofit. Also, OEMs of retrofit equipment should be awarded by way of tax rebates, partial funding by government, etc. to encourage retrofitment.

2.4.6 Retrofit scenario: A global perspective

US EPA and CARB have established mandatory and voluntary retrofit program for most in-use diesel powered vehicles. Both agencies conducted rigorous verification program to ensure that the devices need strict performance and durability requirements. Over 300,000 on road and off road heavy duty engines worldwide had been retrofitted with DOC and over 250,000 on road and off road heavy duty engines with DPFs during 2000-2009.The total number of DPFs sold by MECA members in California in first six months of 2014 was 5,780, a 65% increase over the same period in 2013 [72].

In UK, the most polluting vehicles are encouraged to retrospectively install technologies to reduce its emissions. In Europe, vehicles aged between 9 and 15 years had to be retrofitted with an approved emission control device in order to receive an exemption and to be allowed to travel in Environmental Zones. All vehicles older than 15 years were banned [66].

On 7th June 2013, the French Order on Retrofits was published in the Official Journal of France. The Order defines emissions requirements for the retrofit of Euro II, III, and IV base engines up to Euro III, IV, V or EEV levels. In addition, retrofits to Euro III and IV levels require a minimum performance of 50% on PM and/or NOx reduction. Retrofits to Euro V and EEV require also a PM reduction >90% and/or NOx reduction >70%, according to the type of retrofit device installed. These efficiencies are to be measured on the European Transient Cycle (ETC) [66].

On 25th June 2014, the new UN Regulation concerning the approval of Retrofit Emission Control devices (REC) for heavy-duty, agricultural and forestry tractors, and non-road mobile machinery equipped with compression ignition engines was published as UN Regulation No. 132 [66].

A few projects have been done by few Indian agencies like ARAI, TERI and IOC in India together with ECMA members. US-EPA had also done a program in Pune. These programs have established the feasibility of retrofit devices being installed on the vehicles/engines with environmental benefits but have not been followed up for implementation on commercial scale [66].

Auto fuel policy 2025 report under consideration of the Govt. of India has stated that we should by law enforce retrofitment of emission control devices (catalytic converters and particulate filters) on BS III diesel vehicles within 2 years of BS IV fuel availability [66].

2.5 Quality efforts / actions beginning in India

Like the developed countries, lots of work is being done in India as well for improvement in air quality and emission reduction. Some of the actions beginning in India for better air quality are [14]:

- Implementation of Air Quality Index, 2009 (AQI)
- Leapfrogging from BS IV to BS VI pan India in 2020 (skipping BS V) along with CAFÉ norms and RDE standards.
- Implementation of Thermal power plants' standards
- Star rating of vehicles on the basis of fuel economy from 2016.

Early introduction of BS-VI standards nationwide is expected to reduce net emissions of NOx and PM10 by up to 86% by 2035 [14].

Start rating of vehicles based on fuel economy is expected to enhance vehicle market towards improvement in fuel efficiency and in-line with the energy consumption standards, and to provide the consumer an informed choice about fuel saving and thereby the operational cost saving potential of the vehicle [83].

2.6 Feasible solutions for old vehicles

With the above discussions in view and considering the current status of negligible retrofitment in India, retrofitment cost, adulterated fuel, user mentality, regeneration needs, infrastructure requirements, etc., solutions like SCR, LNT, cDPF, etc. look to be a distant dream. Also, the exhaust temperatures in India are quite low due to traffic congestion and poor roads, and at such temperatures using catalysts would not be effective and regeneration also will be an issue at low temperatures. Also, many catalysts have life of around 30000 km. This will be useless for diesel vehicles in India, where diesel vehicle clock more than a million km [5].

Old vehicles are pre-dominantly mechanical and lacked electronic controls and hence, it will be difficult for retrofitting old vehicles with technologies which are electronically driven.

Bharat Stage (BS) norms started in 2000 which was equivalent to Euro-I norms. In October 2010, BS-III was made compulsory pan India. Thus all the vehicles manufactured prior to October 2010 belonged to pre-BS-III norms, which are plying on roads in big numbers especially in rural areas and small towns. Though BS-IV was implemented pan India effective April 01, 2017 and leap-frogging BS-V, BS-VI implementation pan India is targeted for April 01, 2020, still around 95% vehicles in India belong to pre-BS-IV era as shown in Fig. 1.11.

The total number of registered motor vehicles in India was 210,023,289 as on 31.03. 2015 [84]. Indian auto manufacturers produced a record 25.3 milion motor vehicles in 2016-17. Motor vehicle sales in India (Apr 2016 - Mar 2017) was 21.86 million [85]. The sale of vehicles in India grew by 5 to 9% per year over the years [86, 87].

The inference from the above data is that around 25% vehicles in India belong to pre-BS-III era. Also, as stated above, around 95% vehicles in India belong to pre-BS-IV era. Which means more than 50 million vehicles plying on roads in India as on date belong to pre-BS-III era and around 180-200 million vehicles plying on roads in India as on date belong to pre-BS-IV era.

Since these vehicles cannot be taken off-road, retro-fitting is perhaps the only solution to reduce emissions from theses vehicle. And since DPF and EGR are the simplest technologies (for retrofitting) to reduce emissions from these old engines, and since these have not perhaps been tested on BS-I/BS-II vehicles, it was of great importance to test these technologies on such an old engine to see their effectiveness on old engines.

Hence, uncatalyzed DPF and EGR seem to be feasible solutions as these do not get affected by the sulfur content of the fuel and also do not need huge infrastructural set-up or cost. However, regeneration of DPF and controlling the quantity of EGR (without ECU) will be major challenges.

2.7 Research gap identification

A remarkable development has taken place in the field of emission reduction techniques in IC engines all over world, especially during the last 2 decades and most of the findings have been implemented in the new models of vehicles. However, following research gaps were observed from the detailed literature review:

1. Though lots of studies have already been done w.r.t. compliance to US and Euro norms, similar studies w.r.t. Bharat Stage Emission Standards are limited.
2. Cost implications in India with Bharat Stage Emission Standards for the next 10-20 years need to be studied. It needs to be evaluated what Government subsidies / support are needed which will facilitate the implementation of emission reduction technologies in India. These could be reduction in import duties for fuel cells and other technologies, subsidies, support for research on such technologies, etc.
3. Studies have compared the vehicle mass to fuel consumption and GHG emissions. However, it would be useful to study possibilities of further reduction in vehicle weight for improving fuel consumption economy and hence, further reduced emissions.
4. It would be useful to have a comparison of GHG emissions for the latest models of cars and the emission reduction technologies implemented in market compared to those of last decade and studying the reasons (since generally many technologies / changes are applied in tandem) for the changes in emissions. The changes may occur due to lower fuel consumption, or due to more complete combustion, or due to reduction in emissions using converters, etc.
5. Expected changes in fuel substitution vis-à-vis increase / decrease in cost need to be studied w.r.t. future Bharat Stage Emission Standards.

6. Research needs to be conducted on feasibility of emission reduction techniques for PM and NOx on automobile engines of Euro-I/II/III periods. Most of such studies are conducted on modern engines and/or on stationary engines.
7. With Govt. of India leapfrogging from BS IV to BS VI pan India in 2020, study needs to be done on the desired technologies for meeting the emission norms of BS VI.
8. With BS VI implementation AQI will certainly improve, but old vehicles (BS III and earlier) will remain to be operational, hence, feasible methods for retrofitting old vehicle should be studies with affordable costs and considering probable sulfur levels in the fuel.
9. Since India is going for BS VI in 2020, studies are must on regeneration mechanisms for DPF and other filters in Indian context as active or passive regeneration, both will have issues in Indian conditions.

Hence, it was decided to experimentally study emission reduction technologies which could be most useful on old diesel engines (retrofitting). With high percentage of sulfur in fuel, it was not feasible to test any new technologies with catalysts in old engines. Due to cost constraints, it was not possible to go for experimental studies of effect of vehicle weight on emissions. Hence, uncatalyzed (uncoated) wall flow type DPF and EGR were considered to be the most feasible technologies to be tested experimentally on a Mahindra and Mahindra make, Euro I diesel engine in our labs.

2.8 Objectives

After going through the observed research gaps, the following are decided to be the major objectives of the proposed research work:

- **To study the various emission reduction techniques for I.C. engines to make the vehicles compliant to higher Bharat Stage Emission Standards.**

- **To study the effect of reduction of vehicle weight on emissions.**

- **Prediction of relative importance of various emission reduction techniques for future Bharat Stage Emission Standards.**

2.9 Research methodology

The following methodology was followed to carry out this research:

1. Detailed literature review regarding the following:
   (a) World air quality and health effects, causes for the same
   (b) Greenhouse gas emissions generated by automotive engines
   (c) Various automotive emission standards followed in world and their implementation stage
   (d) Emission reduction technologies (ERTs) developed / implemented globally for automobiles
   (e) Effect of the above techniques on the emissions
   (f) Expected emission reduction techniques in near future
2. Selection of relevant emission reduction techniques (DPF and EGR) to be tested experimentally considering emissions from in-use old vehicles.
3. Selection of a suitable Euro-I (Bharat Stage I) CI automobile engine for experimental validation of the selected emission reduction techniques.
4. Procurement of software applications and equipment for experimental validation of DPF and EGR on the selected engine.
5. Development of experimental set-up to find the effectiveness of DPF and EGR experimentally.
6. Experimental verification of effect of DPF and EGR on emission reduction (NOx and Smoke) and engine performance, individually and then in tandem at various torques and engine speeds.
7. Optimization of EGR flow (EGR valve opening position) for various engine speeds and torques.
8. DPF regeneration by 2 methods – active regeneration and off-board regeneration and comparison of effectiveness of the 2 types of regeneration methods considering smoke reduction and engine performance.
9. Study on impact of vehicle weight on emissions and issues associated with it.
10. Prediction of emission reduction techniques for future Bharat Stage Emission Standards.
11. Documentation of the research work – final report writing.

CHAPTER 3

EXPERIMENTAL SET-UP, PLAN AND PROCEDURE

3.1 Introduction

The current study focused on testing of a diesel particulate filter and exhaust gas recirculation on an old (Euro-I) automotive diesel engine. Hence, a Euro-1, 4-cylinder, water-cooled, direct injection, variable speed, automotive compression ignition (diesel) engine of Mahindra Jeep was used in the laboratory set-up in Jaipur city of Rajasthan state in India. To artificially load the engine and to measure the torque accurately and reliably, an eddy current brake dynamometer (absorption type dynamometer) was coupled to the engine so that the engine RPM and dynamometer RPM was same (1:1). The reaction torque in this dynamometer was sensed by using a load cell with digital indicator.

Air box arrangement was used to determine the air flow rate. Fuel supply system consisted of a burette method to measure the volumetric fuel consumption. AVL Ditest-5 gas analyzer was used to measure CO, CO_2, HC, NO_x and O_2 in exhaust gas. Smoke percentage in the exhaust gas was measured using AVL 437 smoke meter. AVL Ditest / CDS analyzer was used to measure CO_2 in the intake air for EGR% calculation. The detailed description of the instruments used is discussed in this section.

3.2 Details of experimental set-up

3.2.1 Diesel engine and dynamometer

A Euro-1, water-cooled, direct injection, variable speed, compression ignition engine was selected for this research work. Fig. 3.1 (a) and (b) show the engine and dynamometer as at the beginning of the experiment, before making any modifications. Specifications of the engine are given in Table 3.1. Specifications of dynamometer are given in Table 3.2.

A cabinet provided for the control panel of the dynamometer (as shown in Fig. 3.2) had the following instruments:

a) Digital torque indicator (in Nm)
b) Digital RPM indicator (same as engine RPM in this case)
c) Electronic, eddy current dynamometer controller (torque control rotating knob)
d) Excitation current indicator (Amp.) (With 6 Amp. MCB for safety)

(a)

(b)

Fig. 3.1 (a) and (b) Engine and Dynamometer without any modifications as at the beginning of experiment viewed from 2 different sides

Table 3.1: Specifications of the engine [88]

S. No.	Particular	Unit	Description
1.	Type of engine	-	Compression ignition (C.I.) engine
2.	Make and Model	-	Mahindra & Mahindra, XDP 4.90
3.	No. of Cylinders	-	4 (in-line arrangement)
4.	Operating cycle	-	4 stroke (order: 1-3-4-2)
5.	Compression Ratio	-	22.4 : 1
6.	Cubic capacity	m^3	0.0021 m^3 (2112 cc)
7.	Bore	m	0.09 m (90 mm)
8.	Stroke	m	0.083 m (83 mm)
9.	Max. Power	kW	46.5 kW (62 bhp) at 4500 RPM
10.	Max. Torque	Nm	120.5 Nm (12.3 kg.m) at 2000 RPM
11.	Valves	-	Overhead, rocker arm operated
12.	Timing	-	Gear operated
13.	Cooling	-	Water cooled
14.	Recommended fuel	-	Diesel as per IS:1460

Table 3.2: Specifications of the dynamometer [89]

S. No.	Particular	Description
1.	Make and Model	SAL (Schenck Avery Ltd), ASE-70
2.	Type	Eddy current brake type with load cell (Absorption type)
3.	Sensing mechanism	Electric strain gauge type load cell
4.	Cooling	By water
5.	Lubrication	Circulating oil type (Servo System 32 or equivalent)
6.	Max. Torque	328 Nm
7.	Max. allowable error	0.25% of max. torque
8.	Voltage	230 Volt
9.	Frequency	50 Hz

Engine torque was manually controlled using dynamometer settings. In the dynamometer panel, the top left reading shows engine RPM whereas, top right reading is engine torque in Nm and below that is the current rating in Amp. Engine RPM was manually controlled using the accelerator wheel.

Fig. 3.2 Control panel of the eddy current dynamometer

3.2.2 Air flow measurement

An air box with a U-tube manometer as shown in Fig. 3.3(a), (b) and Fig. 3.4 was used to measure the airflow. It also dampens the pulsation of air. At the entrance of one side wall of air box, an orifice (diameter = 50 mm and coefficient of discharge, C_d = 0.6) was fitted. Air induced per second is given by:

$$\text{Air induced/second } (m^3/s) = C_d \times A_{orifice} \times \sqrt{\frac{2gh_w\rho_w}{\rho_a}} \qquad (1)$$

Where,

Coefficient of discharge,	C_d	= 0.6
Area of orifice,	$A_{orifice}$	= 0.00196428571 m^2
Density of water,	ρ_w	= 1000 kg/ m^3
Density of air,	ρ_a	= 1.15 kg/m^3

h_w = Manometer reading in m

Mass flow rate of air can be calculated using the following equation:

Mass flow rate of air = Air induced/second (m^3/s) × Density of air (kg/m^3) (2)

(a)

(b)

Fig. 3.3 (a) Air box, **(b)** Air box outlet to engine air inlet connection

Fig. 3.4 U-tube manometer to measure the pressure drop in air box

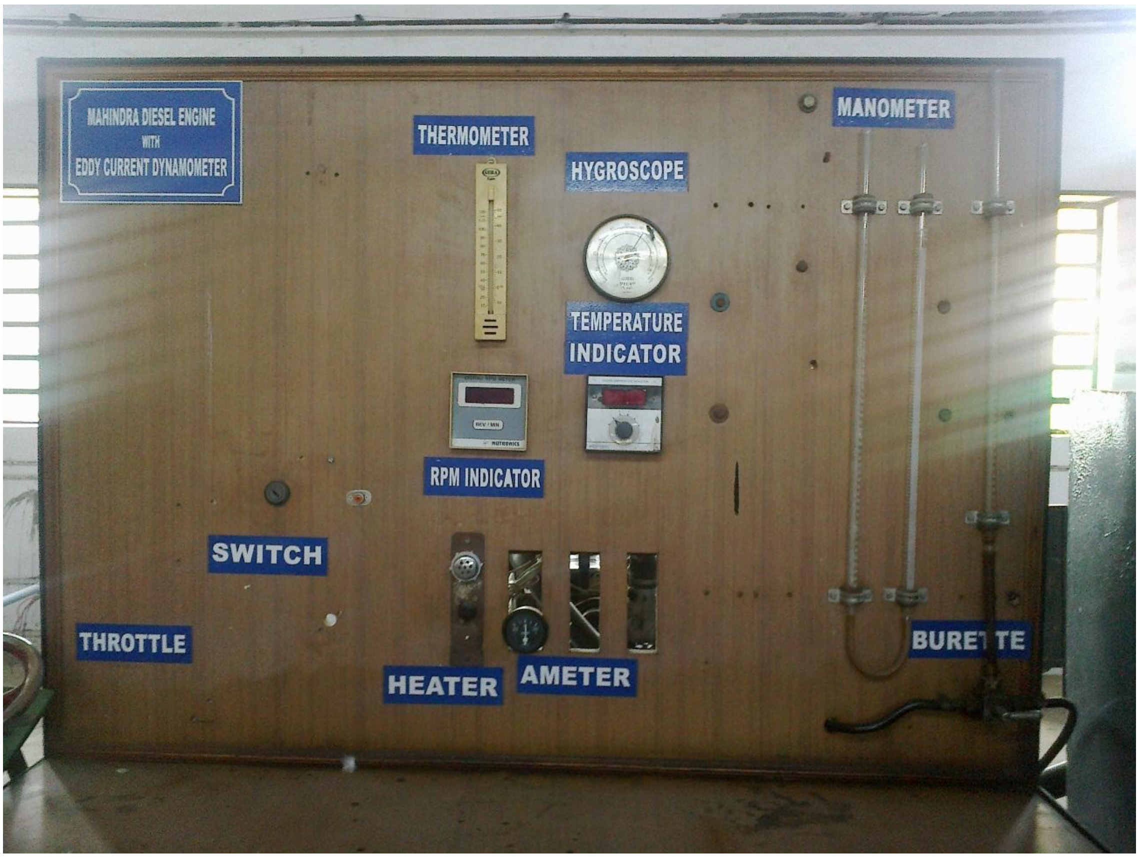


Fig. 3.5 Burette meter and T-valve for fuel flow measurement

3.2.3 Fuel flow measurement

Diesel from the fuel tank was supplied to engine by gravity method through a T-valve as shown in Fig. 3.5. Fuel flow measurement is an important step for quantitative determination of BSFC. Volumetric fuel flow rate was measured by burette method. A glass burette with calibration marks was connected to fuel tank and the engine through a tee valve as shown in Fig. 3.5. Initially, fuel line was connected to the engine and burette, so as to fill the burette with the fuel, while the supply of fuel to the engine was not interrupted. In order to measure the fuel consumption the valve was adjusted so that the fuel started flowing from the burette to the engine. The time taken by the engine to consume a fixed volume (50 cc) of fuel was measured with the help of stopwatch. This volume divided by the time gave the volumetric flow rate.

3.2.4 Exhaust emission analysis

Emissions were noted using AVL gas analyzers and AVL smoke meter, which require calibration to be done annually. For accurate results, all these equipment were calibrated before the start of this study.

A 5-gas analyzer (Make: AVL, Austria, Model: AVL DITEST / AVL DiGas 4000 light) as shown in Fig. 3.6(a) was used to analyze the exhaust emission from the engine. The exhaust emission included NO_x, CO, HC, CO_2 and O_2. The analyzer measures CO, HC and CO_2 by NDIR Technique and NO_x and O_2 using electrochemical sensors. HC and NO_x were measured in ppm whereas; CO, O_2 and CO_2 were measured in percentage. Smoke in exhaust was measured with the help of smoke in opacity % using opacity meter (Make: AVL, Austria, Model: AVL 437) as shown in Fig. 3.6(b). Another gas analyzer (Make: AVL, Austria, Model: AVL DITEST / CDS) was used to measure intake CO_2 % (after mixing of recirculated exhaust gas and ambient air). This analyzer also measured CO_2 in percentage using NDIR technique.

Detailed specifications of exhaust gas analyzer (AVL DiGas 4000 Light) and smoke meter are shown in Tables 3.3 and Table 3.4 respectively. Specifications of the other 5 gas analyzer (AVL DiGas 444), used to measure the quantity of CO_2 in air inlet to engine, are shown in Table 3.5.

(a)

(b)

Fig. 3.6 (a) AVL DiGas 4000 Light 5-Gas Analyzer **(b)** AVL 437 Smoke Meter

Table 3.3: Specifications of 1st 5-Gas analyzer [90]

Type	AVL DiGas 4000 light
Object of measurement	CO, HC, CO_2, NO_x, O_2
Measurement Principle	CO, HC, CO_2 → Infrared O_2, NO_x → Electrochemical
Range of measurement	CO: 0…….10 % by vol. CO_2: 0…….20 % by vol. O_2: 0……. 22 % by vol. HC: 0…….20000 ppm vol. NO_x: 0…….4000 ppm vol.
Resolution	CO: 0.01 % by vol. CO_2: 0.1 % by vol. O_2: 0.1 % by vol. HC: 1 ppm vol. NO_x: 1 ppm vol.
Warm up time	15 min. (self) at 20^0C
Speed of response time	Within 15 s for 90 % response
Weight	14 kg
Dimensions	360 mm x 370 mm x 220 mm
Power draw	150 W
Operating Voltage	195…253 V, 47….63 Hz

3.2.5 Temperature measurement

J-type thermocouples were installed at required points on the engine to measure temperature of intake air, exhaust gas and cooling water. These thermocouples are available in the range of -40°C to 750°C. Standard and special limits of error of this thermocouple were from ± 2.2°C or ± 0.75% and ± 1.1°C or ± 0.4% respectively. Sensitivity and power consumption of this type of thermocouple is about 55µV/^{0}C & 3 mW respectively.

3.2.6 Furnace for off-board regeneration of DPF

A muffle type, electric resistance furnace (size: 0.1524 m × 0.1524 m × 0.3048 m i.e. 6” × 6” × 12”, maximum temperature: 1000^{o}C) as shown in Fig. 3.7 was used for off-board regeneration of DPF.

Table 3.4: Specifications of smoke meter [91]

Type	AVL 437 smoke meter
Measuring value output	Opacity N [%] or absorption k [m^{-1}]
Measuring range	N = 0 ... 100% or k = 0 ... 99.99 m^{-1}
Resolution of displayed values	0.01 % opacity or 0.0025 m^{-1}
Limit of detection	0.1 % opacity
Zero stability	{0.1 % or 0.0025 m^{-1}}/30 min. (drift with zero gas)
Exhaust gas temperature	0 ... 600°C (800°C with high pressure option)
Exhaust gas pressure	-100 mbar ... + 400 mbar(including pulsation peaks) 0 mbar ... +3000 mbar with high pressure option
Calibration	Automatic (Self calibration immediately after switch on or at the press of key)
Dimensions	501mm x 200mm x 330mm (Control Unit) 520mm x 255mm x 455mm (Sensor Unit)
Weight	16 kg (Control Unit) 21 kg (Sensor Unit) 6 kg (Trolley)
Power Consumption	600 W (Overall equipment) 500 W (Measuring Chamber Equipment)
Storage Temperature	-30°C to +65°C
Power Supply	190…..240 V AC, 50….60 Hz, 2.5 A, 11.5….. 36 V DC

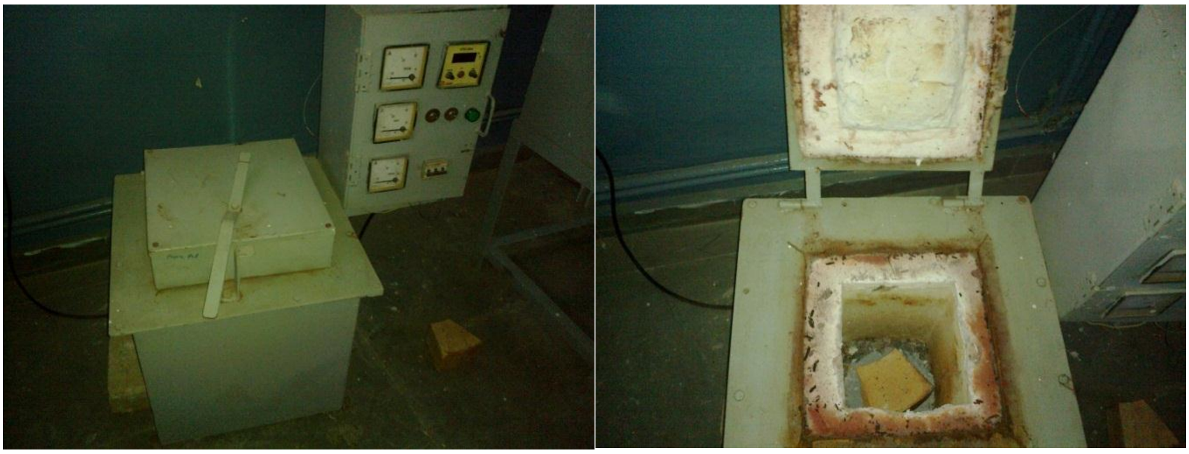


Fig. 3.7 Electric resistance furnace

Table 3.5 Technical specifications of AVL DiGas 444 (the 2nd 5 gas analyzer) [92]

Measured quality:	Measuring range:	Resolution:	Accuracy:
CO:	0... 10 % vol	0.01 % vol	< 0.6 % vol: ± 0.03 % vol ≥ 0.6 % vol: ± 5 % of ind. val.
CO_2:	0... 20 % vol	0.1 % vol	< 10 % vol: ± 0.5 % vol ≥ 10 % vol: ± 5 % v. M.
HC:	0... 20000 ppm vol	≤ 2000: 1 ppm vol, > 2000: 10 ppm vol	< 200 ppm vol: ± 10 ppm vol ≥ 200 ppm vol: ± 5 % of ind. val.
O_2:	0... 22 % vol	0.01 % vol	< 2 % vol: ± 0.1 % vol ≥ 2 % vol: ± 5 % v. M.
NO:	0... 5000 ppm vol	1 ppm vol	< 500 ppm vol: ± 50 ppm vol ≥ 500 ppm vol: ± 10 % of ind. val.
Engine speed:	400... 6000 min^{-1}	1 min^{-1}	± 1 % of ind. val.
Oil temperature:	- 30... 125 °C	1 °C	± 4 °C
Lambda :	0... 9.999	0.001	Calculation of CO, CO_2, HC, O_2

3.3 Experimental set-up for DPF

A wall-flow type cylindrical DPF was used for the purpose. Specifications of the DPF used in this study are shown in Table 3.6.

Table 3.6: Specifications of the DPF used [93]

S. No.	Particular	Description
1.	Type	Wall-flow type
2.	Shape	Cylindrical
3.	Dimensions	Diameter: 0.1437 m (5.66”); Length: 0.1524 m (6”)
4.	Cell density	465,000 cells per m^2 (300 cpsi)
5.	Wall thickness	3.25×10^{-3} m (13 mil) (1 mil = 2.5×10^{-4} m)
6.	Open Frontal Area	37.1% on inlet
7.	Filtration surface area	1.093 m^2
8.	Coating	Uncoated / Uncatalyzed
9.	Material	Ceramic

A mild steel cylinder cage was fabricated to hold the DPF in place as shown in Fig. 3.8(a). To connect this cage with the exhaust pipe a mild steel cone was fabricated and was joined to the cylinder using 9 bolts. Similarly on the other end of the cylinder, another mild steel cone was joined to connect it to the final exhaust pipe to the atmosphere. To keep DPF tightly intact in the cage as also to reduce the outside temperature of DPF cage, glass wool packing was used between DPF and DPF cage wall. A strainer was made and welded inside the exhaust entry cone before the DPF cage, as shown in Fig. 3.8 (b) and (c), for minimizing the flow of soot particles to the DPF. The DPF was at a distance of 2.42 m from the exhaust manifold.

(a)

(b)

(c)

Fig. 3.8 (a) Cylindrical DPF cage and cone with strainer welded inside, **(b)** Inlet cone and strainer, **(c)** Strainer welded inside the inlet cone

3.3.1 Off-board regeneration of DPF

Schematic diagram of the laboratory set-up for DPF testing is shown in Fig. 3.9 and the pictorial view of the laboratory set-up for the same is shown in Fig. 3.10. DPF was connected to the exhaust line after the muffler as shown in Fig. 3.10. Exhaust out from DPF was let into the atmosphere with the help of a long exhaust pipe.

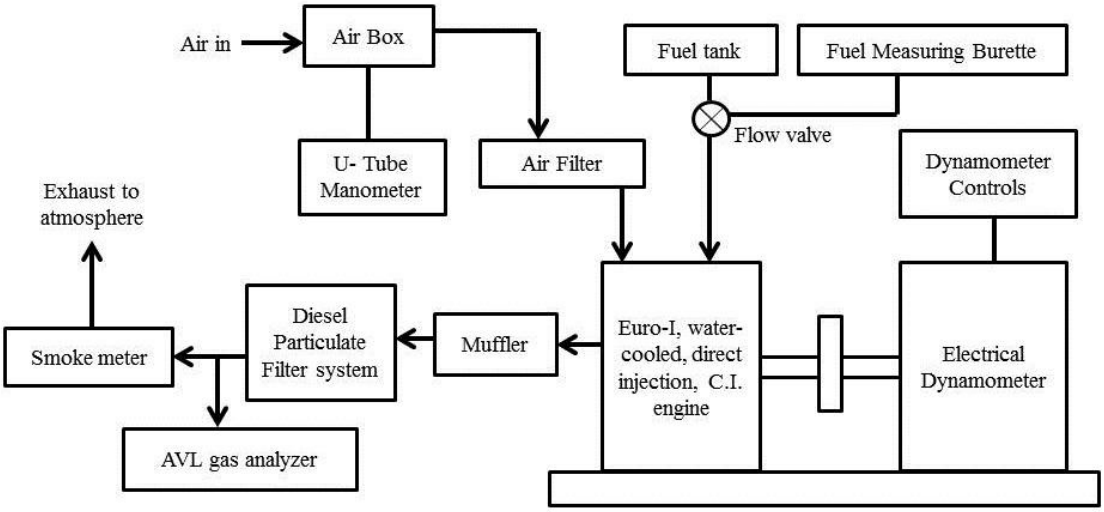


Fig. 3.9 Schematic diagram of the laboratory set-up for DPF testing [31]

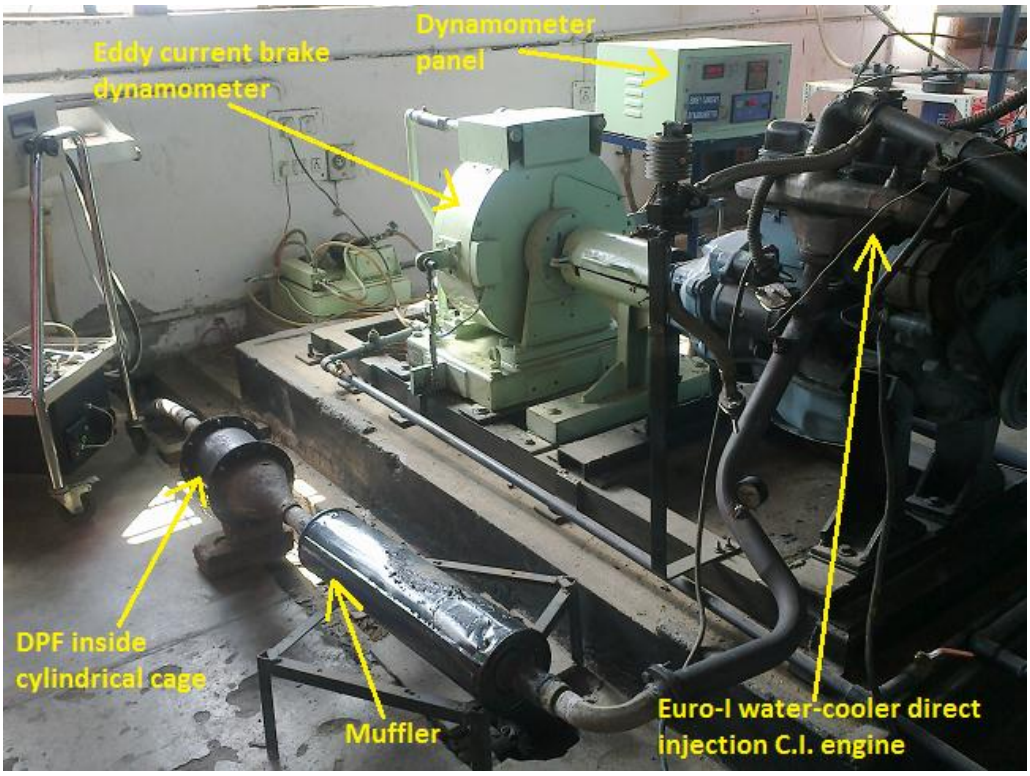


Fig. 3.10 Laboratory set-up showing the diesel engine, dynamometer, DPF cage, muffler and dynamometer panel for base case and off-board generation (without ECU) [31]

3.3.2 Active regeneration of DPF

Fig. 3.11 shows the laboratory set-up for DPF ECU system (for active regeneration). Fig. 3.12 shows the schematic layout of DPF ECU system. DPF ECU is shown in Fig. 3.13 (a) and the connections from DPF ECU to various points in exhaust line are shown in Fig. 3.13 (b). Exhaust was passed through a muffler to the DPF (when readings were taken with DPF) and then to the atmosphere. A by-pass mechanism as shown in Fig. 3.11 and 3.13 (b) was installed to take base case reading, i.e. without DPF.

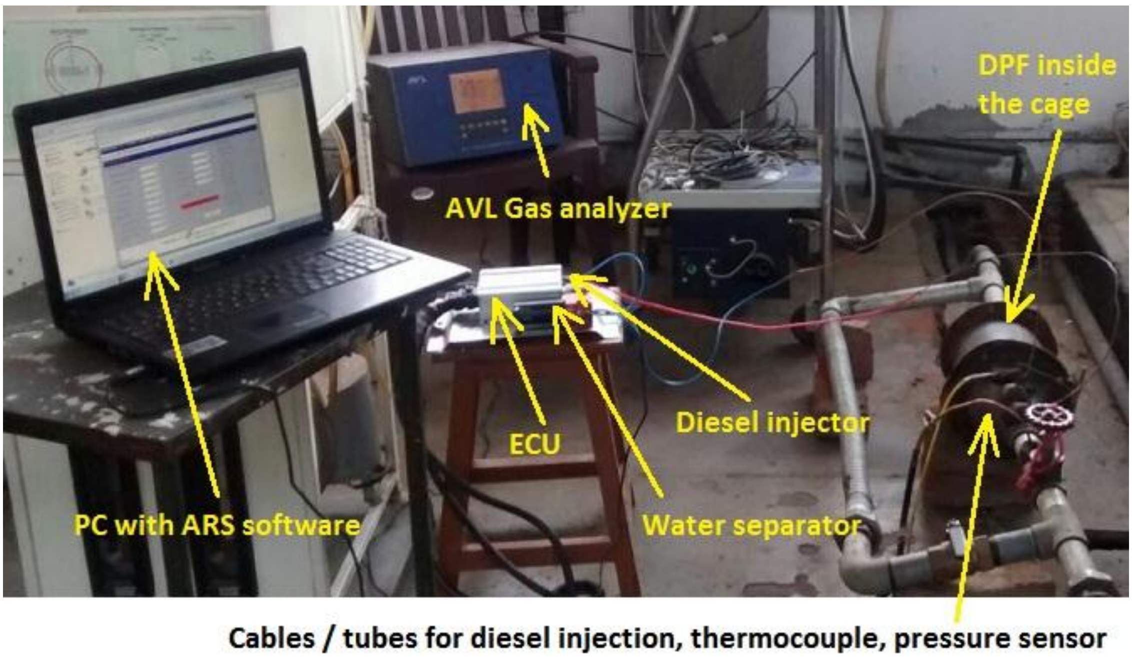


Fig. 3.11 Laboratory set-up for DPF ECU system (for active regeneration) [31]

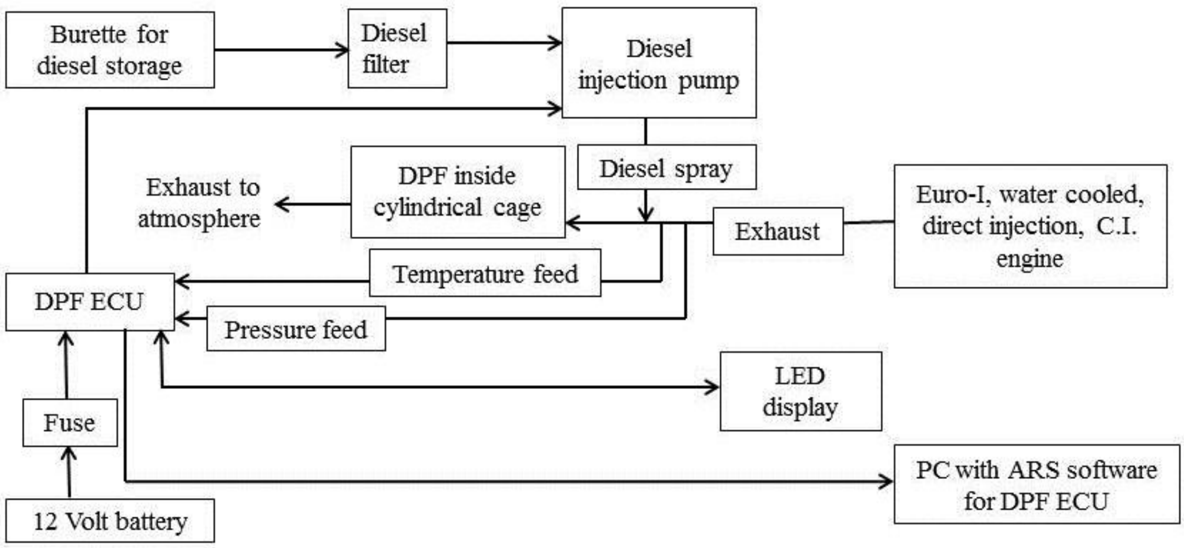
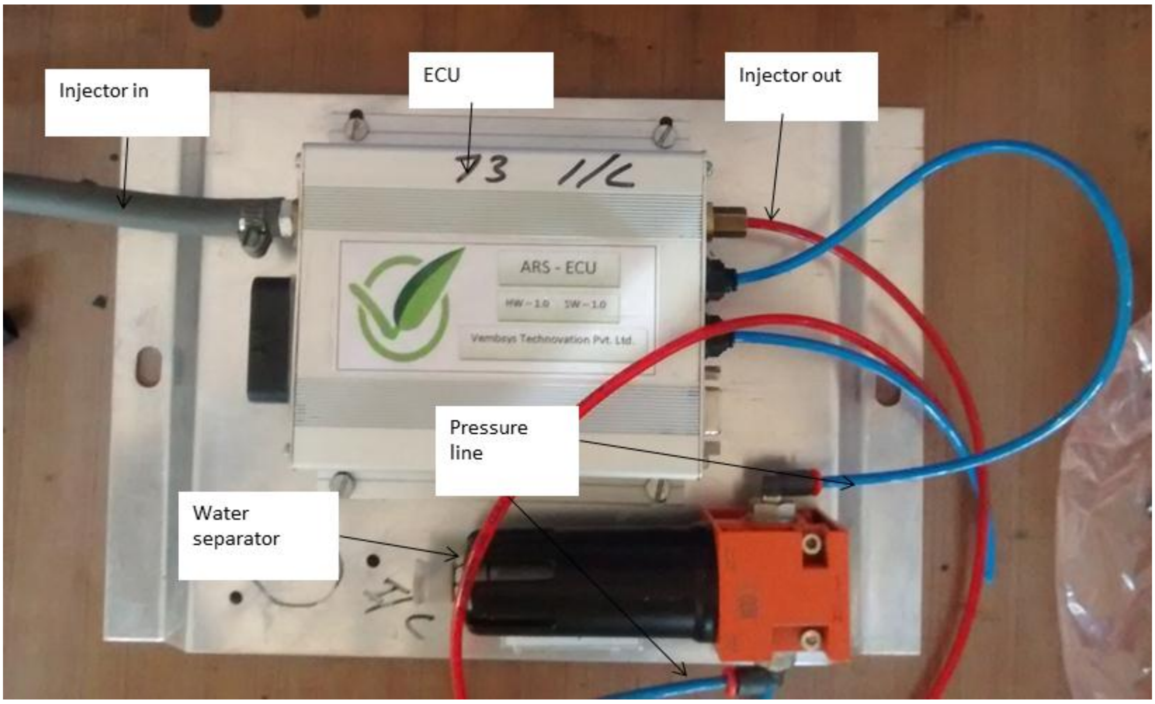
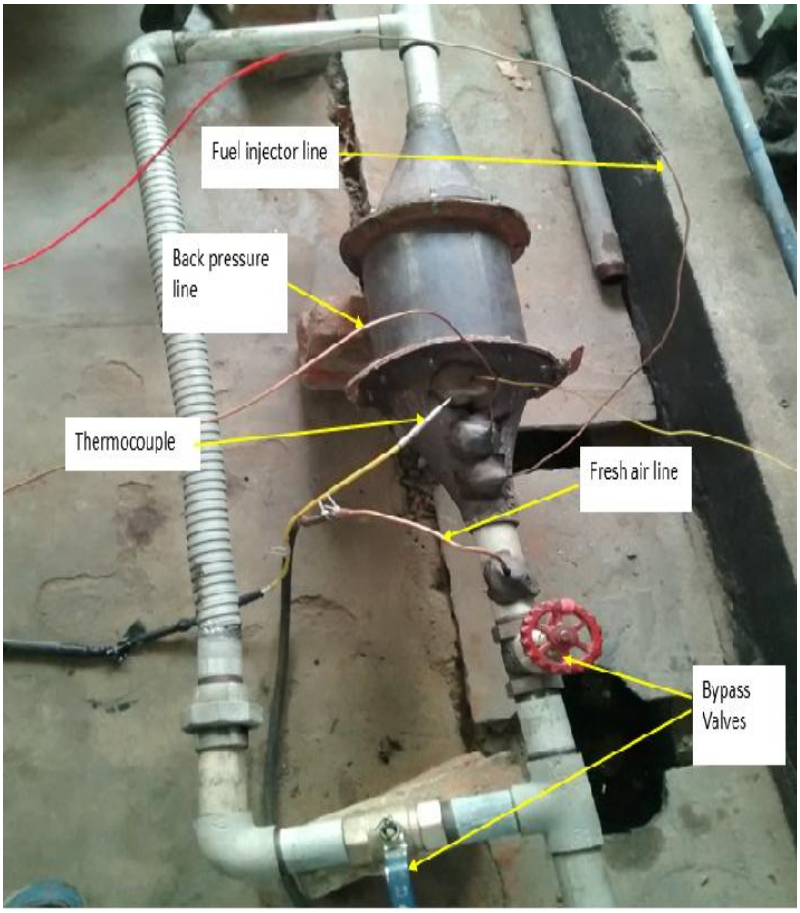


Fig. 3.12 Schematic layout of DPF ECU system [31]



(a)



(b)

Fig. 3.13 (a) DPF ECU, **(b)** Connections from DPF ECU to exhaust line

3.4 Experimental set-up for EGR

Schematic layout of the experimental set-up for EGR is shown in Fig. 3.14. An external EGR system was attached to the set-up as shown in Fig. 3.15.

Some exhaust gas from exhaust pipe was by-passed, and pushed through an electrically operated, ECU-controlled, poppet type EGR valve with maximum lift 4 mm, to the inlet manifold with appropriate plumbing. Hence, 25% EGR valve opening meant 1 mm lift of the valve and 100% EGR valve opening meant 4 mm lift of the valve. Thus, 100% EGR valve opening did not mean 100% EGR. There is no clear relationship between the valve opening and EGR% since the amount of EGR depends on other factors as well like exhaust pressure, engine speed, etc. EGR% means the amount of EGR in the engine intake, whereas valve opening % represents the amount of EGR valve opening. Since the maximum lift of the spring loaded EGR valve was 4 mm, 4 mm lift of the valve represented 100% valve opening, but at 100% valve opening, engine intake did not constitute of 100% EGR.

Insulation of EGR pipes was avoided to allow nominal cooling of recirculated exhaust gas. A mild steel L shaped bracket was fabricated and attached to the engine to hold EGR valve. An electronic control unit (ECU) was attached to the EGR and to the laptop, on which EGR ECU control software, supplied by Vembsys Technovation Pvt. Ltd., was installed. EGR ECU was supplied with electric power from the same battery which was used for starting the engine. Engine RPM was sensed by EGR ECU from the alternator of the engine. Torque was sensed by EGR ECU from the dynamometer panel. EGR valve opening percentage was controlled by feeding the desired percentage at desired RPM and torque combination in the look-up matrix table of the software. The actual percentage of EGR valve opening was displayed on the dashboard of the software application as shown in Fig. 3.16.

3.5 Experimental set-up for EGR as well as DPF testing in tandem

The set-up for testing EGR and DPF in tandem was pretty much same as that for EGR. However, DPF bypass valve was closed and hence, exhaust after EGR was passed through muffler and then through DPF. Off-board regeneration of DPF was done as was done in the case of testing of DPF with off-board regeneration. Schematic layout for the set-up is shown in Fig. 3.17.

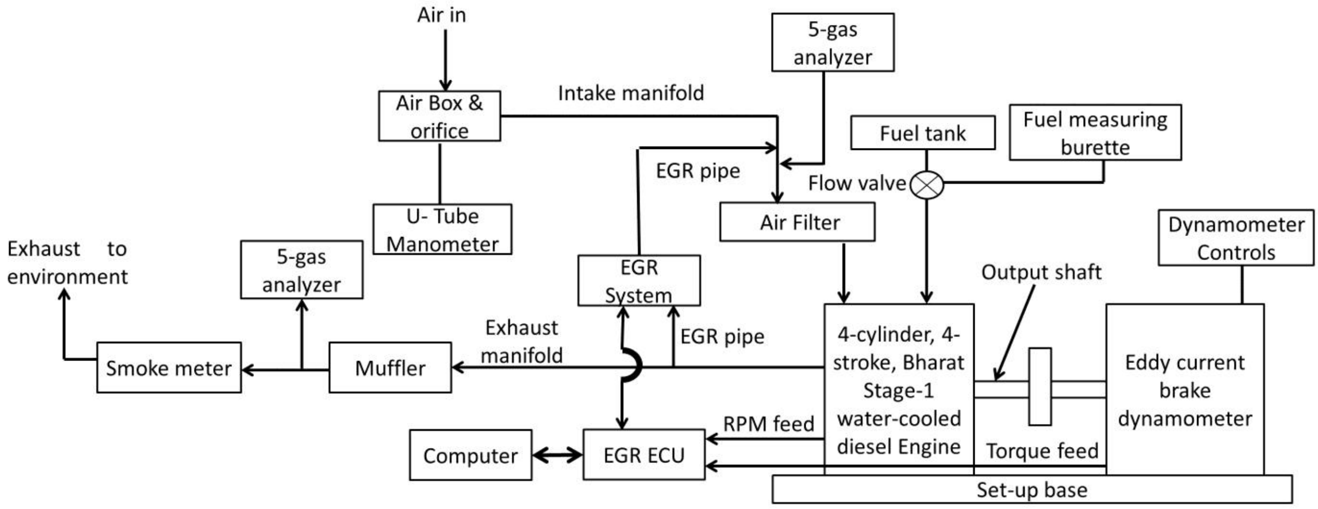


Fig. 3.14 Schematic diagram of the laboratory set-up for EGR testing [32]

Fig. 3.15 Laboratory set-up showing the diesel engine, dynamometer, dynamometer panel, EGR valve and laptop (software) controlling EGR valve opening [32]

Fig. 3.16 EGR ECU software dashboard showing engine RPM, set-point percentage of valve opening and actual percentage of valve opening [32]

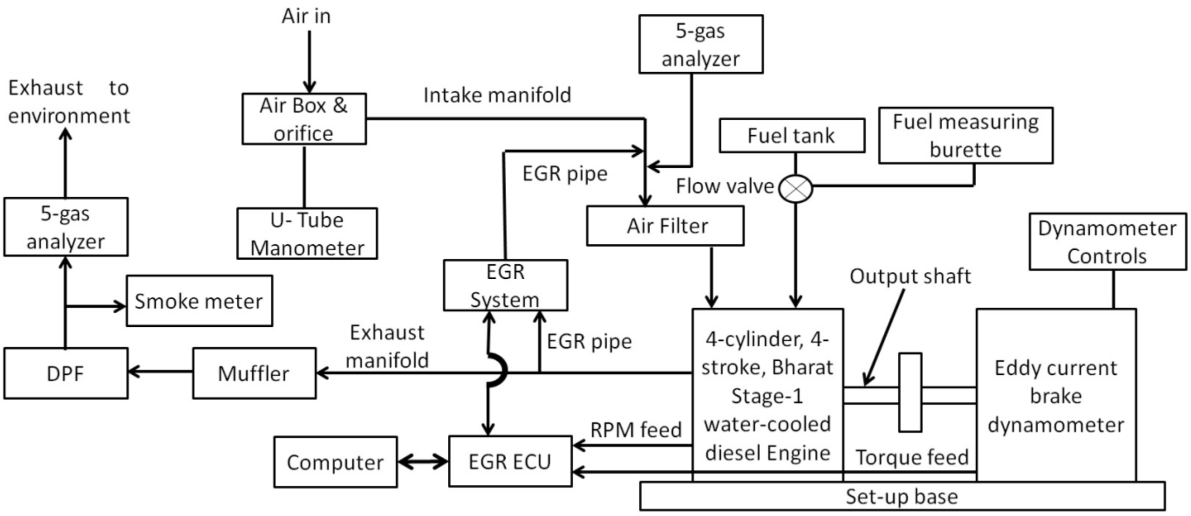


Fig. 3.17 Schematic diagram of the laboratory set-up for testing of EGR and DPF in tandem

3.6 Challenges faced during research work and limitations

i. To start with the exhaust pipe was changed with a new one. Necessary fabrication was done on the exhaust pipe to attach pressure gauge, thermocouples, EGR pipe, etc.

ii. Air box manometer was giving readings out of range for the scale installed. Hence, the orifice of the air-box was changed from 30 mm to 50 mm.

iii. Exhaust pipe became red hot at 3000 RPM with 90 Nm torque, hence, it was decided not to go beyond 3000 RPM, and also not to take readings at 3000 RPM with 90 Nm torque as a precaution since in normal running also, the engine will not go beyond these limits.

iv. Due to excessive vibrations, the thermocouple used to measure the exhaust gas temperature was giving fluctuating readings, hence, a nut was welded to the exhaust pipe and thermocouple was tightened there.

v. Since it was a very old engine, smoke emissions were quite high and DPF got choked quite fast and engine stopped. Active regeneration did not help at that stage, which however did work before complete choking of the DPF. Cleaning with diesel was tried but did not work. Tried to push hot air with very high pressure (using air compressor) through DPF, but that also did not work. Then knowing DPF properties, tried to heat it in a muffle type, electric resistance furnace at 650^oC for 10 hours as the DPF was safe up to 800^oC. This worked, made the DPF like new, and we called it 'off-board regeneration'. And then it was decided to go for off-board regeneration periodically and before each set of readings.

vi. Still to reduce the quantity of PM reaching the DPF, a strainer (see Fig. 3.8) was made and was welded inside the inlet (diverging) cone before the DPF. This had a positive effect.

vii. To measure the back pressure between outlet manifold and DPF, a pressure gauge (0-100 psi) was fitted but the same got melted, hence, another pressure gauge with higher temperature sustainability was added. This was primarily to decide the time/need for regeneration.

viii. Oil started coming from exhaust pipe and on checking, it was found that valve seats on the engine head needed repairs, and the same was done and the problem got fixed.

ix. Dynamometer reading started fluctuating without changing current during steady state. It was found that the load cell of the dynamometer had gone bad and hence, the load cell of the dynamometer was replaced.

x. The alternator, being of very old type, did not have point for RPM sensor. Hence, initially, engine RPM was fed manually from the break-out box of EGR system to open the EGR valve at the desired level at the given RPM. The alternator was replaced with one that had RPM sensor and the readings were taken again, which were found to be quite similar to those taken earlier.

xi. After a few weeks in the experiment, O_2 readings were coming doubtful. Hence, the O_2 sensor of the 5-gas analyzer was changed as it was found defective. Readings with doubt were repeated.

xii. Then after a few days, NOx readings became worrisome. The NOx sensor of the 5-gas analyzer was found defective and the same was changed. Readings with doubt were repeated.

xiii. EGR software gave different errors (runtime error, port problems, etc.) from time to time as it was not fully matured software. The problems were sorted out every time with discussions with the supplier and modifications to the software.

xiv. Midway in the experiment, dynamometer cooling water temperature went quite high, hence, the lubricating oil for the dynamometer was changed after which it worked fine.

xv. Since the fuel used was expected to contain 50-350 ppm (or may be higher) sulfur, no after-treatment device with catalysts could be used e.g., SCR, cDPF, LNT, DOC, etc. Hence, EGR and uncatalyzed DPF were found to be appropriate emission reduction technologies for experimental work.

xvi. Effect of vehicle weight reduction could not be studied experimentally due to cost constraints. Hence, only theoretical studies were conducted for the same.

xvii. Combustion data e.g. maximum pressure, rate of pressure rise, heat release rate, etc. were not captured due to experimental limitations which included non-availability of required equipments.

3.7 Experimental plan and procedure

There is a serious need for controlling exhaust emissions in transportation sector. Though strict automotive emission norms are being implemented by many countries, still the road worthiness of vehicles is tested as per the year of manufacture. Hence, old vehicles (Euro III and earlier), which produce more emissions, will continue to ply on roads, fulfilling the emission norms of their respective year of manufacture, especially in developing countries. Hence, it is desired that appropriate emission reduction technologies are tested on such old engines to analyze their feasibility. Nitrogen oxides (NOx) and particulate matter (PM) emissions from diesel engines require maximum attention, esp. from old engines.

While current studies have been conducted on constant speed stationary engines and modern engines, this study tried to analyze the effectiveness of an uncatalyzed wall-flow type ceramic diesel particulate filter and an electronic control unit (ECU) controlled exhaust gas recirculation valve, individually and then in tandem, on a Euro-1, 4-cylinder, water-cooled, direct injection, variable speed, automotive, compression ignition engine in a laboratory set-up in India.

This study also focused on diesel particulate filter regeneration by two methods: active regeneration by diesel injection in the particulate filter using an electronic control unit; and off-board regeneration.

3.7.1 Experimental plan and procedure for engine performance and emission analysis

The experimental investigation of impact of diesel particulate filter and exhaust gas recirculation on performance and emissions of a Euro-I, 4-cylinder, water-cooled, direct injection, variable speed, automotive, compression ignition engine was divided into various steps.

Here, it is worth mentioning that due to the age of engine, it was found that the maximum achievable torque was 90 Nm. Hence, 0, 25, 50, 75 and 90 Nm torque represented, in this changed scenario, 0%, 27.77%, 55.55%, 83.33% and 100% of peak torque respectively. Also, though the engine was rated for maximum speed of 4500 RPM and min. speed of 1000 RPM, but due to excessively high exhaust temperature, it was not practically safe to go beyond 3000 RPM. Hence, 1000, 1500, 2000, 2500 & 3000 RPM represented 0 to 100% of the possible engine speed.

For each step, observations for engine performance and exhaust emissions were taken for 0, 25, 50, 75 and 90 Nm torque with engine speed of 1000, 1500, 2000, 2500 and 3000 RPM for each torque (leaving exceptions as mentioned below). Performance parameters and emissions were observed / calculated for each set of readings as explained at the end of this section.

In the first step, tests were carried out for each set of RPM and torque as mentioned above to evaluate the engine performance and emissions when it was run without DPF and without EGR (base case).

In the second step, DPF system was added after the muffler, and the same tests were conducted again to evaluate the engine performance and emissions; off-board regeneration was carried out every time before starting the new set of reading with new RPM.

In the third step, DPF ECU facilitated active regeneration as and when required, and all the tests were conducted again for the same RPMs and torques.

In the fourth step, EGR was integrated in the system and DPF was bypassed, and all the tests were conducted again for the same RPMs and torques varying EGR valve opening from 1 mm to 4 mm for each RPM and torque. Then optimum EGR valve opening (corresponding to minimum NOx emission) was determined for each RPM and torque combination.

In the fifth step, the optimum values of EGR valve opening for each RPM and torque condition was fed into the EGR ECU programmatically (look-up table) and then the engine was run again varying RPMs and torques and verifying the observations.

In the sixth and the last step, DPF was added (bypass valve closed) in tandem with EGR with look-up table set for the optimum values of EGR valve opening, and all the tests were conducted again for the same RPMs and torques, with off-board regeneration of DPF.

3.7.2 Off-board regeneration of DPF

Off-board regeneration was achieved by taking the DPF out of the system and heating the same, in a muffle type, electric resistance furnace (size: 0.1524 m × 0.1524 m × 0.3048 m i.e. 6” × 6” × 12”, maximum temperature: 1000^oC), at 650^oC for 10 hours in a furnace. Then the DPF was cooled for 4 hours before putting the same into the system. As informed by the DPF manufacturer, 650^oC was the optimum temperature for off-board regeneration since disintegration of the used ceramic DPF starts at 800^oC.

3.7.3 Active regeneration of DPF

Active regeneration was achieved using diesel mist spray on the DPF with the help of DPF ECU which effectively oxidize the accumulated soot by raising the temperature of exhaust gas. The schematic layout of DPF ECU system is given in Fig. 3.12 which shows that there were 3 probes coming from ECU to the DPF housing, one each for pressure sensor, thermocouple and diesel injector. Temperature, T_{on} and Pressure, P_{on} were set at 350^oC and 15 kPa respectively in the ARS software for the DPF ECU supplied by Vembsys Technovation Pvt. Ltd., India. When the pressure and the temperature inside the DPF cage on the engine side reached P_{on} and T_{on} respectively, the diesel injection, from the burette through a diesel filter, was automatically started by the ECU into the DPF, and was allowed to run for a pre-set time (in the ECU software) of 10 minutes or pressure of 7 kPa, whichever occurred earlier. The diesel mist got burnt due to the high exhaust temperature, further raising the exhaust temperature facilitating soot removal. As the soot gets removed, the back pressure reduced.

Hence, in this study, both active regeneration and off-board regeneration of DPF were done and the results of the two compared.

3.7.4 Testing with EGR

EGR mechanism was attached to the set-up between exhaust pipe and inlet manifold, and the same tests were conducted again to evaluate the engine performance and emissions for 25, 50, 75 and 100% of EGR valve opening corresponding to 1, 2, 3 and 4 mm of valve opening respectively. For both the steps, observations for performance and emissions were taken for 0, 25, 50 and 75 Nm torque with 1000, 1500, 2000, 2500 and 3000 RPM for each torque.

3.7.5 Optimization for EGR

From NOx readings, the optimum (min. NOx for a given torque and RPM set), EGR valve positions (% opening) were determined and tabulated in the look-up table, the format of which is shown in Table 3.7. Then this look-up table was programmatically fed into the EGR ECU software and the engine was then run at different RPMs and torques without making any further changes to the look-up table. This facilitated running of engine at different RPMs and torques with the optimum opening of EGR valve automatically. NOx in exhaust was analyzed and was verified with previous readings. Hence, optimization process was completed.

Table 3.7: Look-up table format for EGR ECU to manage EGR valve lift [94]

<table>
<tr><th>Torque (Nm)</th><th>1000</th><th>1500</th><th>2000</th><th>2500</th><th>3000</th><th>RPM</th></tr>
<tr><td>0</td><td>value</td><td>value</td><td>value</td><td>value</td><td>value</td><td rowspan="4">EGR Lift %</td></tr>
<tr><td>25</td><td>value</td><td>value</td><td>value</td><td>value</td><td>value</td></tr>
<tr><td>50</td><td>value</td><td>value</td><td>value</td><td>value</td><td>value</td></tr>
<tr><td>75</td><td>value</td><td>value</td><td>value</td><td>value</td><td>value</td></tr>
</table>

3.7.6 Testing with DPF and EGR in tandem

DPF was added (bypass vale closed) in tandem with EGR with look-up table set for the optimum values of EGR valve opening, and all the tests were conducted again for the same RPMs and torques, with off-board regeneration of DPF and readings were taken.

3.7.7 Calculation of BSFC, BTE and EGR%

To measure brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) for each test set (combination of torque, RPM and EGR valve opening), time for 50 ml of diesel consumption was noted.

(a) Brake specific fuel consumption (BSFC): BSFC is defined as the ratio of fuel consumed in kg/h to the brake power and the expression of BSFC is given as:

BSFC = (fuel consumed in kg/h / brake power in kW) kg/kWh (3)

$$BP = 2\pi N \tau / (60 \times 1000) \text{ kW} \quad (4)$$

Where, N is revolutions per minute and τ is torque in Nm.

(b) Heat supplied or thermal energy contained in fuel: Heat supplied was calculated by:

$$E_f = (\dot{m}_f \times LCV_f) \text{ kW} \quad (5)$$

Where, LCV_f is lower calorific value of diesel in kJ/kg and $\dot{m}_f$ is mass flow rate of fuel in kg/sec.

(c) Brake thermal efficiency (BTE): BTE of the engine was calculated by the following relation:

$$BTE = BP / E_f \quad (6)$$

Where, BP and E_f are as given by equations (4) and (5) respectively.

(d) EGR percentage: The percentage of exhaust gas recirculation is defined as the percentage of recirculated exhaust in total intake mixture, calculation of which was defined by relating the amount of CO_2 in intake manifold with that in exhaust pipe, through the below equation. CO_2 percentage at (i) inlet manifold (after mixing of EGR with intake air) (i.e. $[CO_2]_{intake}$), (ii) ambient air (i.e. $[CO_2]_{ambient}$) and (iii) exhaust (i.e. $[CO_2]_{exhaust}$) was noted for each set of torque, RPM and EGR valve position.

$$EGR\% = \frac{[CO_2]_{intake} - [CO_2]_{ambient}}{[CO_2]_{exhaust} - [CO_2]_{ambient}} \quad (7)$$

After all readings were taken for the desired RPMs at desired torques with the desired EGR valve positions, different graphs were plotted for various conditions for BSFC and BTE comparing the same for base case. Graphs were also plotted for NOx and smoke emissions for various test sets. Results were analyzed and conclusions drawn.

All readings were taken three times and an average of the three readings was taken for the results to increase the statistical confidence of the findings. Student t-test with 95% confidence interval was conducted to find significance of difference of performance and emission parameters after off-board regeneration and active regeneration of DPF.

CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSIONS

In this section, various parameters defined in the previous chapter such as BSFC, BTE and emissions (NO_x and Smoke) were evaluated / analyzed for (a) testing with and without DPF, that also broken into two parts, one with off-board regeneration of DPF and the other with active regeneration of DPF, (b) testing with and without EGR and (c) testing with DPF and EGR in tandem. All tests were conducted for various loads (no load to max. possible load). As mentioned earlier, maximum load was less than rated peak load since the engine belonged to Euro-I era and was quite old, hence, running that engine at the maximum rated load was not possible. Three sets of readings were taken for all cases. Error analysis is discussed at Appendix C. The following sections show the test results of average values of the three tests for each parameter.

4.1 Engine performance and emission analysis with and without DPF

The results of study for DPF are divided into three sections: (i) Engine performance with and without DPF, (ii) Smoke and NOx emissions with and without DPF and (iii) Impact on oxygen in exhaust with and without DPF; for all the torques and RPMs, also considering the two different regeneration methods adopted.

The engine could not be run at 3000 RPM with 90 Nm torque as the exhaust temperature rose quite high and the exhaust pipe became red hot. As a safety measure, it was decided not to go beyond 90 Nm torque and 3000 RPM. Also, the engine could run at 1000 RPM with DPF at no load condition only, and could not run at 1000 RPM with 25, 50, 75 or 90 Nm torque. Hence, it was decided to omit readings at 1000 RPM wherever DPF was involved. This was due to the fact that the engine was rated for a minimum speed of 1000 RPM and when DPF is connected to the exhaust, there is increased back-pressure on the engine, making it difficult to run.

In the graphs, ‘off-board regen.’ means observations made with DPF after off-board regeneration of DPF, and ‘active regen.’ means observations made with DPF after active regeneration of DPF.

4.1.1 Engine performance analysis

(a) Brake Specific Fuel Consumption (BSFC)

Brake specific fuel consumption is a comparative parameter that shows how efficiently an engine is converting energy of fuel into work. BSFC is ratio of fuel consumed in kg/h to the brake power. For the determination of fuel consumed in kg/h, volumetric flow rate of diesel was measured by burette method and then it was multiplied by the density of diesel.

(b) Brake Thermal Efficiency (BTE)

Brake Thermal Efficiency (BTE) is an important parameter, as it provides a measure of net power developed by the engine, which is readily available for use at the engine output shaft. Formula for BTE is given in the earlier chapter.

From Fig. 4.1 and Fig. 4.2, as also from Table A.3 in appendices (student t-test), it is observed that installation of DPF with off-board regeneration did not have any significant impact on engine performance, whereas, DPF with active regeneration certainly had a significant adverse impact on engine performance as when the soot accumulation in DPF increases, it generates back pressure, resulting in an increased consumption of fuel, which adversely impacts BSFC and BTE. Hence, it becomes all the more important to have a feasible and economically viable periodical DPF regeneration mechanism. This was taken care of during active regeneration by mist spray of fuel in DPF, whereas, for off-board regeneration, the situation needed to be handled by taking the DPF out for regeneration in a furnace, after which the DPF becomes almost new with negligible PM embedded in the filter.

BSFC with active regeneration of DPF, at 2500 RPM and 50 Nm torque, increased to 0.43 kg/kWh from 0.38 kg/kWh for base case, and hence, there was a corresponding decrease in BTE from 21.15% to 18.69% i.e., a reduction of 2.46% in BTE. This was the maximum impact observed on engine performance with DPF. The adverse impact was highest at 50 and 75 Nm torques whereas the effect at 25 Nm torque was negligible. However, this high degree of impact was due to the fact that it was an old Euro-I engine and hence, the quantity of PM emission was quite high which was choking the DPF quite fast and while off-board regeneration was effective in removing the entire PM from DPF, active regeneration was not able to completely remove the accumulated PM in the DPF. While DPF will have an adverse impact on BSFC and BTE even in new vehicles, but the impact will be quite low as compared to this test case.

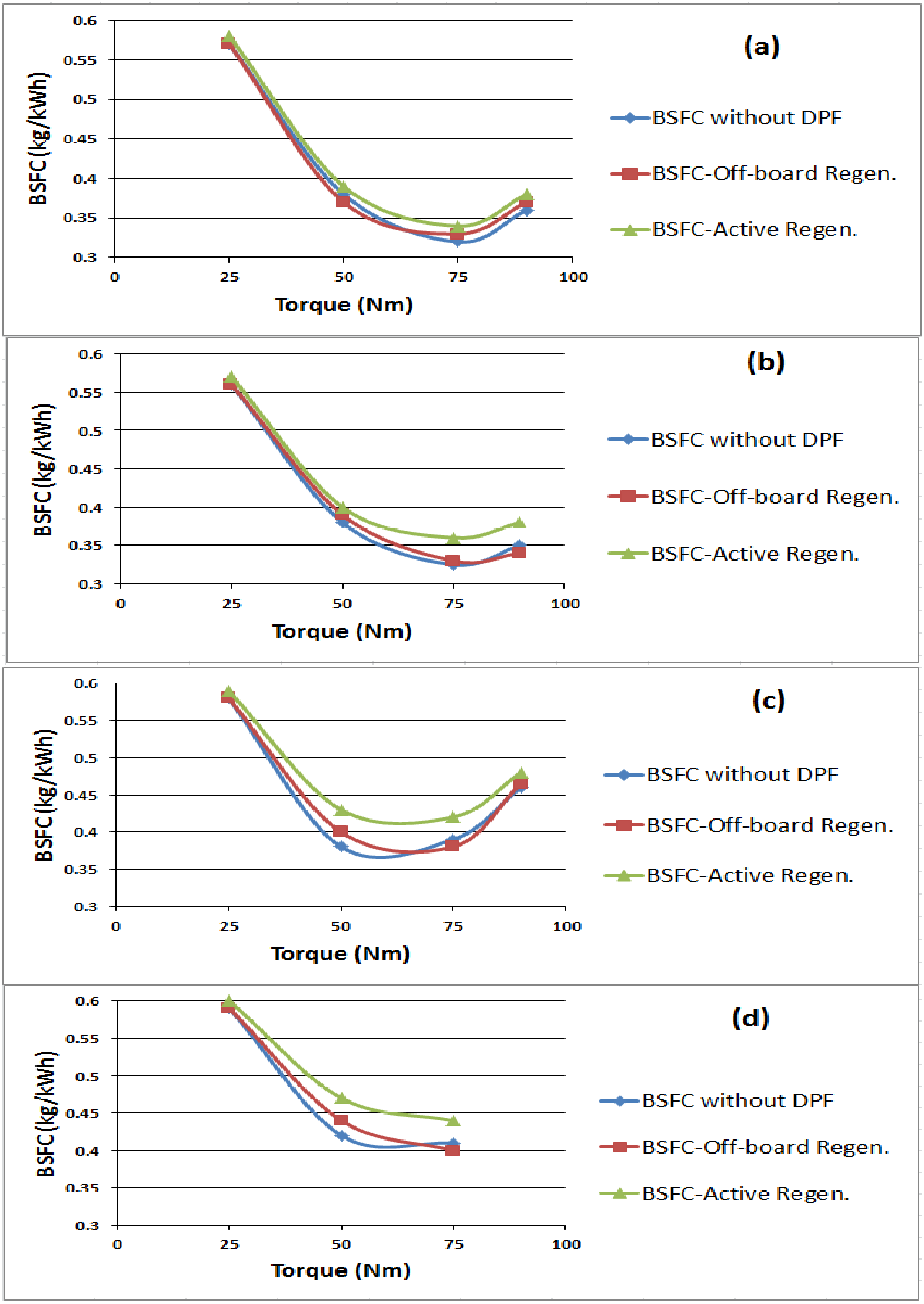


Fig. 4.1 Variation of BSFC with torque without DPF and with DPF considering both the regeneration methods at (a) 1500 RPM, (b) 2000 RPM, (c) 2500 RPM and (d) 3000 RPM

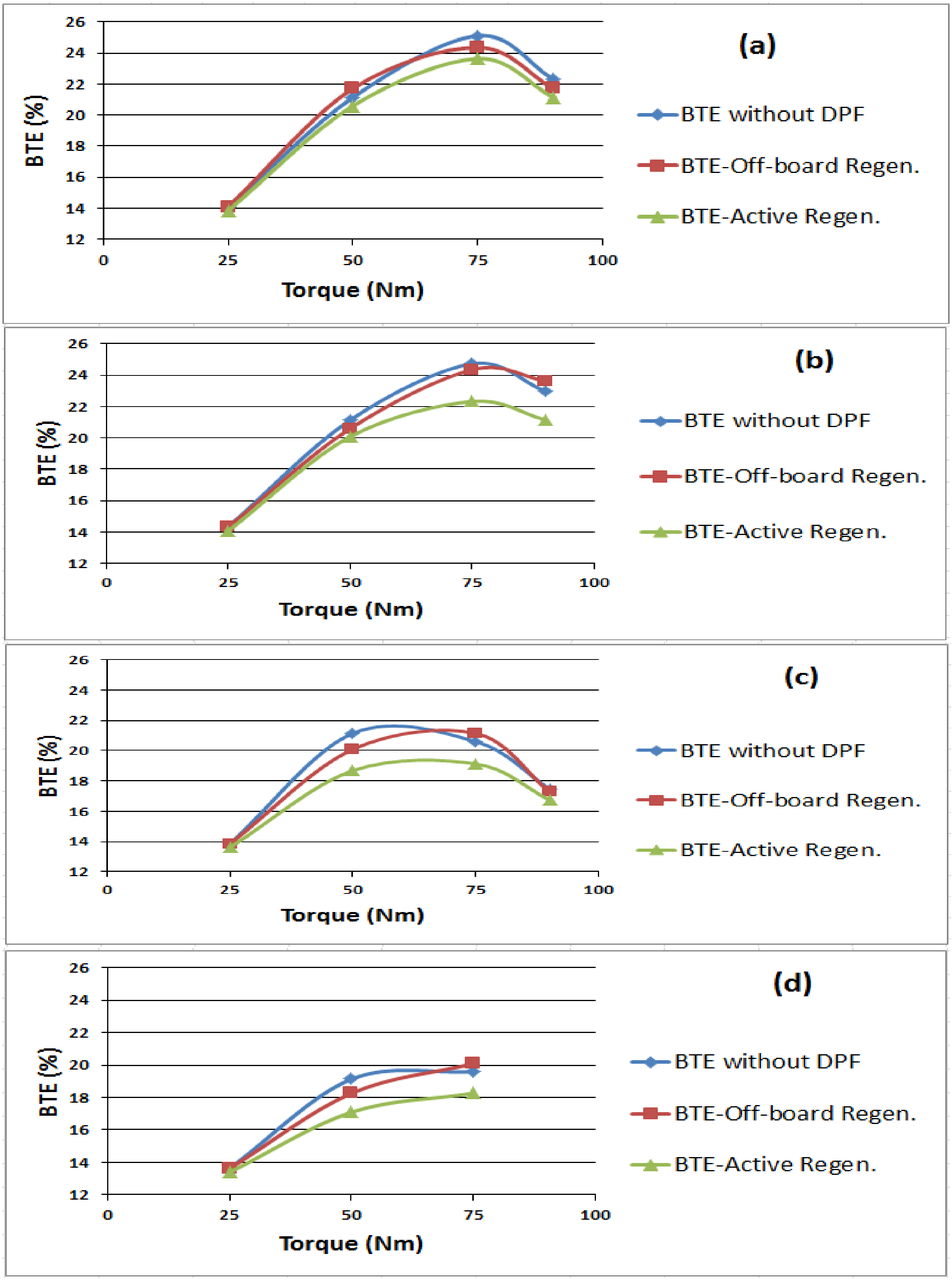


Fig. 4.2 Variation of BTE with torque without DPF and with DPF considering both the regeneration methods at (a) 1500 RPM, (b) 2000 RPM, (c) 2500 RPM and (d) 3000 RPM

4.1.2 Emission analysis

(a) Smoke / PM emissions

PM, responsible for the black smoke in diesel engines, is formed due to thermal cracking (pyrolysis) of hydrocarbons (here, diesel) at high temperatures. Hence, at low temperatures (typically at low loads), PM is less and vice-versa. Reduction of smoke or particulate matter is the most desirable function of using DPF and from the graphs in Fig. 4.3 it is evident that 75-99% of smoke is absorbed by the porous cells of the DPF, emitting negligible amount of smoke to the environment. It was further observed from the results in Fig. 4.4 that the reduction in smoke emission was more after off-board regeneration compared to that after active regeneration because DPF effectiveness got slightly reduced after active regeneration (compared to the new DPF), as some percentage of soot remained stuck to the DPF walls/pores every time. Whereas, the effectiveness of DPF remained almost unchanged (compared to the new DPF) after off-board regeneration because entire soot content got eliminated when heated at 650^{o}C for 10 hours in a furnace. Table A.3 in appendices (student t-test) also shows that there is significant difference between DPF effectiveness after off-board and active regeneration respectively. DPF (the face where the exhaust gas enters), before and after off-board regeneration, is shown in Fig. A.8 (a) and (b) in appendices section [31].

While with active regeneration DPF was able to remove 75-95% PM from exhaust, with off-board regeneration PM reduction was of the tune of 79-99%. Though the DPF was quite effective in PM removal at all loads and RPMs, most reduction took place at 90 Nm torque i.e. at maximum load especially because smoke rose exponentially at high loads in base case i.e. without DPF. While the opacity % without DPF went as high as 46.5% at 1500 RPM with 90 Nm torque, it was 2.4% at the same load and RPM with active regeneration of DPF. The maximum opacity with active regeneration of DPF went up to 5.6% at 3000 RPM with 75 Nm torque, whereas it was 27.2% without DPF at 3000 RPM with 75 Nm torque.

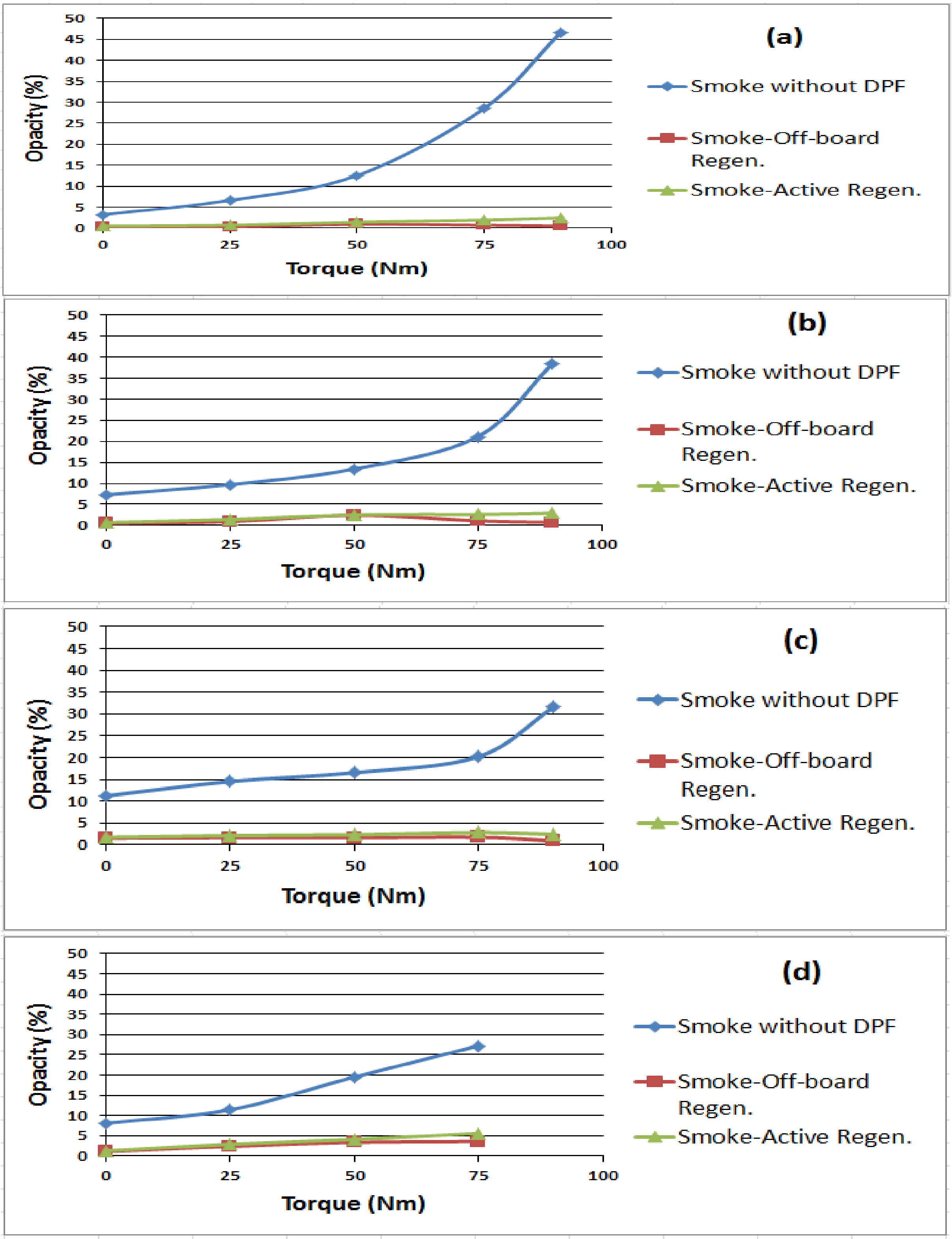


Fig. 4.3 Variation of smoke emission (opacity %) with torque without and with DPF for both regeneration methods at (a) 1500 RPM, (b) 2000 RPM, (c) 2500 RPM and (d) 3000 RPM

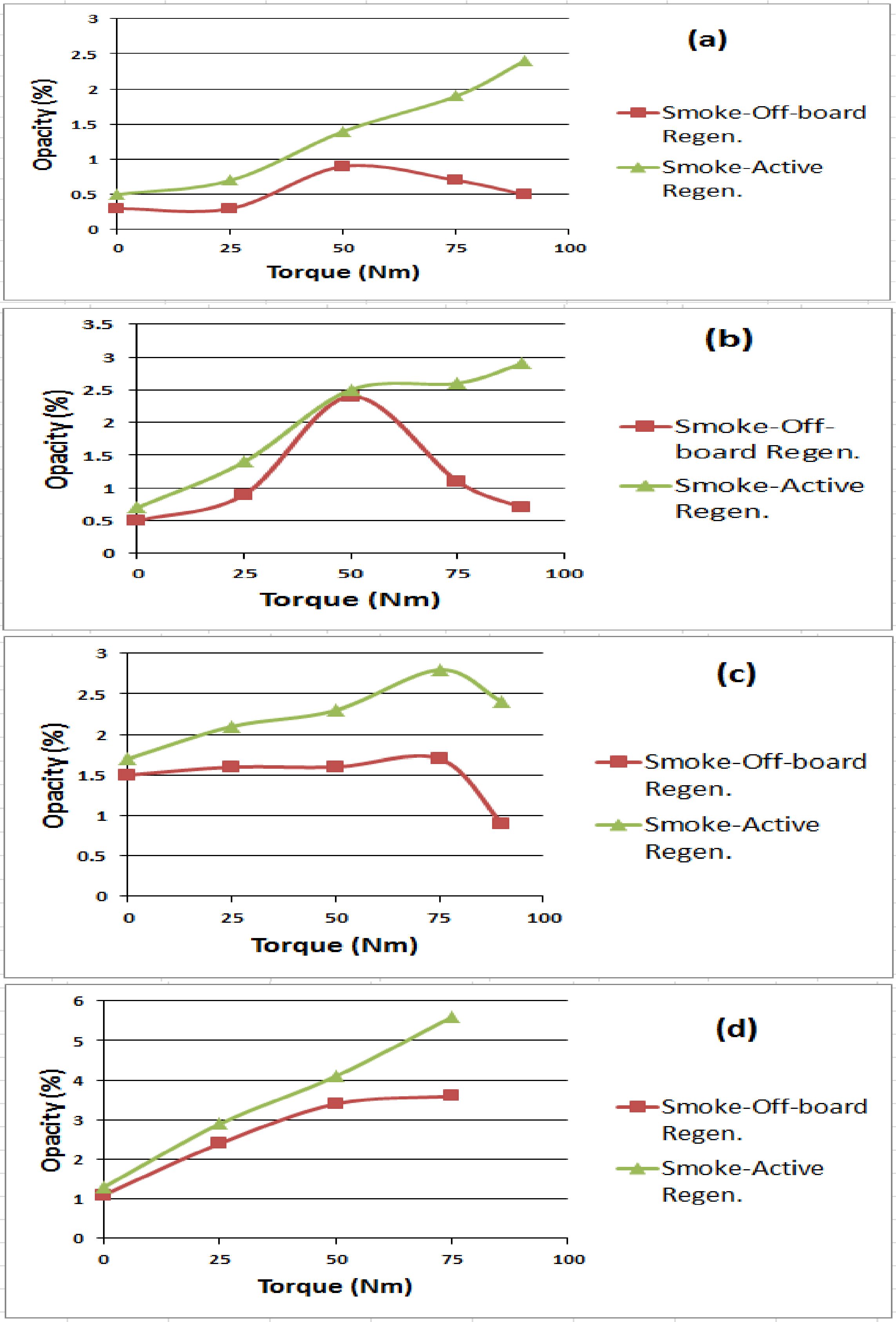


Fig. 4.4 Variation of smoke emission (opacity %) with torque for off-board and active regeneration methods at (a) 1500 RPM, (b) 2000 RPM, (c) 2500 RPM and (d) 3000 RPM

(b) NOx emissions

As is seen from Fig. 4.5, NOx emission increased at all loads at all RPMs with DPF. This is because with DPF, some back pressure is formed and there is a fuel penalty, i.e. more fuel burning in cylinder producing higher combustion temperature and hence, increased NOx formation. The three major causes of formation of NOx are (i) high combustion temperature, (ii) availability of excess oxygen and (iii) duration of availability of excess oxygen. It was also observed that NOx emission after off-board regeneration was lesser as compared to that after active regeneration. This was because the amount of soot that remained stuck inside the DPF was much more in case of active regeneration as compared to that after off-board regeneration, which gave more back pressure and hence, more fuel penalty and higher combustion temperature inside the cylinder.

There was a significant adverse impact of DPF on NOx emission with increase in NOx% reaching up to 132% and 94% in case of active regeneration and off-board regeneration respectively compared to base case, occurring with no load condition at 2500 RPM. The minimum percentage rise in NOx with DPF was 24% and 18% respectively in case of active regeneration and off-board regeneration, occurring with 75 Nm torque at 2500 RPM. However, there was no definite pattern for percentage rise of NOx with DPF.

Hence, while DPF removes almost all of smoke, it results in increased NOx. Therefore, other methods need to be implemented along with DPF in tandem, to work on NOx reduction e.g. EGR.

(c) Impact on O_2 in exhaust with and without DPF

It is clearly seen from the graphs in Fig. 4.6 that O_2 percentage in exhaust decreased substantially with DPF at all loads and all RPMs. The primary reason for this is oxidation of soot (particulate matter) embedded in DPF to form CO or CO_2. It was also observed that oxygen percentage in exhaust after off-board regeneration was more as compared to that after active regeneration, since more soot is accumulated in DPF during active regeneration as compared to off-board regeneration and hence, more oxygen gets converted to CO or CO_2 in case of active regeneration as compared to off-board regeneration.

While O_2 in exhaust varied from 17.9% to 12.3% without DPF at various loads and engine speeds, it was between 17.3% and 3.4% in case of off-board regeneration and between 17% and 3.3% in case of active regeneration of DPF.

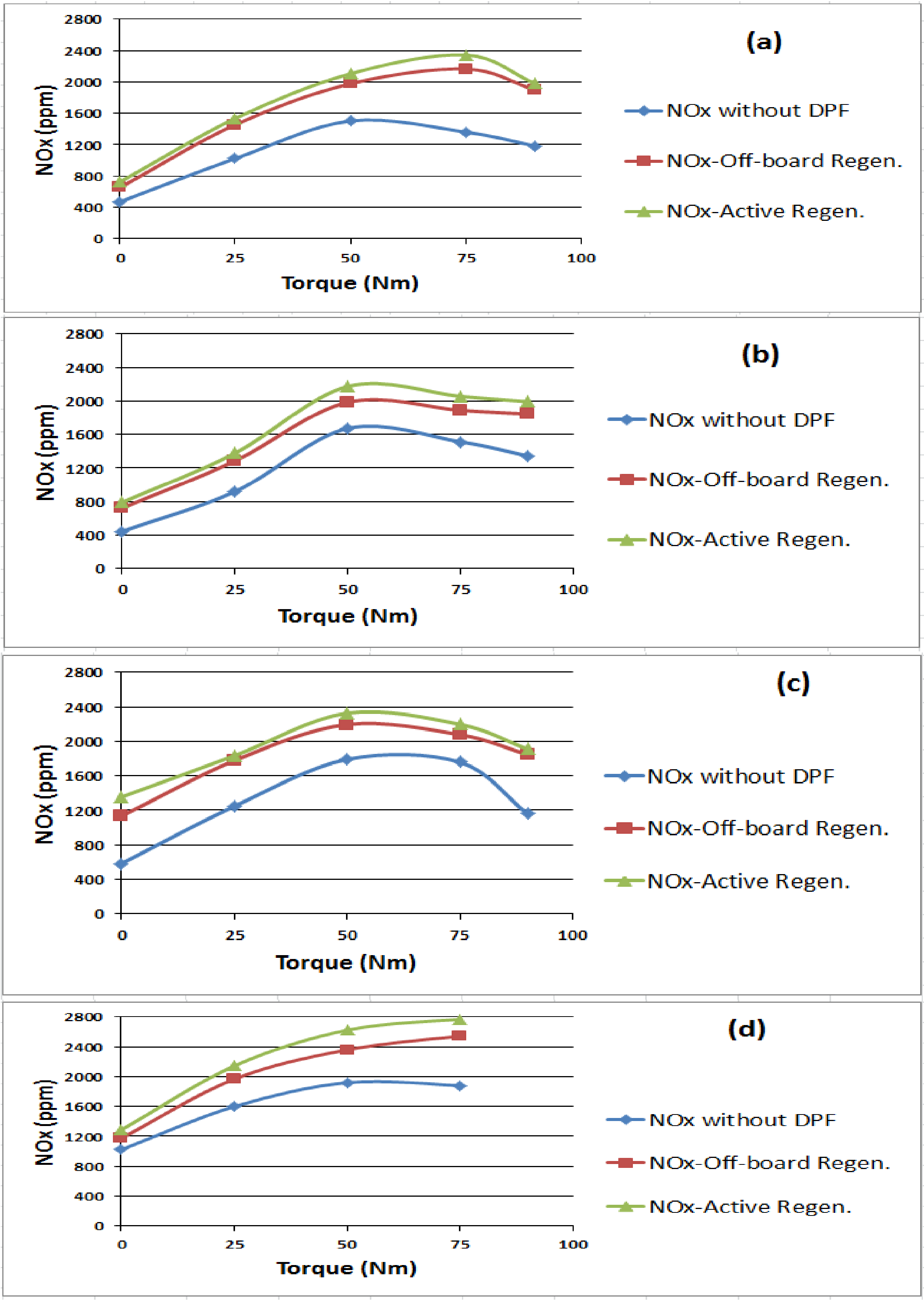


Fig. 4.5 Variation of NOx emission with torque without DPF and with DPF considering both the regeneration methods at (a) 1500 RPM, (b) 2000 RPM, (c) 2500 RPM and (d) 3000 RPM

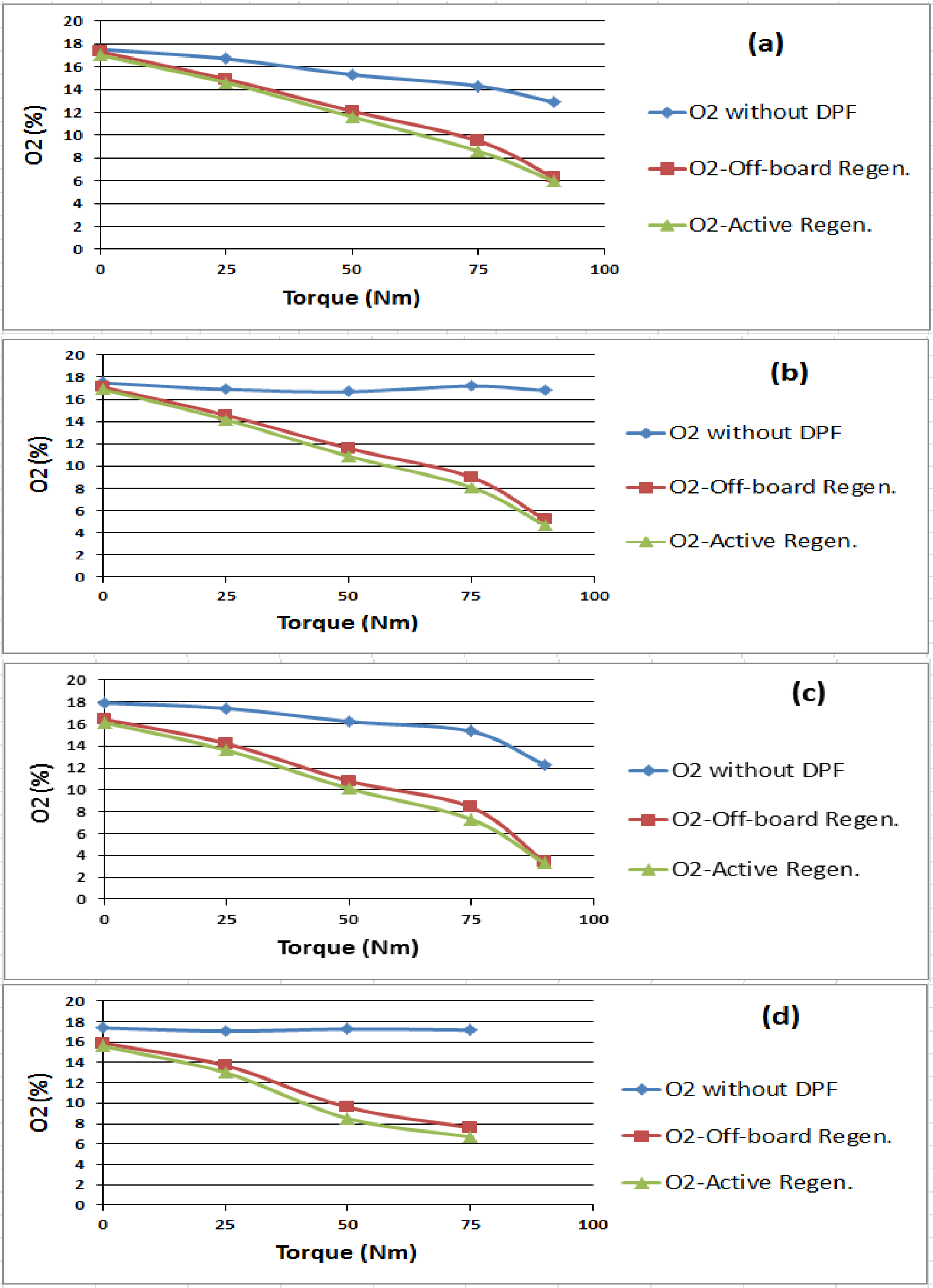


Fig. 4.6 Variation of O_2 (in exhaust) with torque without DPF and with DPF considering both the regeneration methods at (a) 1500 RPM, (b) 2000 RPM, (c) 2500 RPM and (d) 3000 RPM

4.2 Engine performance and emission analysis with and without EGR

With 90 mm torque, the engine could not run with more than 10% opening of EGR valve, whereas the study considered EGR valve opening percentages as 25, 50, 75 and 100%. Hence, it was decided to omit readings at 90 Nm torque whenever taking readings with EGR. This was due to the fact that the engine was quite old and was not possible to run at torque beyond 90 Nm as mentioned earlier. However, engine could run at 90 Nm with fresh air and not with EGR. Hence, when the engine was attempted to run with 90 Nm torque with EGR, it could not run due to extra demand for oxygen for more complete combustion.

EGR valve opening percentage (0, 25, 50, 75 and 100% represent 0, 1, 2, 3 and 4 mm lift of the EGR valve) that gave the best results (minimum NOx emission) for the set of a given torque and a given engine speed is displayed in Table 4.1.

Table 4.1: Optimized percentage of EGR valve opening at a given torque and speed [32]

Torque (Nm)► RPM▼	0	25	50	75
1000	100	50	50	50
1500	75	75	75	75
2000	100	100	100	100
2500	75	75	75	100
3000	75	50	100	100

The optimum EGR percentage (corresponding to the various valve opening–percentages shown in Table 4.1) that gave the minimum NOx emission for the set of a given torque at a given engine speed is displayed in Table 4.2. EGR intake percentage was calculated using CO_2 method as explained in section 3.7.7. It was evident from Table 4.2 that the optimum EGR percentage varied from 22% to 58% at different torque and engine speed for the set-up used. So, this was the percentage of EGR in the air intake of the engine e.g. at 1500 RPM engine speed with 25 Nm torque, minimum NOx was obtained with 75% (as shown in Table 4.1) valve opening (i.e. 3 mm valve lift), and on calculating using CO_2 method, the EGR% in the engine air intake at this setting was found to be 28% (as shown in Table 4.2) [32].

Table 4.2: Optimized EGR % at a given torque and speed [32]

Torque (Nm)► RPM▼	0	25	50	75
1000	22	22	23	25
1500	27	28	30	36
2000	39	42	46	51
2500	31	34	39	54
3000	36	42	53	58

4.2.1 Engine performance analysis

(a) Brake Specific Fuel Consumption

In this section a comparison has been drawn between BSFC with and without EGR (optimized) for 4 different torques at 5 different engine speeds to illustrate the impact of EGR on engine performance.

(b) Brake Thermal Efficiency

In this section a comparison has been drawn between BTE with and without EGR (optimized) for 4 different torques at 5 different engine speeds to illustrate the impact of EGR on engine performance.

From Fig. 4.7 and 4.8, it was observed that EGR had a slight adverse impact on engine performance (BSFC and BTE). EGR reduces the quantity of oxygen in intake which results in incomplete combustion of fuel. This resulted in a fuel penalty thereby increasing BSFC and decreasing BTE. At higher loads, the exhaust pressure increases resulting in higher percentage of EGR for the same amount of valve opening which results in a bigger fuel penalty at higher loads.

BSFC with optimum EGR, at 2000 RPM and 50 Nm torque, increased to 0.43 kg/kWh from 0.38 kg/kWh for base case with 2000 RPM speed and 50 Nm torque. The BTE for the same RPM and torque reduced from 21.15% without EGR to 18.69% with optimum EGR at the above speed and torque.

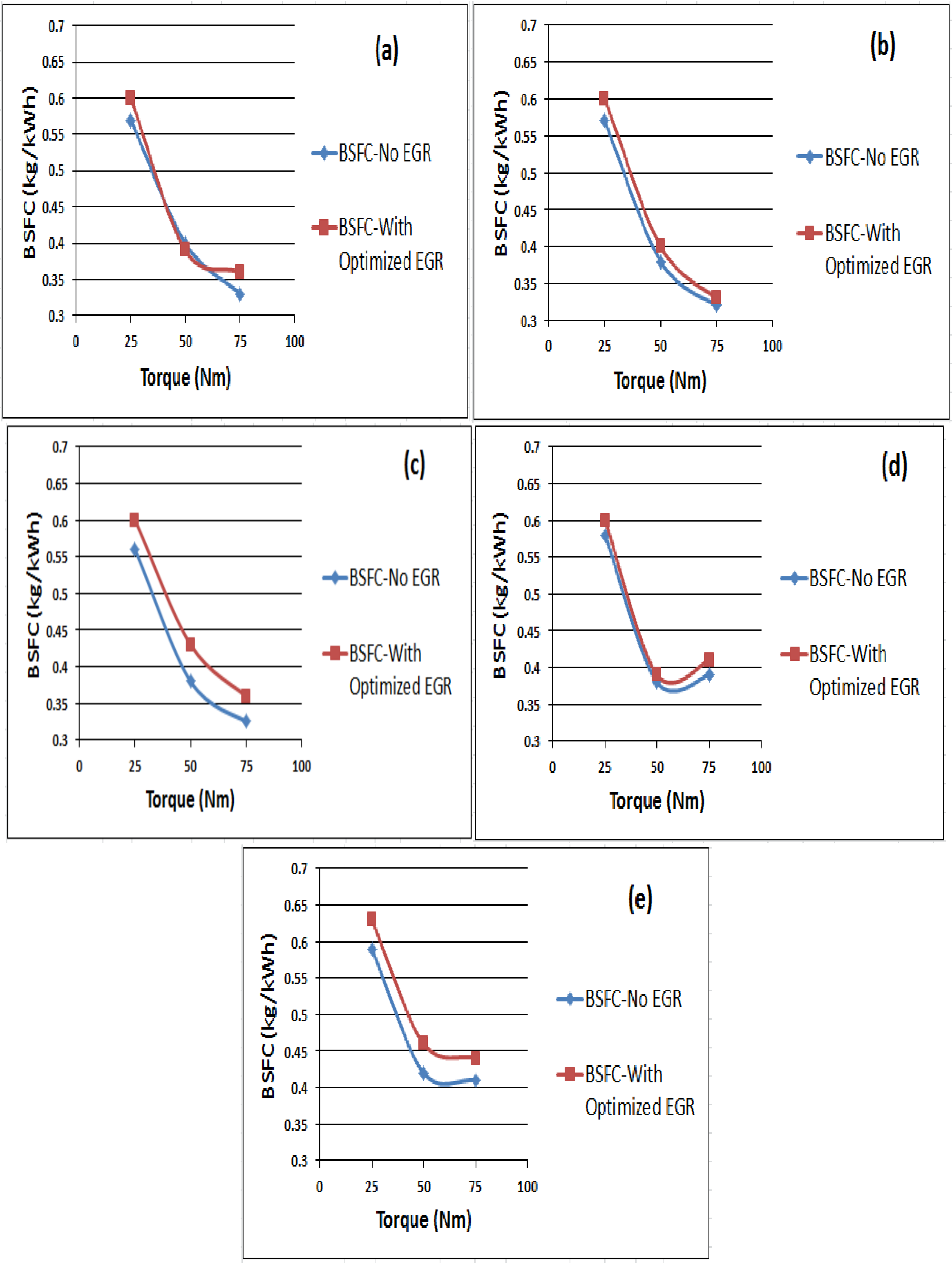


Fig. 4.7 Variation of BSFC against torque with and without EGR at (a) 1000 RPM, (b) 1500 RPM, (c) 2000 RPM, (d) 2500 RPM and (e) 3000 RPM

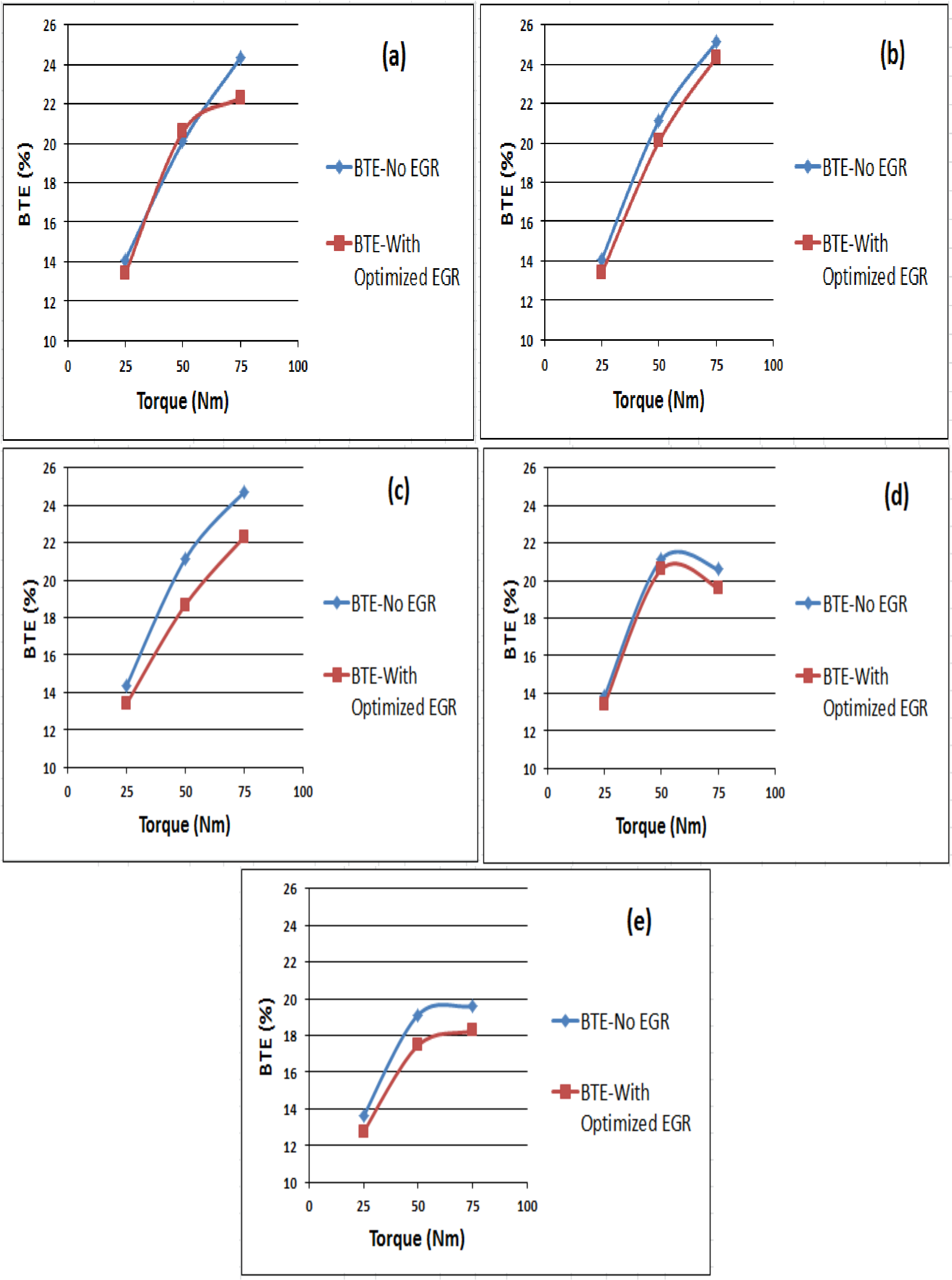


Fig. 4.8 Variation of BTE against torque with and without EGR at (a) 1000 RPM, (b) 1500 RPM, (c) 2000 RPM, (d) 2500 RPM and (e) 3000 RPM

4.2.2 Emission analysis

(a) NOx Emissions

The primary aim of EGR is to reduce NOx. In this section, reduction in NOx with application of EGR (optimized) is analyzed for 4 loads at 5 engine speeds.

Fig. 4.9 clearly shows a very positive impact of EGR in the form of NOx emission reduction at all torques and all speeds. As discussed in the introduction section, the three major causes of formation of NOx are (i) high combustion temperature, (ii) availability of excess oxygen and (iii) duration of availability of excess oxygen. The primary reasons for reduced NOx emissions with EGR in diesel engines are reduction in intake oxygen concentration (as exhaust gas contains much lesser oxygen percentage compared to fresh air) and decreased flame temperatures in the cylinder (by increasing the specific heat capacity of the intake charge by the inert gases in exhaust, mainly CO_2 and water vapor).

The biggest NOx reduction took place at lower loads. At lower loads with EGR, NOx emission was negligibly small due to very low combustion temperature in the cylinder and hence, at such loads, the reduction in NOx with EGR was huge. Average reduction in NOx emission using optimum EGR was found to be 45% proving the usefulness of EGR even on an old Euro-I engine.

(b) Smoke / PM Emissions

While reduction of NOx is the primary aim of EGR, study of its impact on smoke emission is important since diesel engines' main issues are NOx and smoke emissions. Hence, in this section, the impact of application of EGR (optimized) on smoke emission is analyzed for 4 loads at 5 engine speeds.

As observed from Fig. 4.10, Smoke emission increased at all torques and at all RPMs with EGR. EGR implementation results in lowering of in-cylinder temperature and reduction in oxygen concentration which results in effective reduction of NOx emissions with increasing EGR%. Whereas, the same reasons decelerate the oxidation of soot and consequently, soot emission increases with increase in EGR%. Smoke (opacity) percentage increased from 6.6% without EGR to 6.7% with optimum EGR at 1500 RPM with 25 Nm torque. Whereas, opacity% increased from 11.4% without EGR to 23.3% with optimum EGR at 3000 RPM with 25 Nm. Hence, other emission reduction technologies should be appended to counter the negative impacts of EGR.

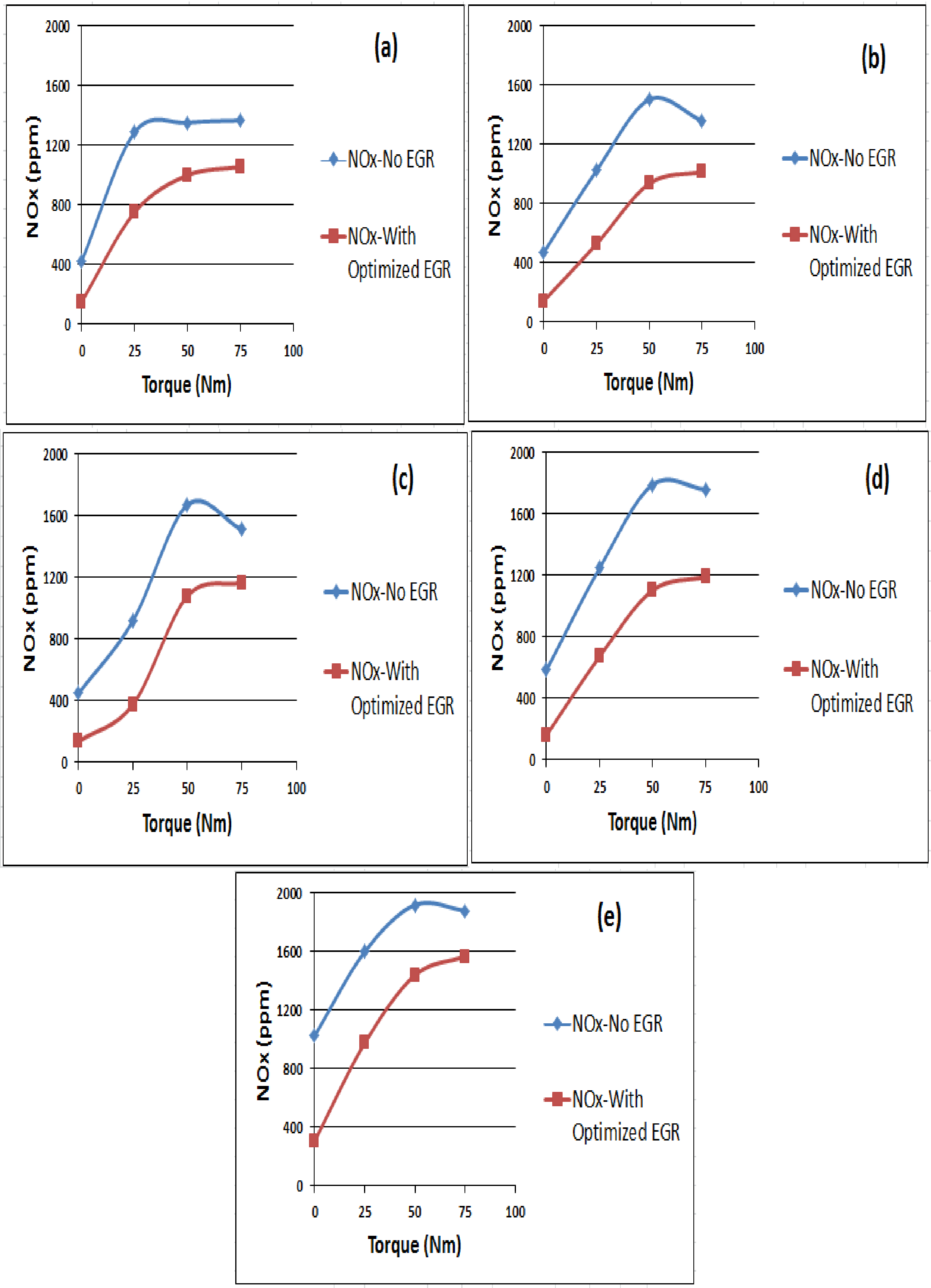


Fig. 4.9 Variation of NOx emission against torque with and without EGR at (a) 1000 RPM, (b) 1500 RPM, (c) 2000 RPM, (d) 2500 RPM and (e) 3000 RPM

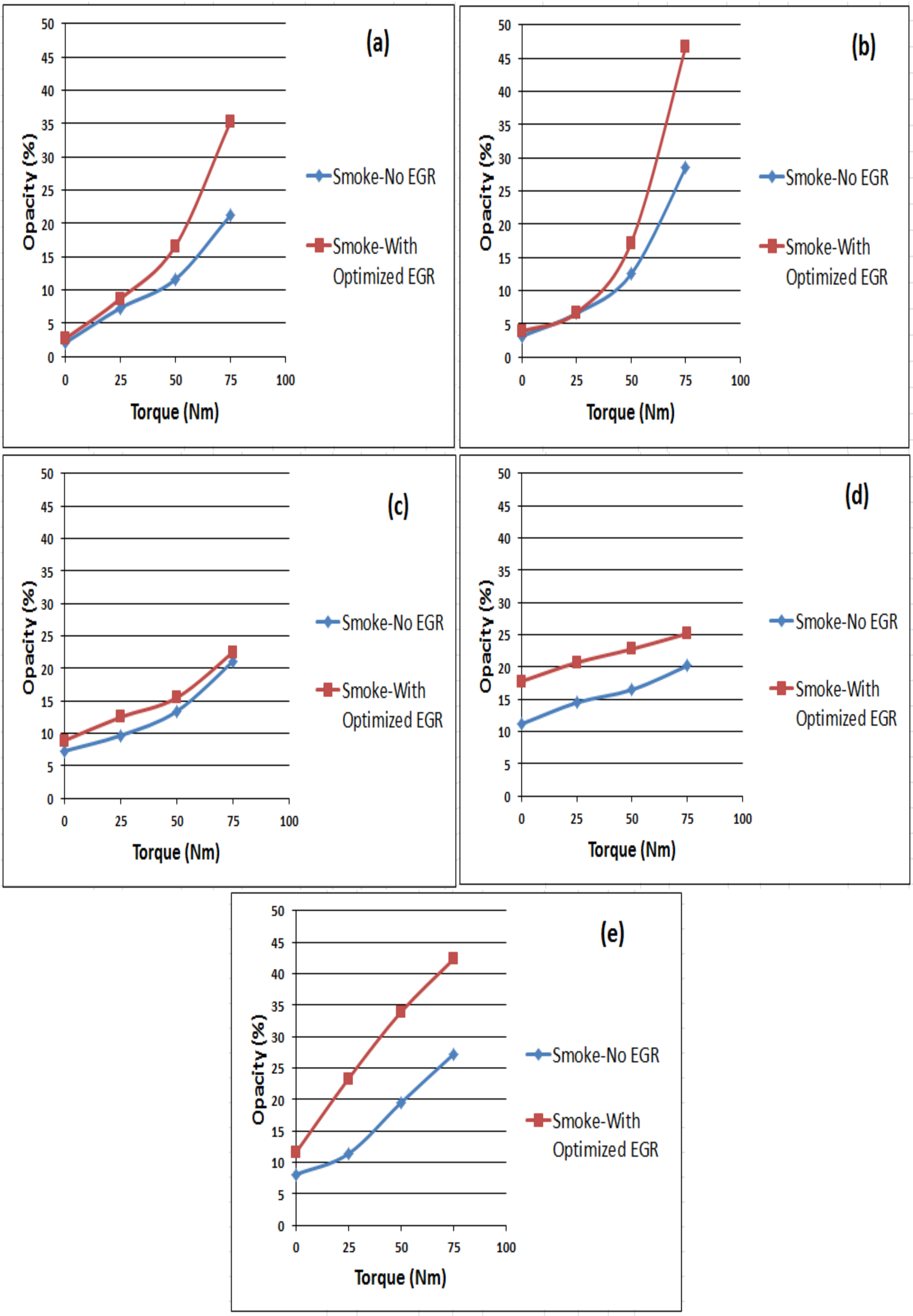


Fig. 4.10 Variation of opacity (smoke emission) against torque with and without EGR at (a) 1000 RPM, (b) 1500 RPM, (c) 2000 RPM, (d) 2500 RPM and (e) 3000 RPM

4.3 Engine performance and emission analysis with DPF (off-board regeneration) and EGR (optimized) in tandem

On comparing the performance and emission results of off-board regeneration with that of active regeneration of DPF, it was observed that off-board regeneration has several advantages over active regeneration viz., lesser NOx emissions, lesser smoke emissions, lesser BSFC and more BTE. Hence, it was decided that while testing DPF in tandem with EGR, off-board regeneration method shall be adopted, which is already explained earlier.

With 90 mm torque, the engine could not run with more than 10% opening of EGR valve, whereas the study considered EGR valve opening percentages as 25, 50, 75 and 100%. Also, the engine could run at 1000 RPM with DPF at no load condition only, and could not run at 1000 RPM with 25, 50, 75 or 90 Nm torque. The reasons for the same have already been mentioned earlier. Hence, it was decided that, in case of testing DPF and EGR in tandem, readings at 1000 RPM engine speed for all torques and readings at 90 Nm torque for all RPMs shall not be taken. Thus, the test was conducted for 0, 25, 50 and 75 Nm torque at 1500, 2000, 2500 and 3000 RPM engine speeds.

Each graph of section 4.3 and its sub-sections has 4 curves, one each for base case, off-board regeneration (no EGR), optimized EGR (no DPF) and DPF + EGR (both EGR and DPF in tandem). This test was conducted at 1500, 2000, 2500 and 3000 RPM for 0, 25, 50 and 75 Nm torque with optimized EGR. Off-board regeneration of DPF was done at regular intervals so that no undue impact is there on the readings.

4.3.1 Engine performance analysis

(a) Brake Specific Fuel Consumption

Since both DPF and EGR had a light adverse impact on BSFC, when both DPF and EGR are put in tandem, it results in a significant fuel penalty impacting BSFC adversely. From Fig. 4.11, it was observed that while BSFC rose marginally to 0.58 kg/kWh with DPF and EGR in tandem at 1500 RPM and 25 Nm torque from 0.57 kg/kWh with base case; at 3000 RPM with 50 Nm torque, the rise was more significant i.e., from 0.42 kg/kWh to 0.54 kg/kWh. While the BSFC varied from 0.32 kg/kWh at 1500 RPM with 75 Nm torque to 0.59 kg/kWh at 3000 RPM with 25 Nm torque, the same with DPF + EGR varied from 0.39 kg/kWh at 1500 RPM with 75 Nm torque to 0.63 kg/kWh at 3000 RPM with 25 Nm torque.

Hence, though using DPF and EGR in tandem will be highly desired for reduction in NOx as well as smoke emissions simultaneously, further studies need to be conducted to minimize the adverse effect of DPF + EGR on BSFC.

(b) Brake Thermal Efficiency

From Fig. 4.11 and 4.12, it was observed that EGR + DPF in tandem had a significant adverse impact on engine performance (BSFC and BTE). EGR reduces the quantity of oxygen in intake which results in incomplete combustion of fuel, whereas DPF creates a back pressure. Both these reasons resulted in a severe fuel penalty thereby increasing BSFC and decreasing BTE. At higher loads, the exhaust pressure increases resulting in higher percentage of EGR for the same amount of valve opening which results in a bigger fuel penalty at higher loads. Also, at higher loads, the back pressure due to DPF increases. Hence, once again, both these reasons result in increased BSFC and decreased BTE and the effect is quite phenomenal as we see from the graphs. The maximum reduction in BTE after adding EGR and DPF in tandem as compared to that in base case was 4.25% occurring at 3000 RPM with 50 Nm torque decreasing to 14.88% from 19.13% at base case.

BTE with EGR and DPF in tandem varied from 12.76% at 3000 RPM with 25 Nm torque to 20.60% at 2000 RPM as well as 1500 RPM with 75 Nm torque. Whereas, BTE for base case varied from 13.62% at 300 RPM with 25 Nm torque to 25.11% at 1500 RPM with 75 Nm torque. Hence, in absolute terms, the BTE got reduced by an average of approx. 4.5% or lower.

Hence, though using DPF and EGR in tandem will be highly desired for reduction in NOx and smoke emissions, further studies need to be conducted to minimize the adverse effect of DPF + EGR on BSFC.

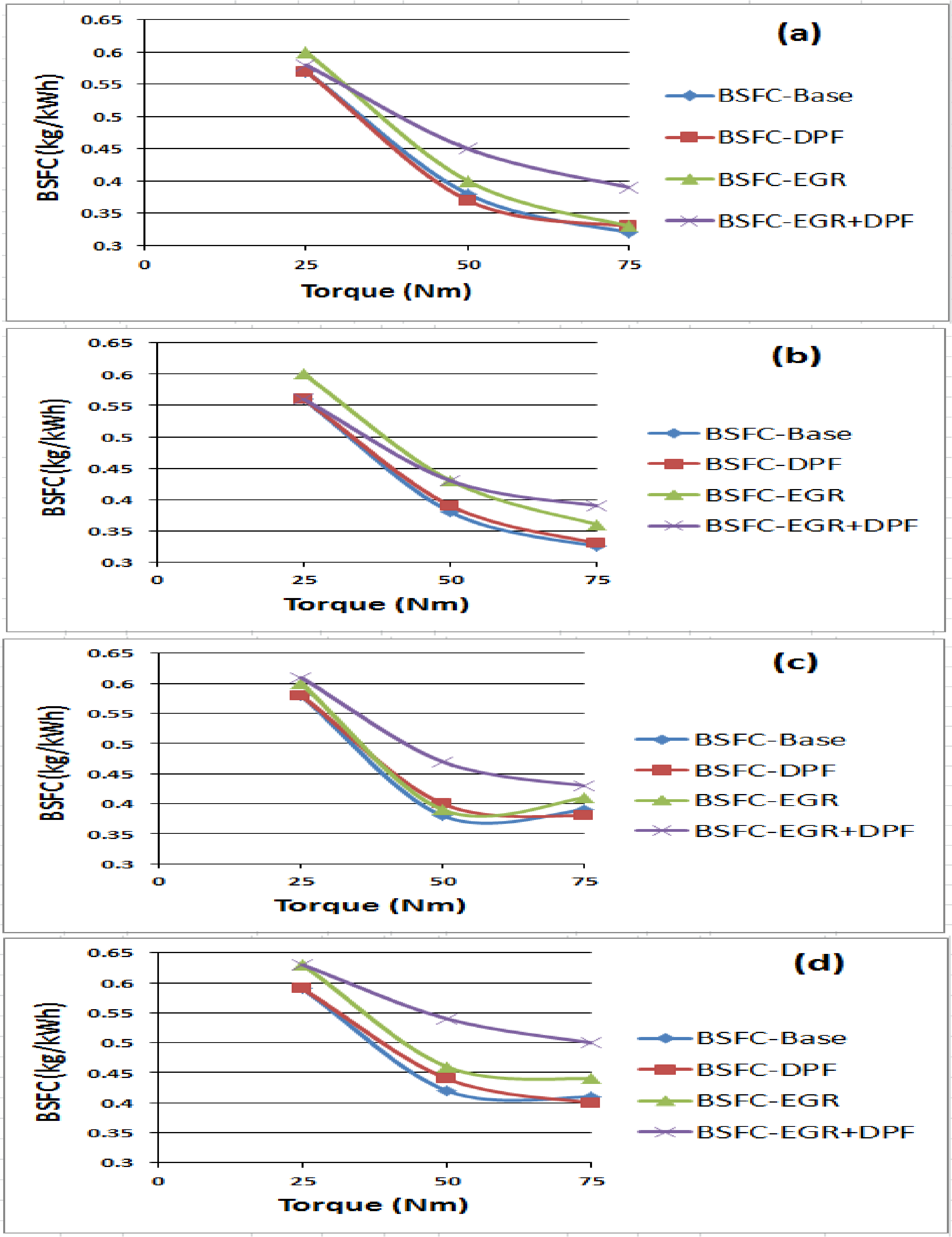


Fig. 4.11 Variation of BSFC with torque for base case, with DPF, with EGR, and with DPF & EGR in tandem at (a) 1500 RPM, (b) 2000 RPM, (c) 2500 RPM and (d) 3000 RPM

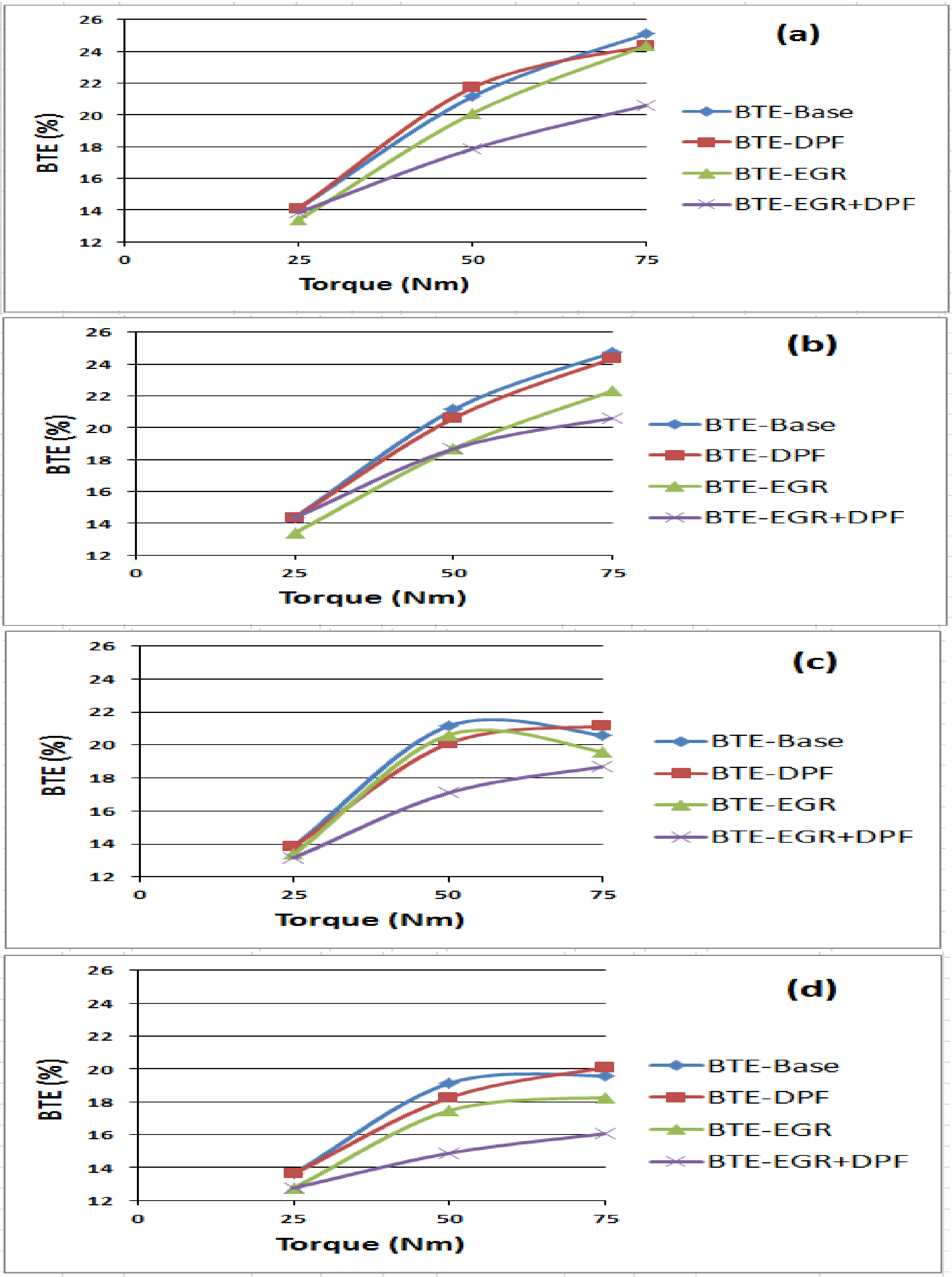


Fig. 4.12 Variation of BTE with torque for base case, with DPF, with EGR, and with DPF & EGR in tandem at (a) 1500 RPM, (b) 2000 RPM, (c) 2500 RPM and (d) 3000 RPM

4.3.2 Emission analysis

(a) Smoke / PM emissions

As we have seen in earlier sections, smoke emission gets reduced with DPF and increased with EGR. Hence, when DPF and EGR are used in tandem, we could expect a result in between the two cases. While smoke (opacity %) with DPF and EGR in tandem was more than that with DPF alone for all loads and all RPMs, it was much lesser than that for base case or with EGR alone as is clear from Fig. 4.13. However, it was still a marked improvement as compared to base case, with maximum smoke reduction reaching 82.9% at 2000 RPM with 75 Nm torque.

(b) NOx Emissions

This is also explained in earlier sections that NOx emission gets reduced with EGR and increased with DPF. Hence, it was expected that NOx emission results will be somewhat between those obtained from DPF alone and EGR alone cases. While NOx emission with DPF and EGR in tandem was more than that with EGR alone for all loads and all RPMs, it was lesser than that for base case or with DPF alone as is clear from Fig. 4.14. However, it was still a marked improvement as compared to base case, with maximum NOx reduction reaching 34.25% at 2500 RPM with 0 Nm torque (no load condition).

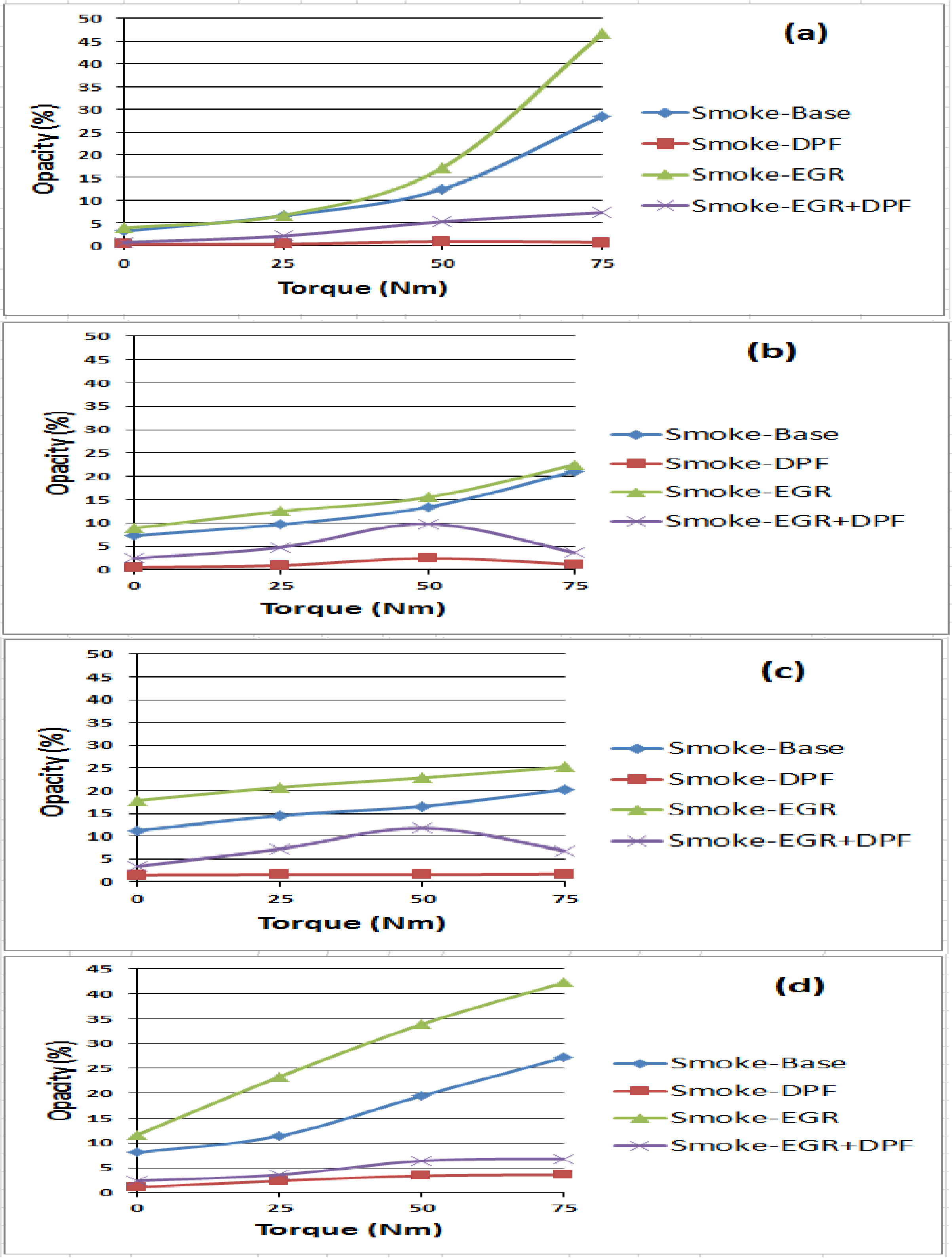


Fig. 4.13 Variation of smoke (opacity %) against torque for base case, with DPF, with EGR, and with DPF & EGR in tandem at (a) 1500, (b) 2000, (c) 2500 and (d) 3000 RPM

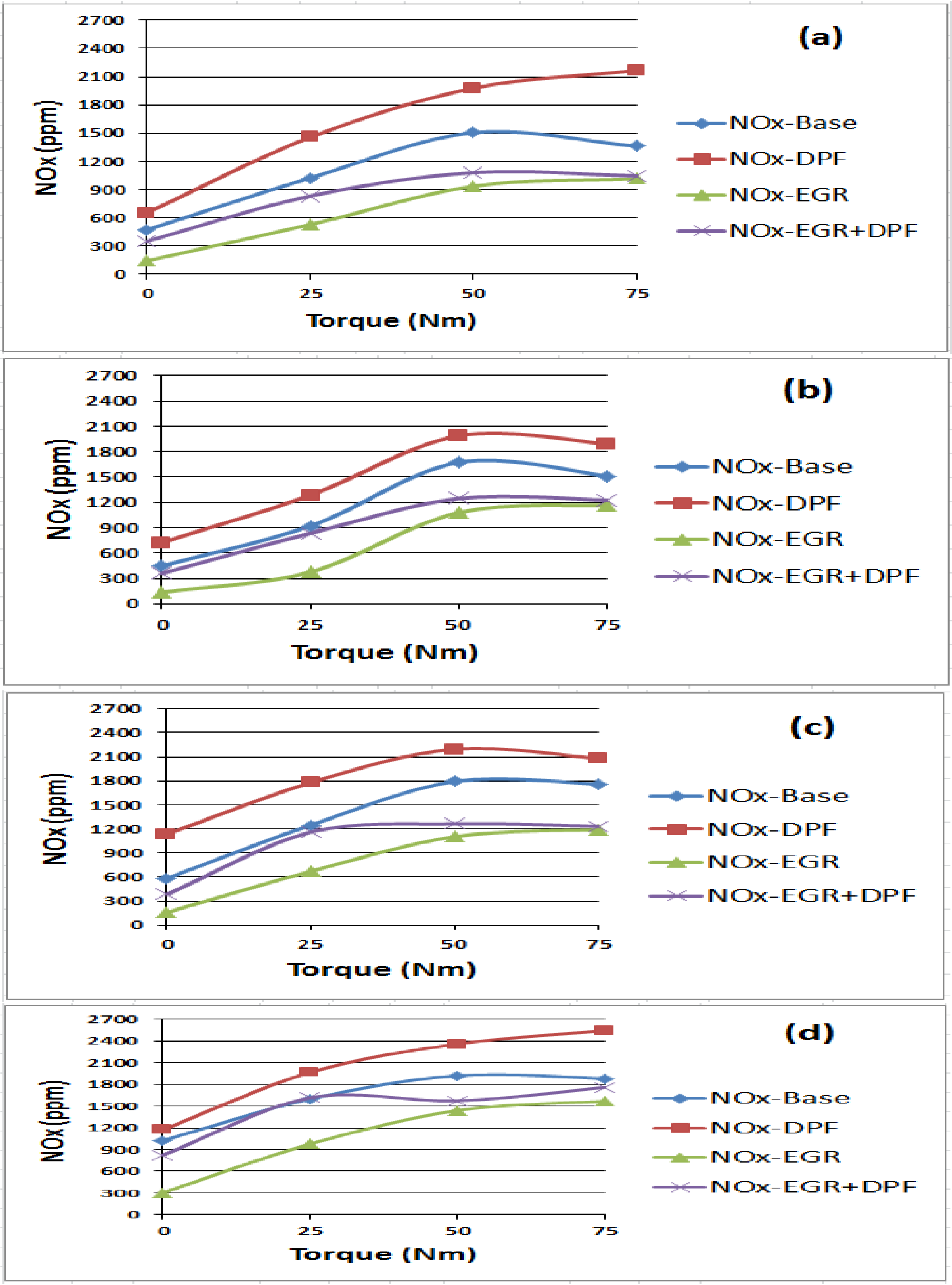


Fig. 4.14 Variation of NOx emission against torque for base case, with DPF, with EGR, and with DPF & EGR in tandem at (a) 1500, (b) 2000, (c) 2500 and (d) 3000 RPM

CHAPTER 5

EFFECT OF VEHICLE WEIGHT ON AUTOMOTIVE EMISSIONS

5.1 Introduction

In this chapter, starting with the current problem of excessive emissions, ways to reduce the emissions, the effect of these ways on emissions and other parameters like safety and cost are discussed followed by the results of the study on the effect of vehicle weight on emissions and ways to achieve it are discussed.

5.2 Current situation

With India going for BS-VI in 2020 and there being vast gap between the emission limits of BS-IV and BS-VI, lots need to be done to fill this gap. The PM and NOx emission limits for BS-IV and BS-VI are shown in Fig. 5.1.

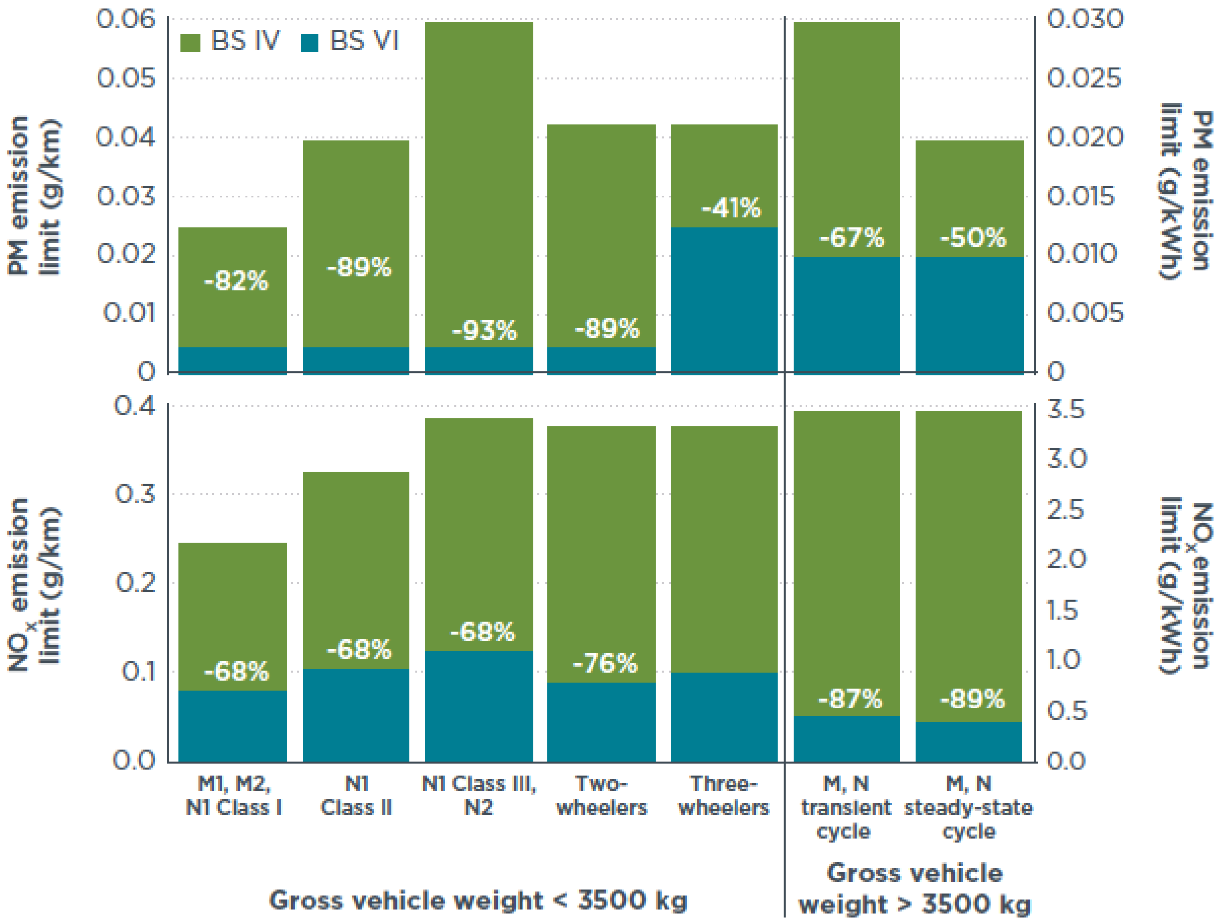


Fig. 5.1: PM and NOx limits for BS IV and BS VI for various categories of vehicles [16]

GHG emissions associated with vehicles can be reduced by four types of measures [95]:

1. Reducing the loads (weight, rolling and air resistance and accessory loads) on the vehicle, thus reducing the work needed to operate it;

2. Increasing the efficiency of converting the fuel energy to work, by improving drive train efficiency and recapturing energy losses;

3. Changing to a less carbon-intensive fuel; and

4. Reducing emissions of non-CO_2 GHGs from vehicle exhaust and climate controls.

Vehicle weight reduction is one of the major methods to reduce automotive emissions. The basic concept behind this is that reduction in weight results in fuel economy and hence, lesser quantity of emissions per km running. Cheah (2010) observed that every 10% reduction in vehicle weight reduces 5-7% fuel consumption [96], whereas some other researchers found the emission reduction up to 8% with every 10% weight reduction, depending on changes in vehicle size and whether or not the engine is downsized [95].

In the U.S., vehicle weight reduction is essential for meeting future, more stringent fuel economy standards. New vehicles are required to achieve at least 34.1 miles per gallon (MPG) on an average [96].

5.3 Effect of vehicle weight on fuel economy, emissions, safety and cost

Fig. 5.2 shows a graph of the (EPA adjusted) fuel consumption and corresponding curb weights of all light-duty vehicles for model year 2006-2008 offered in the U.S., revealing a linear positive correlation among these two variables. On average across all vehicle models, every 100 kg weight reduction was expected to achieve a reduction of 0.53 L/100 km in fuel consumption. While this figure is useful to detect a general trend, such data is not normalized for performance, size, or other vehicle attributes [68].

Cheah (2010) also analyzed reduction in fuel consumption (FC) vis-à-vis mass reduction for gasoline vehicles, using various methods viz., literature review, empirical data and simulation. The results as displayed in Table 5.1 show that for gasoline vehicles, fuel consumption gets reduced by 5.6-8.2% and by 0.36-0.58 L/100 km on 10% and 100 kg mass reduction of the vehicle respectively [96].

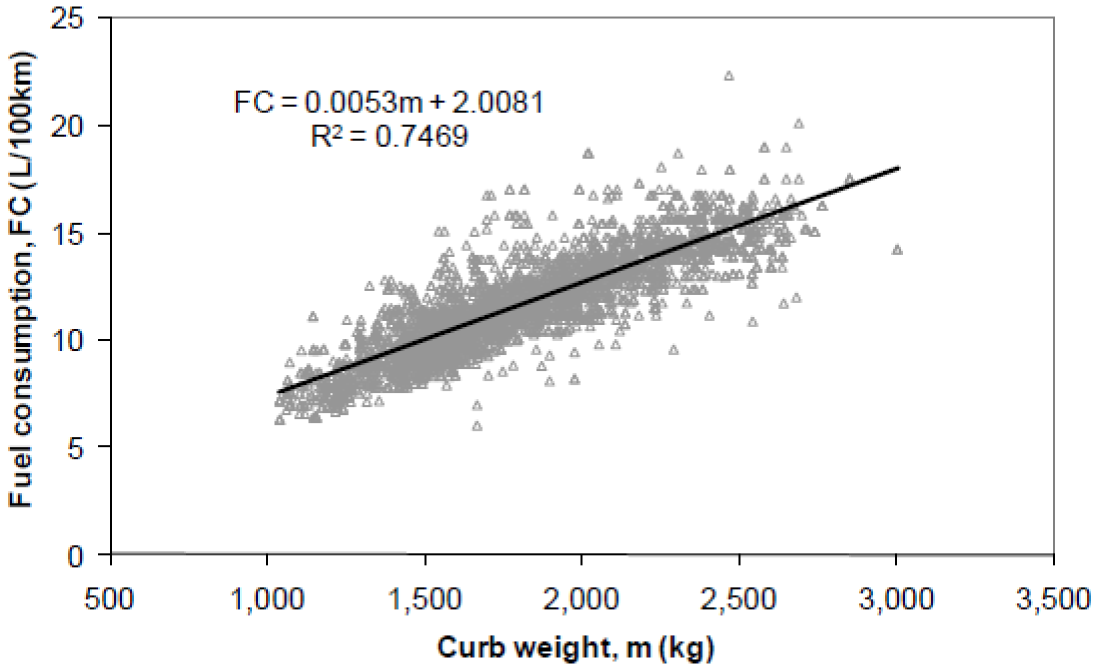


Fig. 5.2: Curb weight and fuel consumption of U.S. MY2006-2008 vehicles [97]

Table 5.1: FC - curb weight relationship for conventional gasoline midsize cars [96]

Approach	FC reduction per 10% mass reduction	FC reduction per 100 kg mass reduction
Literature review	5.6-8.2%	0.36-0.58 L/100 km
Empirical data (MY2006-08)	5.6%	0.36 L/100 km
Engineering simulation (ADVISOR)	6.9%	0.39 L/100 km

Cheah (2010) also analyzed the expected reduction in fuel consumption in gasoline vehicles in 2030 for 100 kg reduction in vehicle mass as given in Table 5.2. The conclusion was that the reduction in fuel consumption per 100 kg mass reduction of an average car is expected to decrease from 0.39 (as in 2010) to 0.30 in 2030 [96].

Table 5.2: Fuel consumption sensitivity to weight reduction for various vehicles [96]

Gasoline vehicle	Fuel consumption reduction per 100 kg mass reduction (L/100 km)	
	Current	Future (2030)
Average car	0.39	0.30
Average light truck	0.48	0.35

The strong correlation between CO_2 and weight follows from the strong physical relationship between the weight of the vehicle and the energy required to accelerate the vehicle and overcome resistances. This means that reducing vehicle weight is an effective way of reducing the energy needed to drive the vehicle and therefore reducing emissions [98]. Fig. 5.3 shows European market situation in 2006 / 2009 and target line 2015 for average CO_2

emissions against average weight of vehicles of 10 manufacturers which also establishes the facts that CO_2 emissions are directly proportional to vehicle weight and that lots need to be done to further reduce automotive emissions and reducing vehicle weight forms to be a strong criteria for the same.

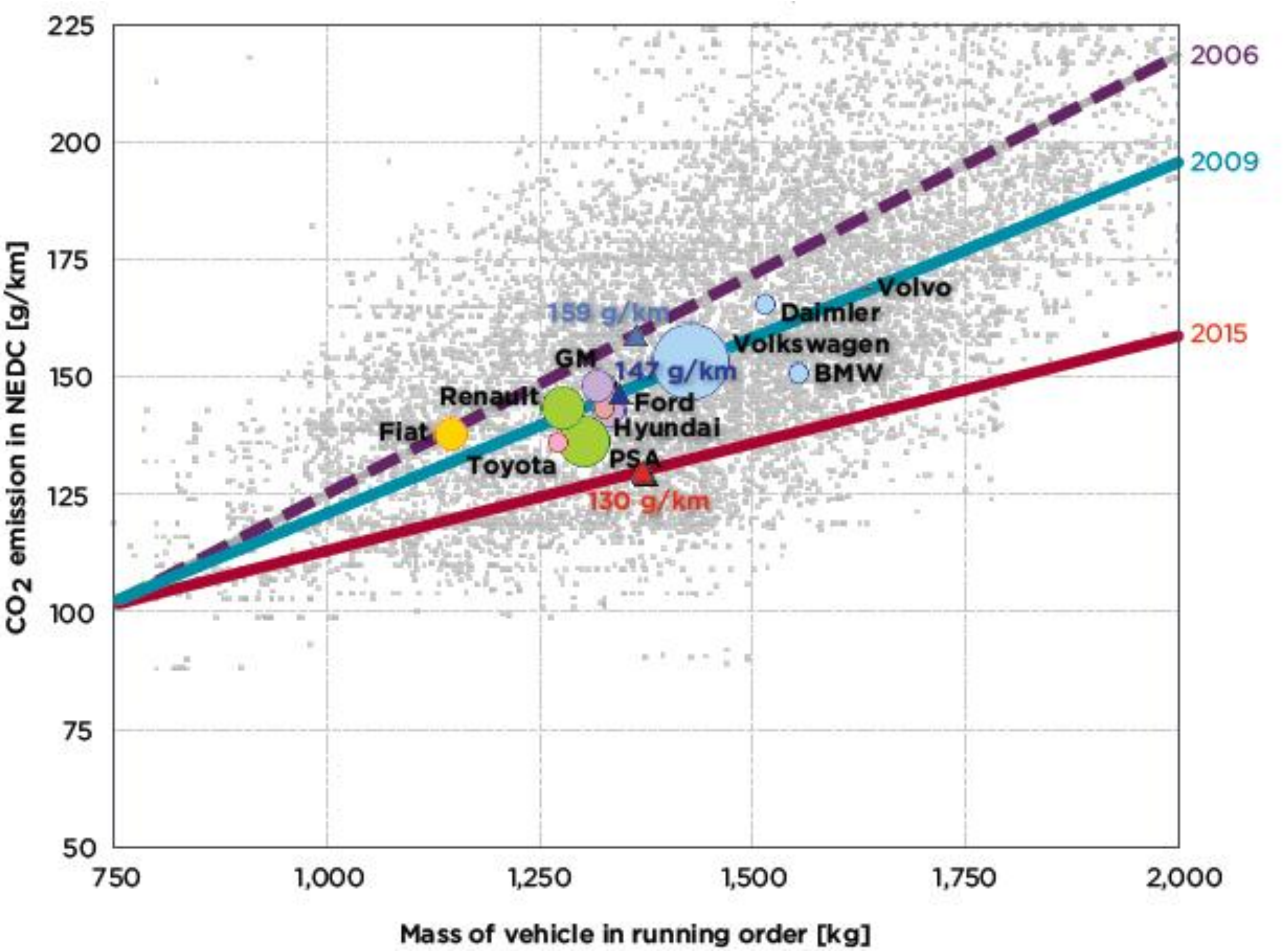


Fig. 5.3: CO_2 emission vs. vehicle mass for European market in 2006 / 2009 against target for 2015 [98]

From Fig. 5.4, it is evident that CO_2 emissions increase with increase in vehicle weight and also, CO_2 decrease with increase in vehicle speed up to 80 kph beyond which it starts increasing.

Previous studies have shown that with application of 1 kg aluminum, car weight can be reduced by 2 kg. And it has been found that by reducing 100 kg weight of vehicles, CO_2 emission can be decreased by about 5 g/km. In 2010, CO_2 emission standards by the EU was about 230 g/km. Smerd et al. (2005) used Audi A8 as an example, which used the aluminum body. Audi A8 mass was 2075 kg, the average fuel consumption was 9.9 L/100km and emissions were 199 g/km. Since the body system is about 20%-30% of total vehicle weight, if using steel body, this car mass would have been about 2500 kg. Based on the above information, comparison for the energy consumption and emissions was drawn between steel and aluminum body which is shown in Table 5.3 [100, 101]. However, body weight may go up to 40% of total weight as shown in Fig. A.9 [96, 102].

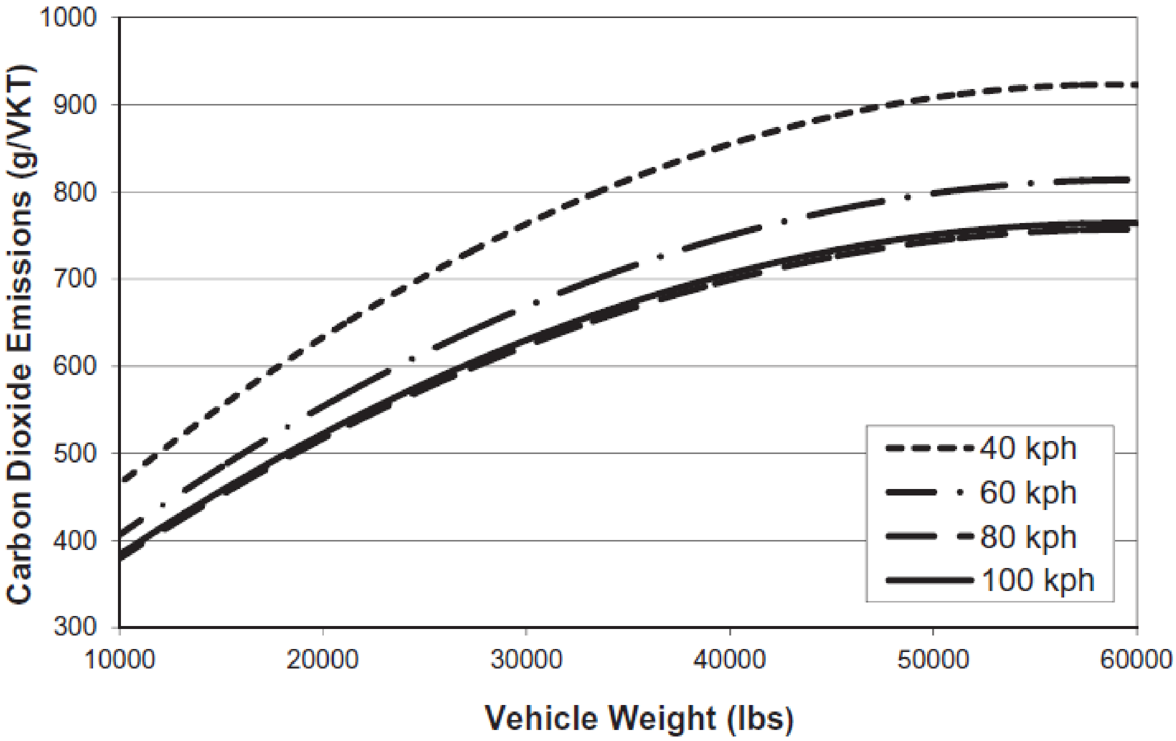


Fig. 5.4: Vehicle weight vs. CO_2 emissions at various travel speeds (EPA, 2006) [99]

Table 5.3: Comparison, between steel and aluminium body, for average energy consumption and CO_2 emissions [100]

	All steel body	All aluminium body
Gross vehicle weight	2500 kg	2075 kg
Average energy consumption	11.8 L/100 km	9.9 L/100 km
CO_2 emissions	220 g/km	199 g/km

Simulations show that a 5% and 10% reduction in vehicle weight will lead to a reduction in CO_2 emissions between 1.3–1.8% and 2.7–3.6% respectively, with most vehicles lying close to the upper values [103].

Hirsch (2011) found that 34% weight reduction was achieved using aluminium alloys with a cost increment of 7.8 € per kg of weight reduction. 100 kg saved on the mass of a car can save about 9 grams of CO_2 per kilometer. Today's European cars contain an average of 132 kg of Aluminium components and industry is working on new improved Aluminium alloys and solutions for automotive applications [104].

Brodrick et al., from their research, concluded that an increase in gross vehicle weight from 52,000 lb to 80,000 lb resulted in approximately 40% or greater increase in NO_X emissions during the accelerations and higher-speed steady-state operations [105].

Gajendran and Clark (2003) found, by combining an empirical equation with theoretical truck loads, that NOx emissions increased by approximately 54% on doubling the test weight. Emissions data were gathered from specific tests performed using different test weights and using various test schedules. It was found experimentally that NOx emissions have a nearly linear correlation with vehicle weight and did not vary much from vehicle to vehicle. Also, PM emissions were found to be a strong function of weight during transient operation. However, PM emissions were found to be insensitive to vehicle weight during nearly steady-state operation [106].

While certainly an effective option for reducing CO_2 emissions, reducing the weight of vehicles is a controversial topic. In the past, conventional wisdom held that a heavier vehicle is safer than a light one. Recently, however, some studies have challenged the weight-safety connection. Also, during the public comment period for NHTSA's 2006 light truck CAFE rule, some auto manufacturers, notably Volkswagen and Honda challenged the traditional weight-safety connection. This traditional position was also challenged by the Aluminum Association which said that a 10% weight reduction is possible without affecting safety [107-109].

It was found that the weight reduction which carbon fiber composites provided by replacing steel body parts resulted not only in lower fuel consumption, but also allowed the trucking industry to achieve much higher payloads. It also led to safety improvements in respect of crash behavior, as has been demonstrated for many years by Formula 1 racing cars [110].

5.4 Case studies

Two case studies have been considered for the study on the effect of vehicle weight on automotive emissions, which are discussed below.

5.4.1 Maruti Suzuki India Ltd.

Maruti Suzuki India Ltd. (MSIL) studied effect of curb weight on CO_2 emissions for their 3 cars and the data so obtained is plotted in graphs at Fig. 5.5. From the graph, it is evident that CO_2 increases proportionally with curb weight and by line-fitting an empirical formula for a straight line is also derived (embedded in the Fig. 5.5) where y is the amount of CO_2 in g/km and x is the curb weight in kg [28].

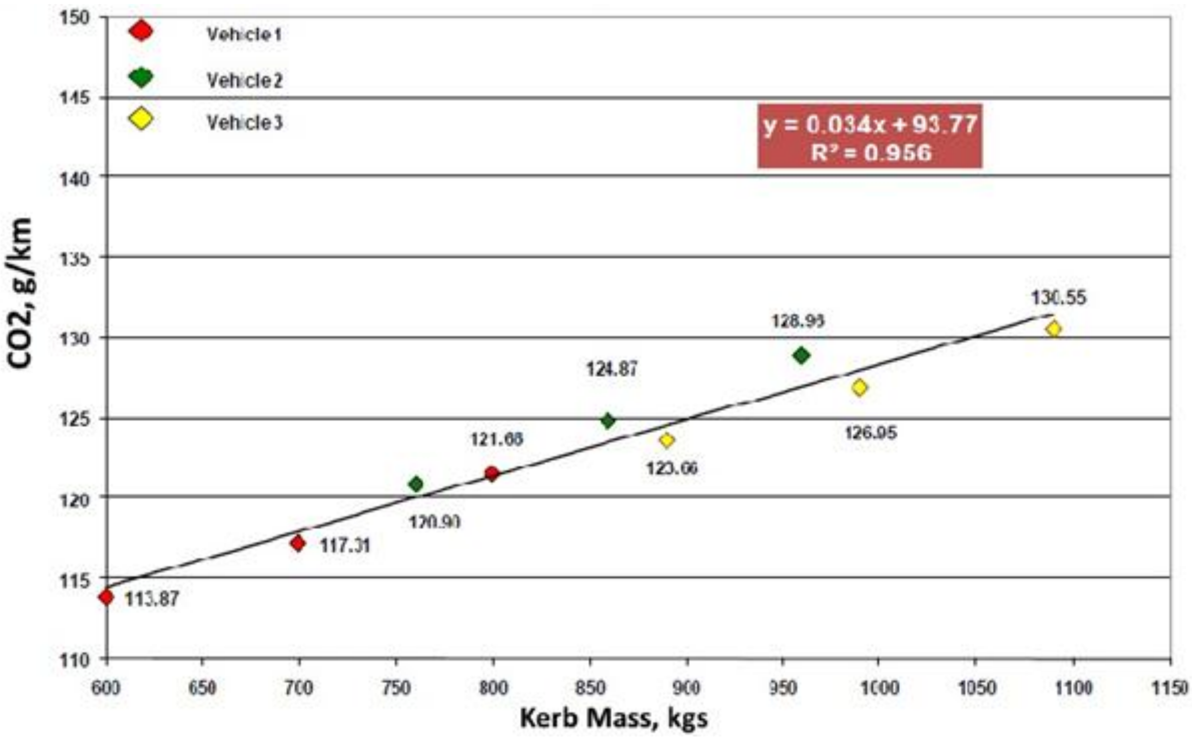


Fig. 5.5: MSIL: Impact of curb weight on CO_2 emissions tested on 3 vehicles [28]

Also, Fig. 5.6 from MSIL data shows that there is substantial gap between the CO_2 limits to be achieved in 2022 and the simulated values considering the proposed curb weight and using the same empirical relation as discussed above. To remove this gap, CO_2 emission needs to be reduced further [28].

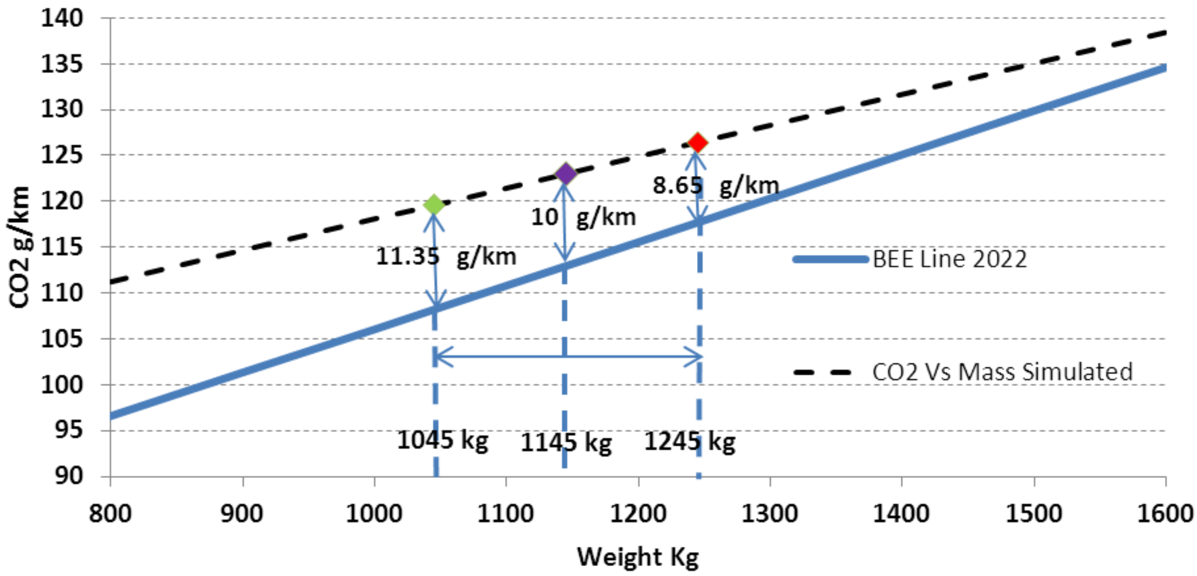


Fig. 5.6: Gap from 2022 BEE target of CO_2 emissions for expected curb weight in MSIL [28]

5.4.2 The EU funded SLC (Super Light Car) project

The European Union (EU), for different parts of vehicles, had analyzed various feasible materials, their performance, fabrication and joining costs in a multi-material body-in-white concept for a running VW Golf V car, including detailed life-cycle analysis (LCA) of all materials involved. The final concept and prototype build reached a 34% weight reduction without compromising performance and safety, however, with a cost increment of 7.8 € per kg saved [104].

Fig. 5.7 shows various vehicle components where aluminum has replaced steel successfully resulting in substantial weight reduction without any adverse effect. The project proved that 100 kg saved on the mass of a car can save about 9 grams of CO_2 per kilometer running. Hence, it was inferred that a reduction of vehicle mass is mandatory, as the most effective measures to reduce CO_2 emission [104].

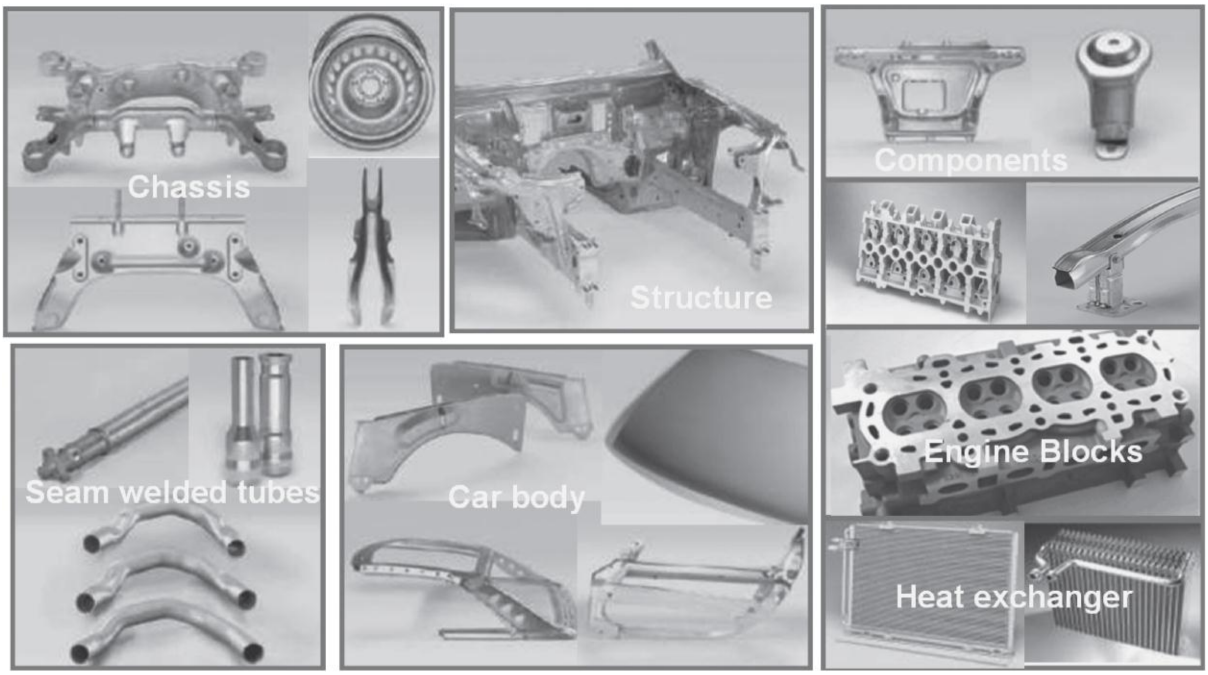


Fig. 5.7: Various aluminium products for advanced automotive applications [104]

5.5 Methods to reduce vehicle weight

Weight reduction can be achieved by:

(i) changing the materials of engine and/or body, or

(ii) design changes, or

(iii) size / footprint change.

While design/size changes (including body gauge reduction) are time-taking and cumbersome, changing the materials is cost intensive. Also, while going for weight reduction, safety needs to be kept in mind. While aluminium and magnesium alloys are good options for weight reduction, the same are not preferred for body since these materials reduce impact resistance substantially resulting in serious safety issues. Also, usage of these alloys increase the cost to a great extent. Carbon fiber and plastics are other choices for weight reduction. Research is on for successful implementation of carbon fiber for various shafts and other parts. Plastics have already replaced steel for bumpers, fenders, etc. However, with all the changes, the weight of a vehicle can be reduced to a maximum of 35% as observed so far [68].

Vehicle weight and size reduction could significantly reduce fuel consumption and greenhouse gas emissions. Direct weight reductions through the substitution of lighter materials as well as basic vehicle design changes (which, for example, maximize the interior volume for a given vehicle length and width) enable secondary weight reductions as other vehicle components are appropriately downsized [68].

A shift in vehicle size distribution away from larger vehicles also reduces average weight and initially can be accomplished by changes in production volumes. The estimates indicate that sales-weighted average vehicle weight could be reduced by 20% over about 25 years. The maximum potential vehicle weight reduction at plausible cost is 35%. These estimates allow for the additional weight of future safety requirements and convenience features. Vehicle weight reductions of this magnitude could alone result in some 12–20% reduction in vehicle fuel consumption [68].

In addition to using aluminum, magnesium, plastics and carbon fiber, switching to high strength steels (HSS), evolution of lighter design concepts and forming technologies can also result in reduced vehicle weight. Ford’s P2000 concept car has demonstrated that up to 300 kg of Al can be used in a 900 kg vehicle. Aluminium is twice as strong as an equal weight of steel, allowing the designer to provide strong, yet lightweight structures. Magnesium has a density of 1.7–1.8 g/cc, about ¼ that of steel, while attaining a similar (volumetric) strength. Major hurdles for automobile application of magnesium are its high cost and performances issues such as low creep strength and contact corrosion susceptibility. At present, the use of magnesium in vehicle is limited to only 0.1–0.3% of the whole weight. Fiber-reinforced plastic (FRP) is now widely used in aviation, but its application to automobiles is limited due to its high cost and long processing time. However, its weight reduction potential is very high, maybe as much as 60% [95]. Fig. 5.8 shows the comparison of total weight and cost of different automobile parts when made from various feasible materials considering steel at 100%. This shows that while carbon fiber could reduce weight by 50%, it will result in cost escalation by more than 5 times as compared to steel.

Fig. 5.9 shows the cost comparison of different automobile parts when made from carbon fiber vis-à-vis magnesium in 2010 and the same in 2030 (predicted cost). This shows that in case of mass production, carbon fiber cost will be substantially reduced by 2030 and hence, while carbon fiber is costing almost 4.5 times that of aluminum today, it will cost less than 1.5 times that of aluminum in 2030, making it perhaps the most feasible solution at that time.

Fig. A.10 shows the material composition of the average automobile in the U.S. for the period 1977-2007 [112]. Summarized evaluation of lightweight automotive materials is shown in Table A.4 [96].

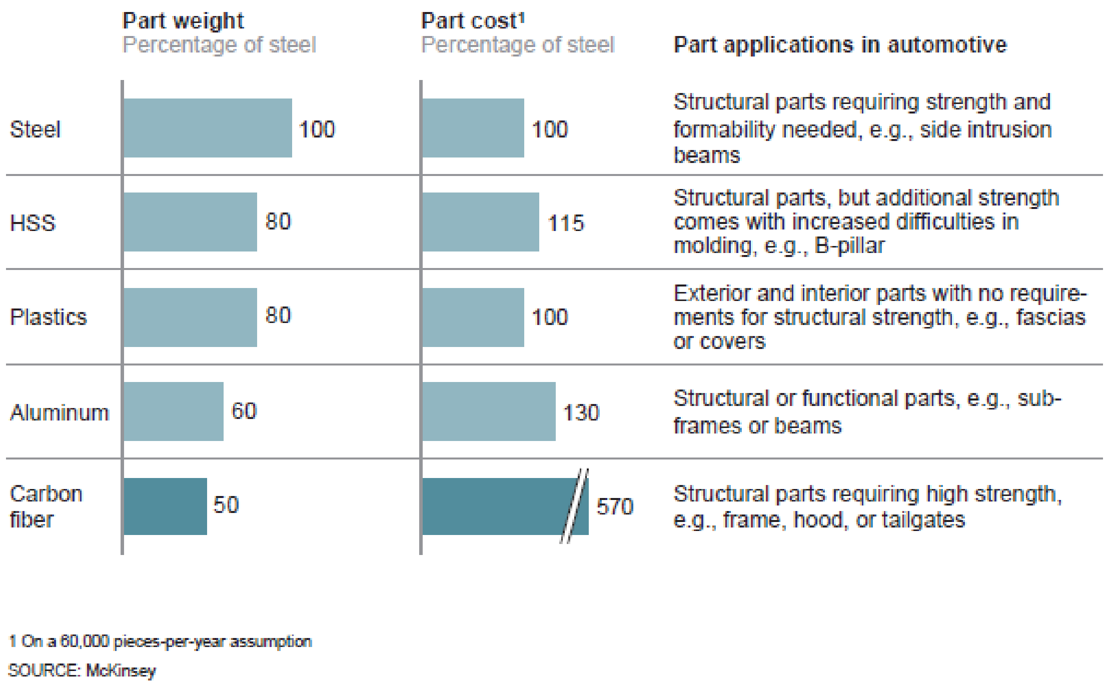


Fig. 5.8 Total weight of different parts when made from various feasible materials [111]

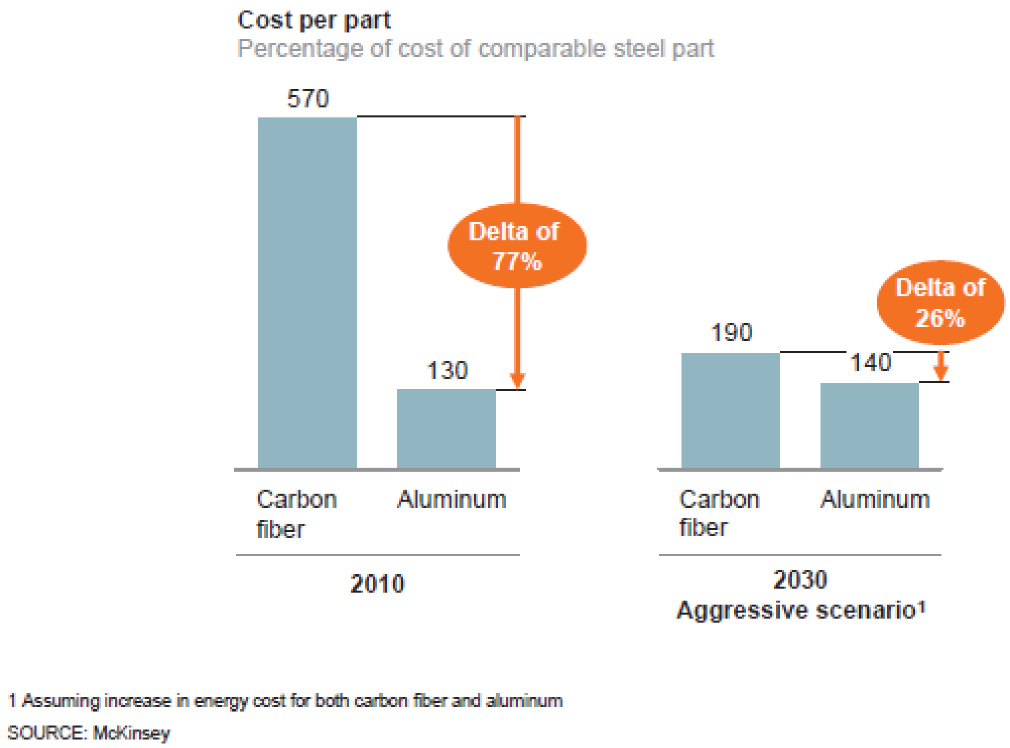


Fig. 5.9 Cost comparisons of different automobile parts when made from carbon fiber vis-à-vis aluminum in 2010 and the same in 2030 (predicted cost) [111].

5.6 Results and discussions

Due to poor road conditions in India, the maintenance cost of vehicles go up exponentially, and to contain the same, vehicles are made durable and thus heavy. This results in a fuel penalty which is more than 1% fuel consumption.

However, a weight-based vehicle emission standard, like that in EU, discourages the reduction of vehicle weight, as lighter vehicles are subject to a lower CO_2 target. This weakness of a weight-based system is also noted by manufacturers. For example, Volkswagen commented on the 2008–2011 U.S. rulemaking that a weight-based system would discourage investments in vehicle weight reduction [98, 113, 114].

Also, with the desire of more power and safety needs, the engine size is increasing and steel body is preferred, which results in increased vehicle weight, though clubbed with latest technologies to reduce fuel consumption and emissions. Hence, no straight relationship could be established between vehicle weight and emissions [68]. This fact is also clear from Table A.5 which shows the sales/registrations-weighted averages per manufacturer in EU for 2009 vis-à-vis average CO_2 emissions [98] and from Table A.6 which shows details of selected baseline vehicles in USA [107]. However, it is certain that keeping all other parameters same, reduction in weight reduces emissions to the extent mentioned above. Hence, it is best to say that the emission per unit power generation certainly gets reduced to the tune of 5-10% for every 10% reduction in vehicle weight [68].

Vehicle weight is not visible to the customer, does not create value for the customer, and therefore generally is not part of the purchase decision. Curb weight therefore is not a proxy for utility from a customer’s perspective. More importantly, this disinterest of consumers toward the weight of their vehicle allows for gaming: manufacturers can, at relatively low cost, increase the curb weight of a vehicle (within certain boundaries) without the customer noticing it, resulting in a higher target for this now heavier vehicle [98].

Deploying technologies such as component-level lightweight material substitution (high-strength steel, aluminum, and composites) and using more comprehensive mass-optimized vehicle structural designs that integrate parts and employ more advanced lightweight bonding and forming techniques can reduce vehicle mass by up to 30% without any compromise in vehicle size or function [115-118]. Various engineering studies estimate that mass reductions on this scale would reduce CO_2 emissions by approximately 20% [68, 115, 119-121].

We can reduce weight by substituting some of the iron and steel used in vehicles with lighter-weight high-strength steel or aluminum, redesigning the vehicle, and/or downsizing the vehicle. Using these approaches, it is possible to achieve up to 40% (690 kg) vehicle weight reduction. However, the cost associated with manufacturing lighter-weight vehicles is a nontrivial \$3 to \$4 per kilogram of total weight saved. In addition, the life-cycle energy impacts of using alternative lightweight materials, which tend to be more energy-intensive to process, must also be considered [96].

Secondly, the topic of vehicle weight reduction should be studied with a life-cycle perspective. That is, one should assess the impacts of reducing vehicle weight over the entire vehicle life cycle, from "cradle to grave". This is because alternative lightweight materials used to reduce vehicle weight tend to be more energy-intensive to produce than conventional steel used in automobiles (see Fig. 5.10). An aluminum component with the same stiffness as its steel counterpart requires three times as much energy to produce [96].

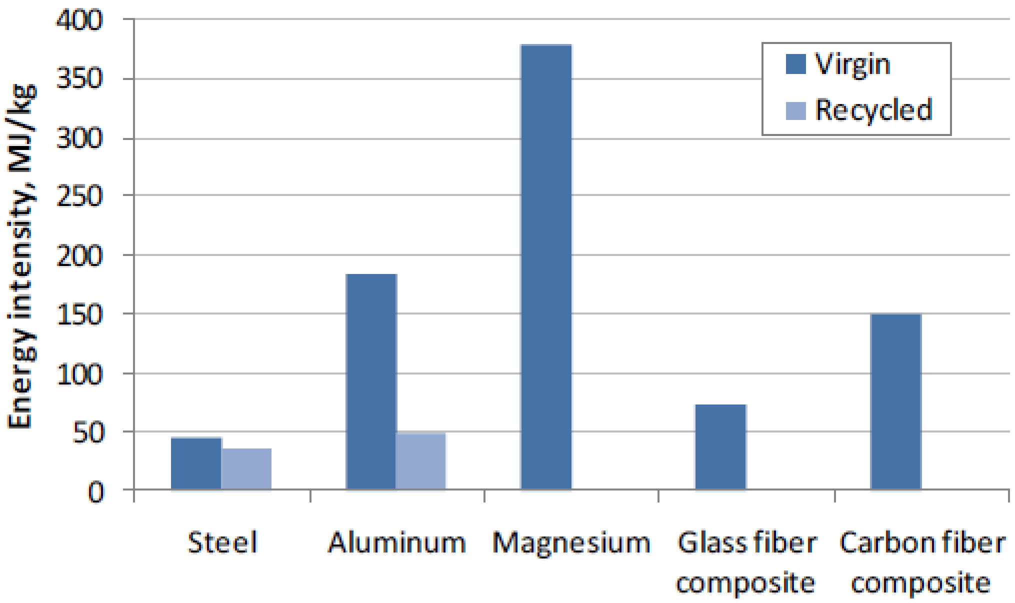


Fig. 5.10 Material production energy intensity of various automotive materials [122]

Cost estimates in the literature are found to vary widely from (-) \$2 to \$14 per kilogram of weight savings, depending on the type of material, the design of the vehicle component, and the scale of production. In general, the cost per unit weight savings is lower for HSS, and is followed by aluminum and polymer composites [96].

CHAPTER 6

PREDICTION OF RELATIVE IMPORTANCE OF VARIOUS ERTs FOR FUTURE BS NORMS

BS IV is implemented pan India on April 1, 2017. India is leapfrogging to BS VI pan India as on April 1, 2020. BS VI norms are comparable and in some aspects stricter than Euro VI standards.

SCR will be mainstream technology, with NOx adsorber (LNT), for Euro VI (or BS VI) LDVs (passenger cars and commercial vans) and by the implementation of the Real Driving Emissions (RDE) procedure for Euro 6c (in 2017) [39]. SCR technology is one of the most cost-effective and fuel-efficient technologies available to help reduce NOx emissions. SCR can reduce NOx emissions up to 90 percent while simultaneously reducing HC and CO emissions by 50-90 percent, SCR systems can also be combined with a diesel particulate filter to achieve even greater emission reductions for PM [71, 72].

One of the questions that are still unanswered by technologists and researchers is - which catalyst technology to choose, iron zeolites, copper zeolites or vanadium based [24, 73, 80]. Fig. 6.1 suggests that the SCR technology should be selected based on the DPF regeneration strategy and vice-versa considering the exhaust temperatures. For 100% passive regeneration vanadium based SCR should be used whereas in case of 100% active regeneration, copper zeolite solution is feasible. In between, iron zeolites can be used.

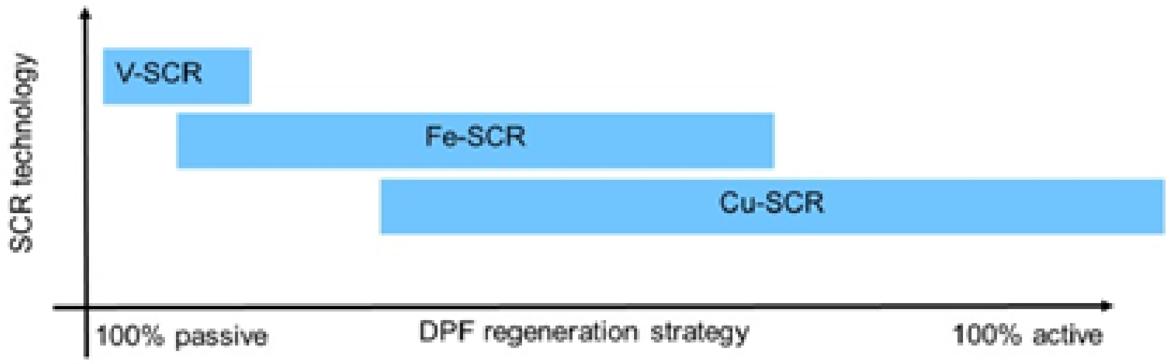


Fig. 6.1 DPF regeneration strategy vis-à-vis SCR technology [24]

Table 6.1 shows the typical emission reduction percentages and current cost of various after-treatment devices along with their installation timing. The information provides estimated emission reductions which may be used in the selection of appropriate technologies for air quality programs. However, there have been more technological advancements after this report and the current reduction in percentages are higher than these. EPA has mentioned with this table that "Actual emissions reductions and costs will depend on specific manufacturers, technologies and applications." In India the cost would be lower with domestic manufacturing.

Table 6.1: Typical emission reduction % and cost of various after-treatment devices [71]

Technology	Typical emission reduction				Typical cost ($)
	PM	NOx	HC	CO	
DOC	20-40		40-70	40-60	Material: 600-4000 Installation: 1-3 hours
DPF (Active or Passive)	85-95		85-95	50-90	Material: 8000-50000 Installation: 6-8 hours
pDPF	Up to 60		40-75	10-60	Material: 4000-6000 Installation: 6-8 hours
SCR		Up to 75			10000-20000 Urea: $0.80/gal
CCV	Varies		40-70		
EGR		25-40	40-70		
LNC*		5-40	40-70		6500-10000

*May be combined with DOC or DPF to reduce PM, HC and CO emissions (Source: EPA).

Fig. 6.2 shows a decision matrix, which suggests that the selection of after-treatment systems depends on the quantity of various emissions. For example, the matrix suggests that if the NOx emissions are above desired limit and NOx conversion required in more than 70% clubbed with PM also above allowable limits and PM conversion desired in more than 50%, then one will have to go for DOC + cDPF + SCR. Whereas, in the same case if the required NOx conversion is less than 70% then the choice of after-treatment system should be DOC + cDPF + LNT, since LNT's NOx conversion efficiency is lesser than SCR. The matrix also suggests that if PM is within limits, there is no need to go for DPF. If PM and NOx both are within limits, DOC itself is sufficient. However, considering the strict norms of BS VI clubbed with the reduce limits of CO_2 it looks like DOC + cDPF + SCR or DOC + cDPF + LNT is going to be the solution for vehicle of BS VI and beyond.

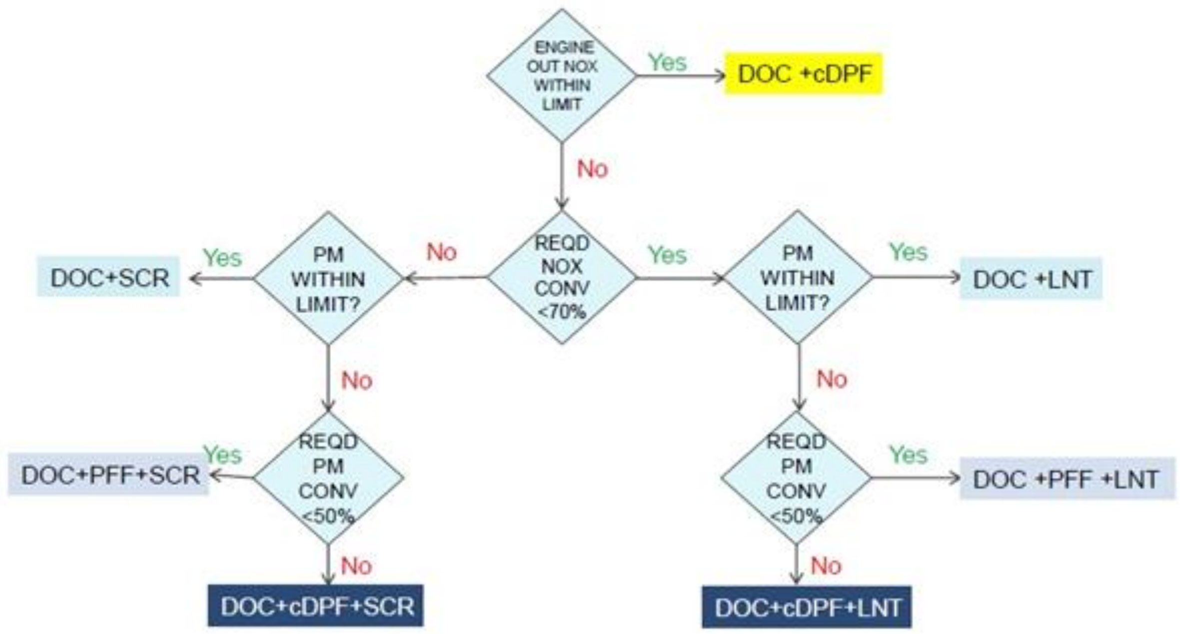


Fig. 6.2 Decision Matrix: Final AFT system configuration depends on emissions [74]

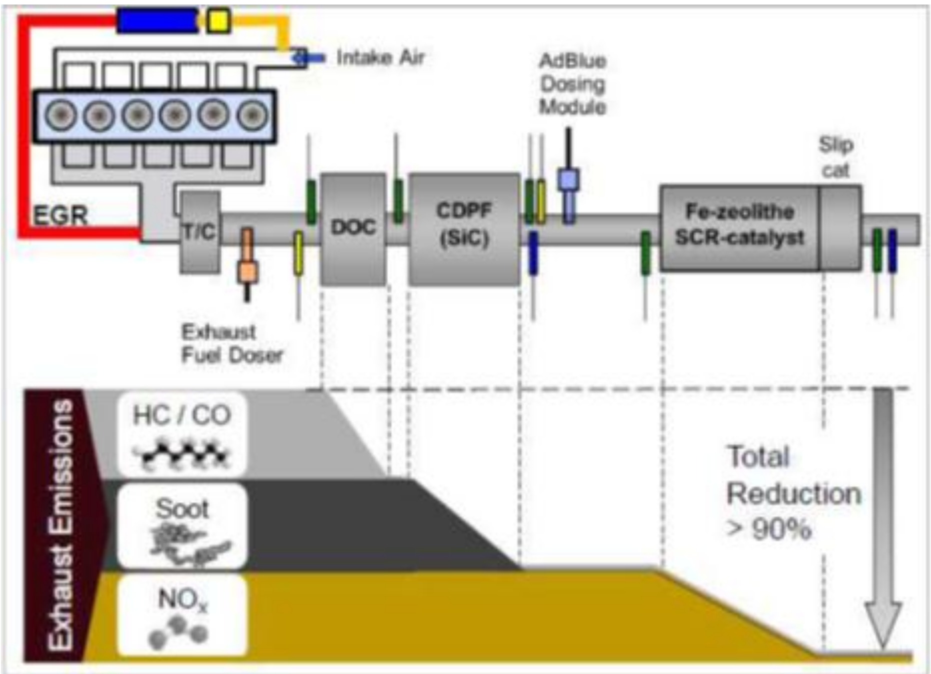


Fig. 6.3 A fully integrated after treatment system [6]

Fig. 6.3 shows a probable combination for a fully integrated after-treatment system in BS VI scenario clearly displaying turbocharger, EGR, exhaust fuel doser, DOC, cDPF, AdBlue dosing module Fe-zeolite SCR catalyst and slip catalyst. The figure also displays the reduction in various emissions upon passing through various devices. First DOC reduces CO and HC substantially, and then cDPF reduces PM (soot) after which SCR works on NOx reduction followed by further NOx reduction by slip catalyst.

Post BS VI emission reduction technologies: Some of the possible methods for fuel economy post BS VI are [6]:

- Variable speed water pump
- Clutched air compressor
- Electric water pump
- Reduced tension oil control rings
- Further advancements to pistons, liners and bearings
- Low viscosity oil
- Smart alternator

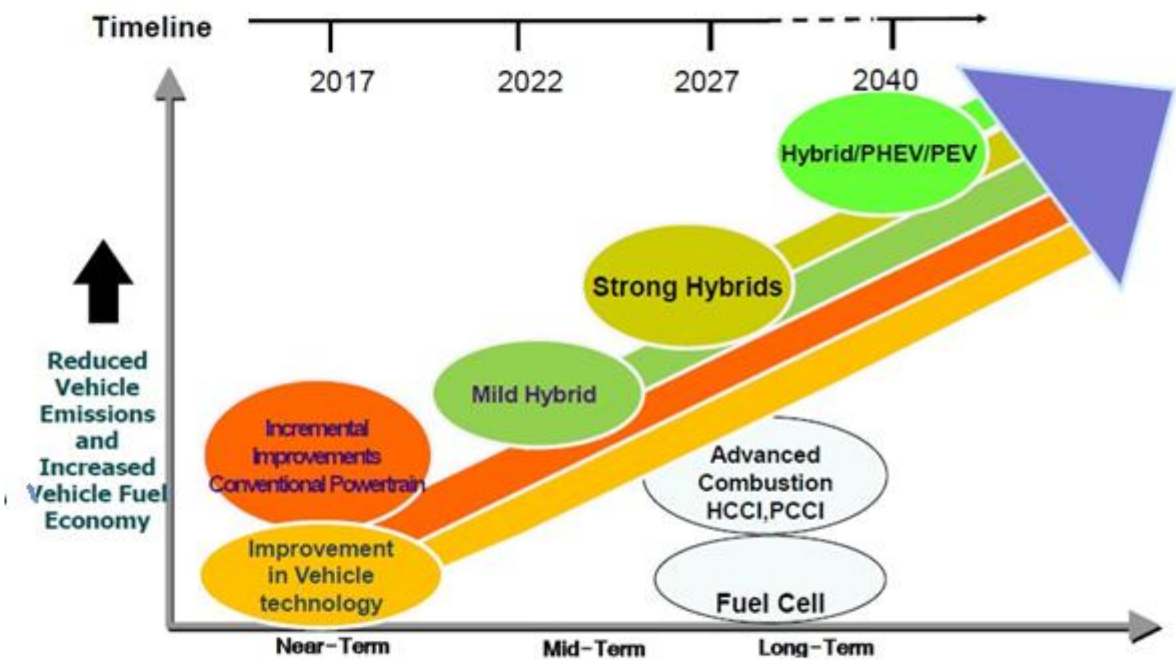


Fig. 6.4 Technology road-map for automobile industry [28]

Fig. 6.4 predicts the future of automobile industry based on reduced emission limits with time, according to which during period around 2014-2019, the industry will see improvement in powertrain and current vehicle technology, whereas around 2020-2024, mild hybrid vehicles will occupy a decent share in market. Around 2024-2029, strong hybrids will come, followed by fuel cells operated vehicles and advanced combustion technologies like HCCI, PCCI. Around 2040, strong presence of hybrid vehicles / PHEV / PEV vehicles is expected.

CHAPTER 7

CONCLUSIONS

An uncoated (uncatalyzed) wall-flow type ceramic DPF was installed on a Euro-I, 4-cylinder, water-cooled, direct injection, variable speed, automotive C.I. engine in a laboratory set-up in India and its impact on performance, and smoke and NOx emission was observed. Also, a detailed comparison was made between active and off-board regeneration of DPF in light of performance, emissions, cost and ease of use. The following conclusions could be drawn from the results obtained: (i) Particulate matter emission (smoke) was reduced by 79-99% on using DPF, (ii) DPF adversely effected NOx emission due to back pressure and resultant fuel penalty increasing combustion temperature, and to counter this negative impact, suitable actions need to be taken, e.g. SCR, EGR, etc. in tandem, (iii) Addition of DPF had slight adverse impact on BSFC and BTE because of the back pressure due to soot accumulation in DPF. Hence, regeneration of DPF is of utmost importance, (iv) DPF effectiveness gets slightly reduced after active regeneration, whereas, the effectiveness of DPF remains almost unchanged (compared to the new DPF) after off-board regeneration.

Another precious finding of this study was that off-board regeneration has the following advantages over active regeneration: (i) Off-board regeneration produced better results for smoke emission, NOx emission, BSFC and BTE, (ii) Off-board regeneration does not need the vehicle to be run on freeways/highways for a suitable period of time as required in the case of active regeneration, (iii) Off-board regeneration is more economical as compared to active regeneration as there is no initial cost for ECU system, etc. The cost of off-board cleaning shall be quite comparable to that for active regeneration cost of running for couple of hours and spending that much time, (iv) Also, since the removal of soot is more thorough in case of off-board regeneration, the frequency for need of regeneration will be lesser in case of off-board regeneration, and (v) Even in case of active regeneration, after certain number of regenerations, the filter will have to be taken for off-board regeneration for complete removal of soot.

An ECU-controlled external EGR valve was installed on the same engine and its impact on performance and emission was observed at various speeds, various torques and with varying percentages of EGR. Then the optimized position of EGR valve for each set of engine speed (RPM) and torque was determined and ECU was then programmed for the optimized values of EGR valve opening to verify the engine performance and emissions from the earlier readings. EGR% was calculated using CO_2 method. The following conclusions could be drawn from the results obtained: (i) There was a significant reduction (average 45% reduction) in NOx emission with optimum EGR, (ii) There was a slight adverse impact of EGR on engine performance, (iii) The optimum EGR % varied from 22% to 58% at different torque and engine speed for the set-up used, (iv) EGR installation adversely effected smoke emissions, and to counter this negative impact, suitable actions need to be taken, e.g. catalytic reduction, particulate filter, etc., and (v) In nutshell, ECU-controlled EGR proved to be a very effective emission reduction technique for NOx reduction even in a Euro-I variable speed engine. Hence, EGR in tandem with other technologies can be very productively applied to eliminate automotive emissions from vehicles belonging to Euro III and earlier standards.

While using DPF and EGR in tandem, both smoke and NOx emissions were much less than the base case, but smoke emission was more than that with DPF alone and NOx emission was more than that with EGR alone. Hence, using both in tandem in old vehicles will perhaps be the best option. Catalyst based converters/filters may not be viable for old engines considering the cost of catalysts and the amount of sulfur present in fuel before 2020, since catalysts need sulfur content less than 15 ppm and such diesel will be supplied in India not before 2020. Diesel with 50 ppm sulfur (and may be higher), as supplied today pan India, will just kill the catalysts. Hence, uncatalyzed DPF and simple EGR (not ECU controlled) seem to be the best option for retrofitting as of now till 2020, after which catalyzed DPF, LNT, SCR, etc. might become technologies for successful retrofitting as well.

As far as cost of DPF is concerned, it varies based on specifications (cpsi, coating, size, etc.) which in turn depends on engine size and speed, Euro/Bharat norm to be followed, required life of the filter, manufacturing quantity, etc. Currently manufacturing of EGR valves and DPF does not happen in India and for research/testing purposes, these are being imported. Once the manufacturing starts in India, the costs will be more realistic and affordable. The cost of DPF is expected to vary between INR 4000 and INR 75000 (plus an additional INR 5000 to INR 10000 fitment cost) based on the above parameters. Similarly, the cost of ECU controlled EGR is expected to be in the range of INR 10000 to INR 30000. If retro-fitting is made compulsory, the feasibility will not be a question but the cost of vehicles will go up.

Companies like Ecocat, Bosch, Umicore, Corning, Faurecia, etc. specializing in automotive components, filters, substrates, catalytic coatings, etc. are expected to manufacture these components. Also, automobile companies like Maruti Suzuki India Ltd., Tata Motors, Hyundai, Toyota, Mahindra & Mahindra, etc. or their subsidiaries may also perhaps manufacture these devices in mass quantity and in cost effective manner.

From the studies on effect of vehicle weight on emissions, it was found that CO_2 emission increases almost proportionally to vehicle weight. Also, though increase in weight adversely effects other emissions as well, but no clear relationship could be established. Contrary to the belief, reduction in vehicle weight does not always reduce safety and up to 10% reduction in weight could provide same level of safety. Carbon fiber could be a promising replacement for steel parts in automobiles for further reduction of weight (beyond current maximum of 35% reduction) without compromising on safety.

No literature could be found mentioning regeneration of DPF by taking it off-board and heating the way done in this study. It looks to be promising and practical, esp. in Indian conditions where active as well as passive regeneration will be a challenge for different reasons. Also, almost all studies of emission control have been conducted on modern or stationary engines, whereas this study focused on an old Euro-I automobile engine.

Based on the finding of this research work and seeing the usefulness of off-board regeneration of DPF, especially in the Indian context where application of both, active as well as passive regeneration technologies will be a challenge, the following steps are suggested:

1. DPF (at least uncoated) should be made compulsory on all old vehicles i.e., those of BS-I, BS-II and BS-III norms as exhaust without DPF will be extremely harmful in Indian conditions in coming times with PM levels already reaching danger zones.
2. Attachment should be designed for an easy and quick removal and mounting of DPF to facilitate DPF off-board regeneration, esp. for retrofitting old vehicles.
3. Concept of DPF Bank should be tried, where users will give their clogged DPF and will receive a treated/regenerated DPF of the same type, with a service cost, much like the LPG cylinders in Indian households.
4. Service of off-board regeneration (if it starts commercially) of DPF should be exempted from service tax / GST to make it economical for all.
5. Uncatalyzed DPF manufactured in India should be exempted from all duties and taxes to encourage usage of DPF and to have minimal cost impact to owners of old vehicles.
6. It will be expensive to have ECU controlled EGR on old vehicles, hence, it is advisable to make simple arrangements to facilitate a simple EGR in old vehicles, throwing a small quantity of exhaust gas to the inlet manifold.

7. More automobile parts made of steel should be replaced with that of carbon fiber to reduce weight of vehicle, directly effecting fuel economy, for good.

The optimum protocol for off-board regeneration shall vary depending on the type of substrate, type and amount of catalytic coating, cpsi of DPF, method of canning, etc.

Further research can be done to have an easy attachment for DPF to be able to quickly install and uninstall DPF but at the same time is tightly secured in its position. Provision for electrically heating DPF at around 600^0C in nights for (say) 8 hours like off-board regeneration executed in this work, should be explored, especially for HDD vehicles like trucks and buses. Also, uncatalyzed pDPF should be tested on old engines (like the one used in this study) to check frequency for regeneration.

APPENDIX A: FIGURES

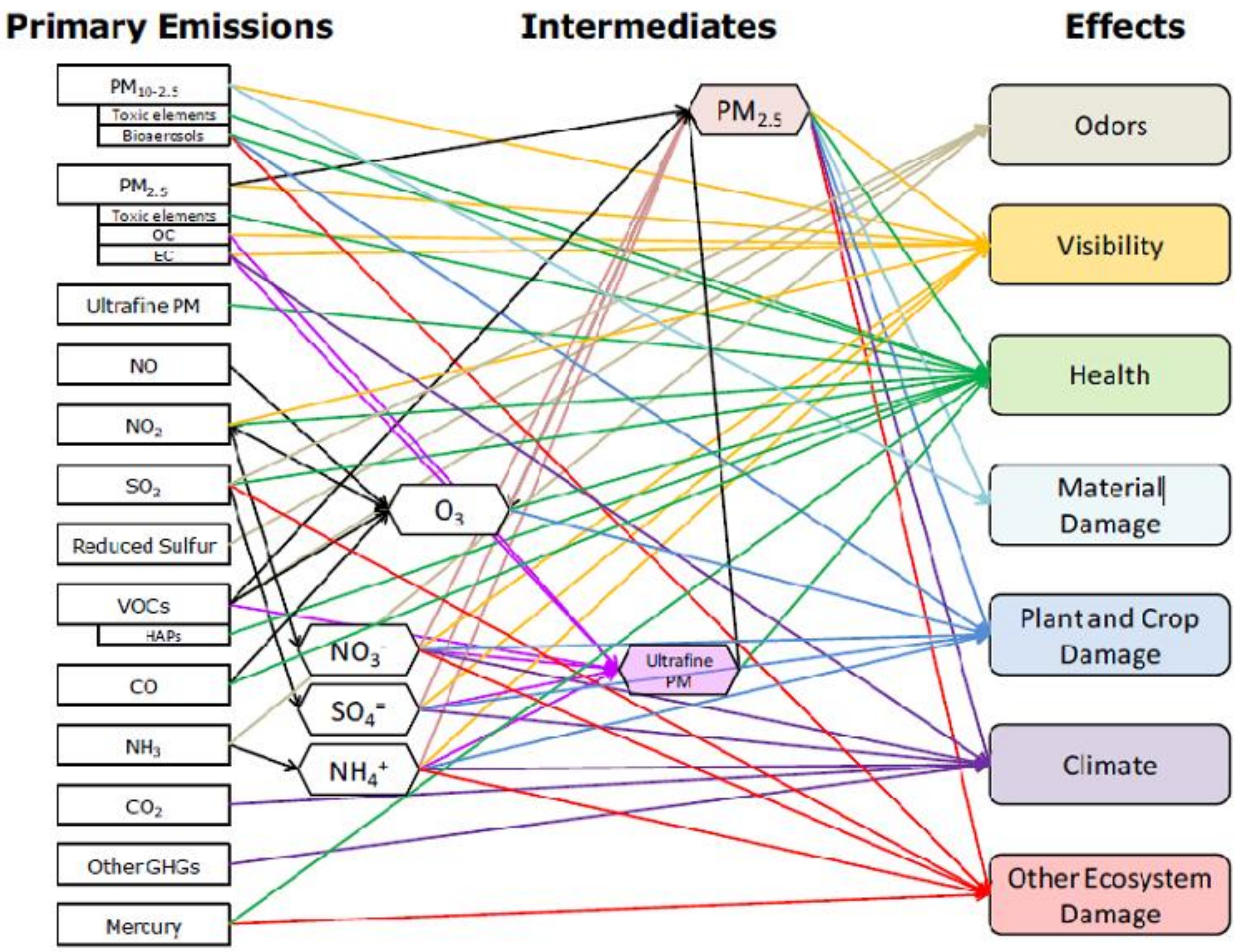


Fig. A.1 Various air pollutants and their adverse effects [3]

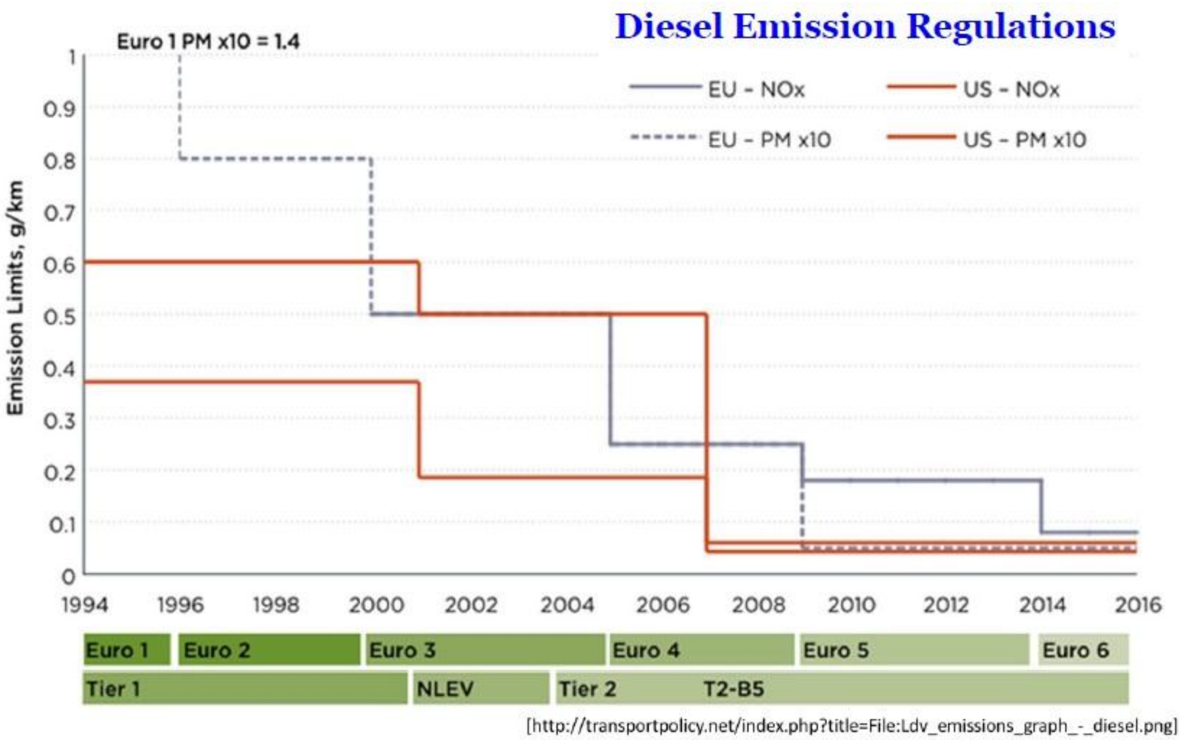


Fig. A.2 PM and NOx limits for various Euro and US emission standards for LDVs [79]

EURO Norms	
Norm stage	Year
EURO 1	1992
EURO 2	1998
EURO 3	2000
EURO 4	2005
EURO 5	2008
EURO 6	2014

BS Nationwide	
Norm stage	Year
BS I	2000
BS II	2005
BS III	2010
BS IV	2017
BS VI	2020

Fig. A.3 Comparison of implementation schedule of various Euro and BS norms [6]

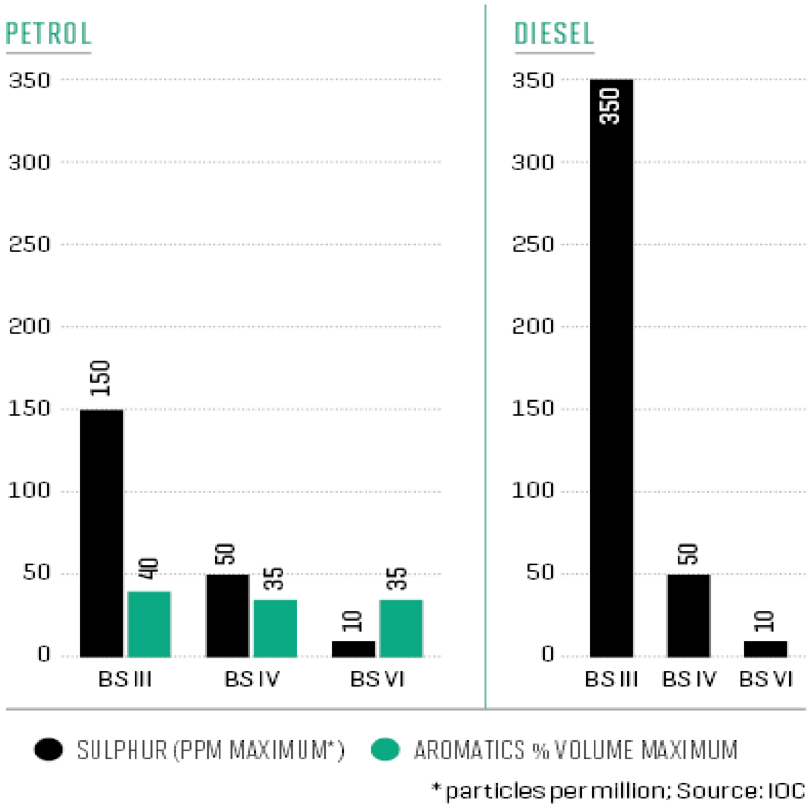


Fig. A.4 Sulfur (ppm) and Aromatics limits for BS III, IV and VI fuels [6]

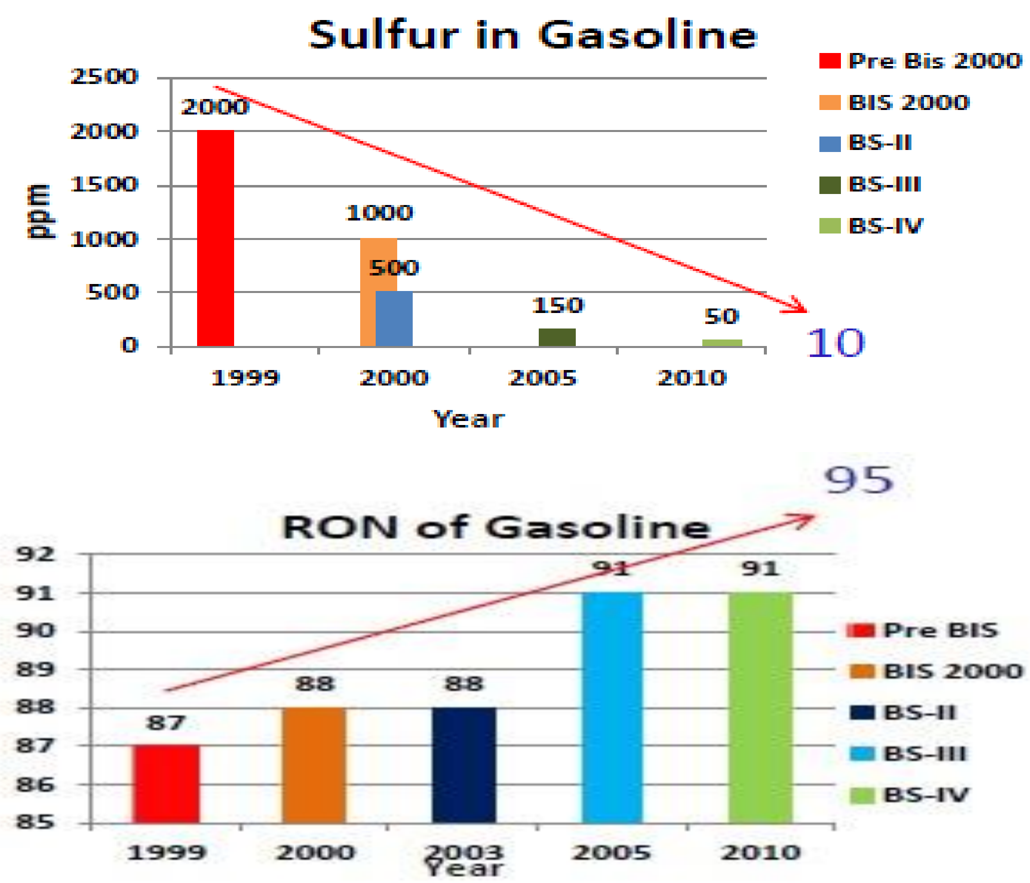


Fig. A.5 Maximum sulfur content and Min. octane no. for gasoline for various BS norms [11]

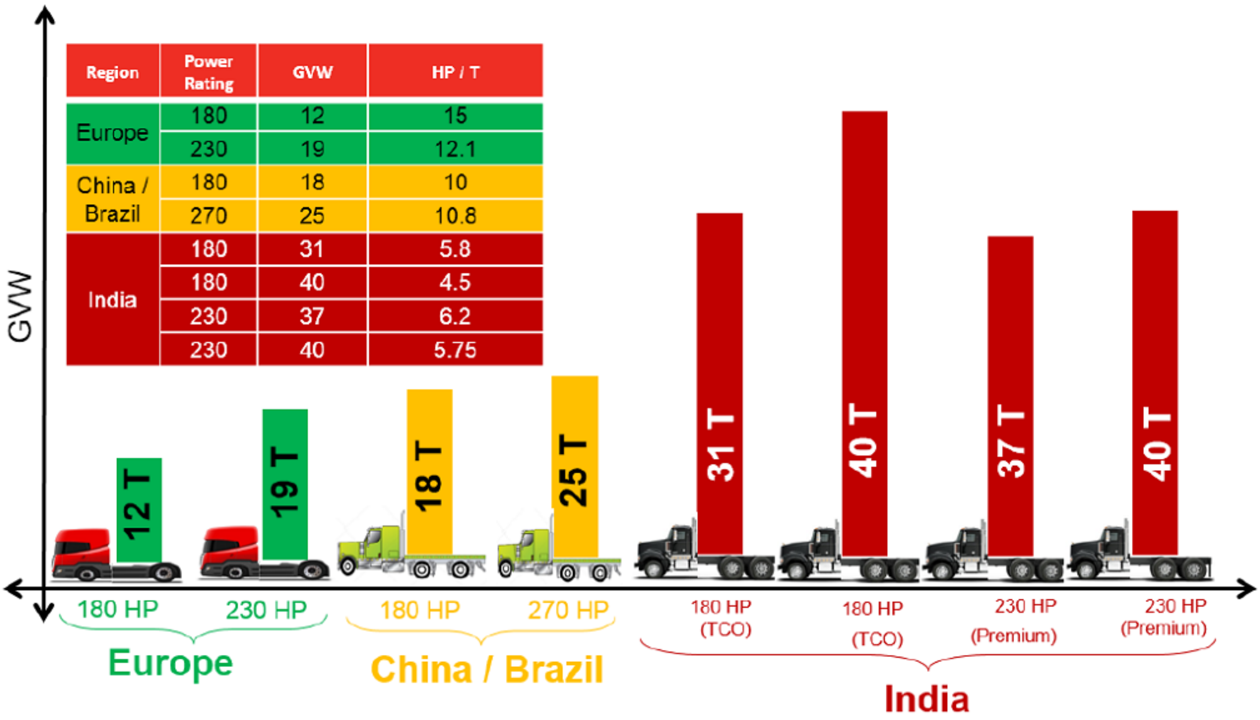


Fig. A.6 Gross vehicle weight v/s engine power for various regions [14]

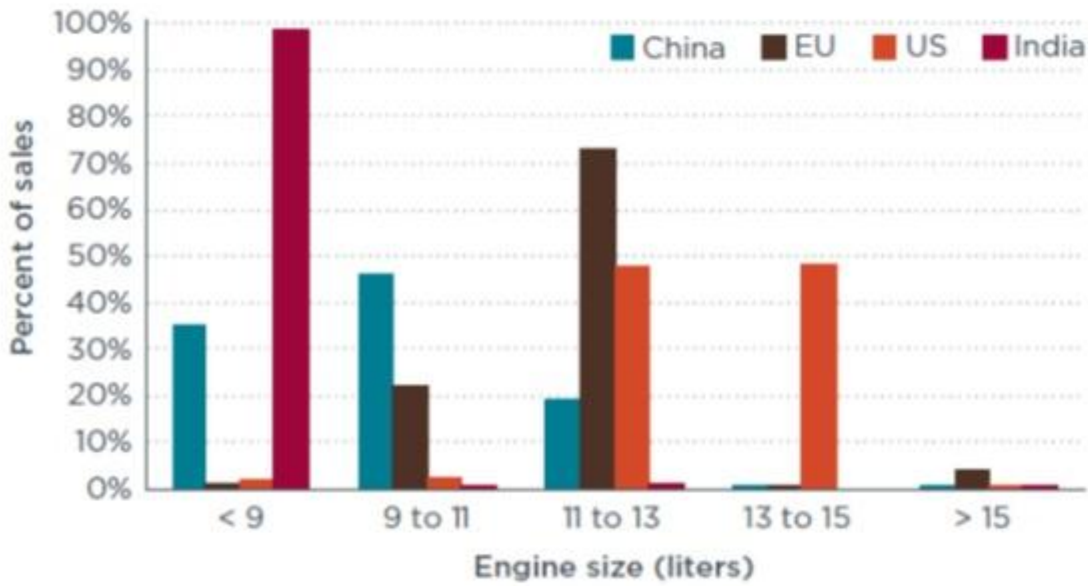


Fig. A.7 Country-wise engine size distribution for vehicles weighing > 15 mt [24]

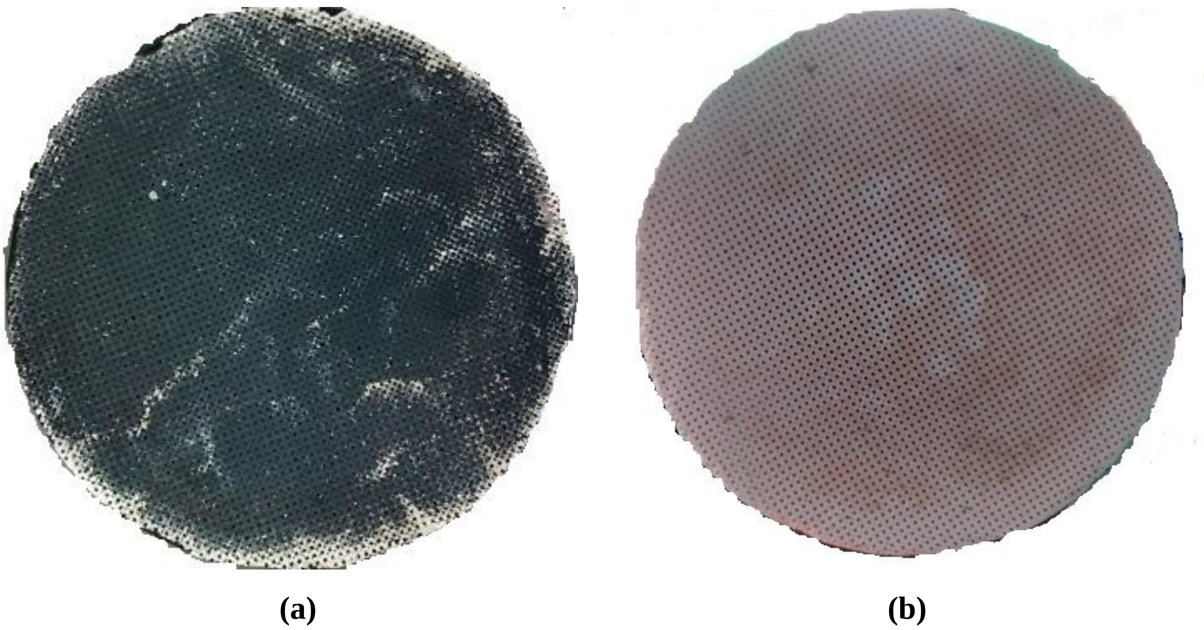


Fig. A.8 DPF - exhaust gas entry face **(a)** before and **(b)** after; off-board regeneration [31]

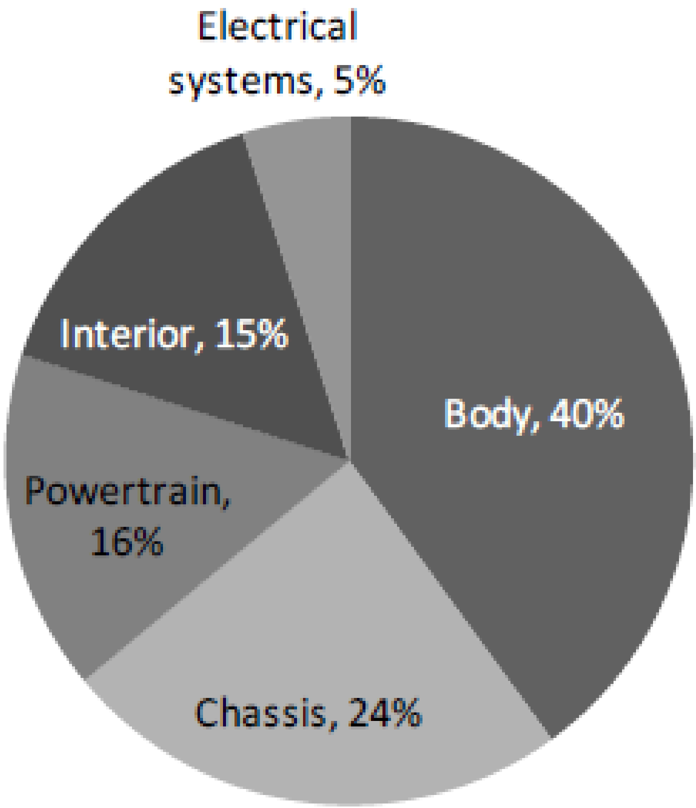


Fig. A.9: Vehicle mass distribution by subsystem [96, 102]

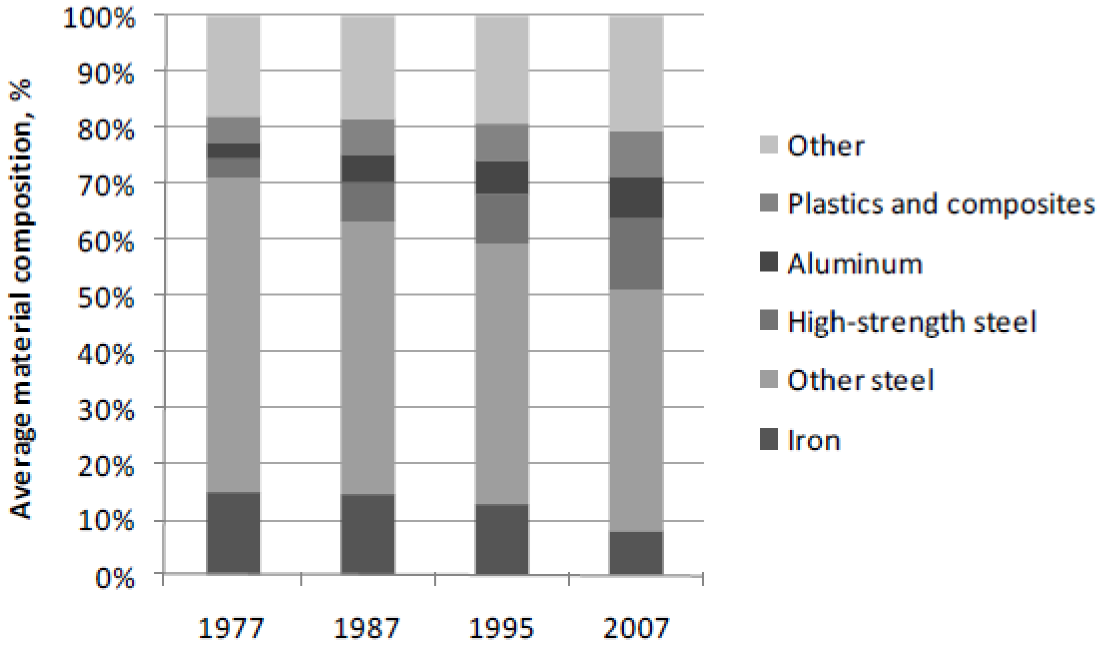


Fig. A.10: Material composition of the average automobile in the U.S. for 1977-2007 [112]

APPENDIX B: TABLES

Table A.1: Base engine technologies to reduce emissions [27, 79]

Parameter	Technology / Solution	Impact
Fuel system Fuel injection parameters and controls	High pressure common rail or unit injector systems or equivalent. Multiple injection events. Dynamic timing control.	Better atomization and mixing. More controlled combustion. Better control on NOx and PM emissions in wide operating range.
Air handling system	Electronically controlled variable geometry turbines or equivalent solution. Better air flow estimates and control through capable sensors.	Better control of air/fuel ratio. Better and flat torque characteristics. Better fuel economy over wide engine operating zone. Helps in emission reduction.
In-cylinder NOx reduction	Low or high EGR solutions with EGR coolers or internal EGR for in-cylinder NOx control strategy.	High EGR: Lower NOx at cost of PM or Low/internal EGR: Low PM and moderate NOx – to be treated through after-treatment solutions.

Table A.2: After-treatment devices to control emissions [27, 79]

Parameter	Technology / Solution	Impact
PM reduction	DOC: PM, HC and CO reduction DPF: PM reduction through passive and active soot regeneration	DOC converts only soluble organic fraction (SOF) part of PM. Good reduction in HC and CO. DOC is essential for passive and active regeneration of DPF.
NOx reduction	Vanadium SCR. Zeolite based SCRs – Cu-Z/Fe-Z Urea dosing system Ammonia oxidation catalyst (AMOX)	NOx reduction: 80-95% efficiency Ammonia slip control though after-treatment system.
ATS controls and OBD	Closed loop controls along with catalyst models. High accuracy temperature sensors, NOx sensors, Delta 'P' sensors, PM sensors.	Optimal ammonia dosing. Ultra high efficiency of NOx conversion. Better soot load management. After-treatment system protection. Effective conversion efficiency over lifecycle.

Table A.3: Test of significance using paired t-test with 95% confidence interval [31]

	Without DPF and Off-board Regeneration			Without DPF and Active Regeneration			Off-board and Active Regeneration		
Parameter	t value	P value	Whether significant	t value	P value	Whether significant	t value	P value	Whether significant
Smoke (Opacity)	6.36	0	Yes	6.38	0	Yes	-5.45	0	Yes
NOx	-9.14	0	Yes	-9.24	0	Yes	-8.39	0	Yes
O_2	6.37	0	Yes	6.81	0	Yes	8.06	0	Yes
BSFC	1.1	0.289	No	-3.96	0.001	Yes	-7.05	0	Yes
BTE	-1.4	0.182	No	3.53	0.003	Yes	5.87	0	Yes

Table A.4: Summarized evaluation of lightweight automotive materials [96, 102]

Material	Current use	Advantages	Challenges
High-strength steel	230 kg/vehicle, in structural components e.g. pillars, rails, rail reinforcements	Makes use of existing vehicle manufacturing infrastructure, there is OEM support for near-term use	- More expensive at higher volume scale - Lower strength-to-weight ratio compared to other lightweight materials
Aluminum	140 kg/vehicle, 80% are cast parts e.g. engine block, wheels	- Can be recycled - Manufacturers familiar with metal forming	- High cost of aluminum - Stamped sheet is harder to form than steel - Softer and more vulnerable to scratches - Harder to spot weld, uses more labor-intensive adhesive bonding
Magnesium	5 kg/vehicle, mostly thin-walled cast parts e.g. instrument panels and cross car beams, knee bolsters, seat frames, intake manifolds, valve covers	- Low density - Good strength-to-weight ratio - Ability to consolidate parts and functions, so less assembly is required	- Higher cost of magnesium components - Production of magnesium in sheet and extruded forms
Glass-fiber reinforced polymer composite	Rear hatches, roofs, door inner structures, door surrounds and brackets for the instrument panel	- Ability to consolidate parts and functions, so less assembly is required - Corrosion resistance - Good damping and NVH control	- Long production cycle time, more expensive at higher volume scale - Not easily recycled - Lack of design know-how and familiarity
Carbon-fiber reinforced polymer composite	Drive shaft	Highest strength-to-weight ratio, offering significant weight-saving benefit	- As above - High price volatility and cost of fibers ($13-22/kg)

Table A.5: Sales/registrations-weighted averages per manufacturer in EU for 2009 [98]

	CO_2 [g/km]	Ref. mass [kg]
BMW	151	1,554
Daimler	165	1,516
Fiat	135	1,119
Ford	143	1,331
GM	148	1,319
Honda	146	1,366
Hyundai	143	1,327
Mazda	151	1,314
Mitsubishi	163	1,347
Other	196	1,664
PSA	136	1,302
Renault	143	1,278
Suzuki	143	1,159
Toyota	136	1,272
Volkswagen	153	1,427
Volvo	169	1,636

Table A.6: Description of a few baseline vehicles [107]

Vehicle Class	Standard Car	Full Size Car	Small MPV	Large MPV	Large Truck
Baseline Vehicle	Toyota Camry	Chrysler 300	Saturn VUE	Dodge Grand Caravan	Ford F-150
CO_2 emissions (g/mi)[1]	327	409	415	435	575
Base Engine	DOHC I4	SOHC I6	DOHC I4	OHV V6	SOHC V8
Displacement (L)	2.4	3.5	2.4	3.8	5.4
Rated Power (HP)	154	250	169	205	300
Curb Weight (lb)	3108	3721	3825	4279	5004

[1] Estimated CO_2 equivalent, taken from EPA adjusted combined fuel economy ratings

APPENDIX-C: ERROR ANALYSIS

The values of various parameters obtained during the experiments could have errors or uncertainties due to operating conditions, environmental conditions, experimental methods adopted, calibration of equipment, accuracy and precision of equipment, human observations, test case planning, etc. Measurement errors fall into two main categories such as Systematic error and Random error. Imperfect calibration of measuring instruments (zero error), changes in environment which interfere with the measurement process and imperfect methods of observation caused the main sources of systematic error. Random error is caused by inherently unpredictable fluctuations in the readings of a measurement apparatus or in the experimenter's interpretation of the instrumental reading. In this investigation, the uncertainties were estimated from the minimum values of measured values as far as the individual measurements are concerned. To calculate the combined uncertainty of measurements a root-sum-square method was used. If a physical fundamental depends on n number of parameters, the combined uncertainties of each function was calculated by Pythagorean summation of uncertainties given by the equation.

$$z = f\,(x_1, x_2, x_3, x_4, \ldots\ldots x_n)$$

$$\sigma_z{}^2 = \left[\frac{\partial f}{\partial x_1}\right]^2 \sigma_{x_1}{}^2 + \left[\frac{\partial f}{\partial x_2}\right]^2 \sigma_{x_2}{}^2 + \left[\frac{\partial f}{\partial x_3}\right]^2 \sigma_{x_3}{}^2 + \ldots\ldots\ldots\ldots\ldots\ldots\ldots. + \left[\frac{\partial f}{\partial x_n}\right]^2 \sigma_{x_n}{}^2$$

σ_z = uncertainty of the function

σ_{x_n} = uncertainty of the parameter

f = function

x_n= parameter of the measurement

n = number of variables

Uncertainty analysis is presented here. The resolution of the measurements and the maximum uncertainties in the calculated results are given in Table A.7.

Table A.7: Percentage uncertainty in measurement of different quantities

Measured quantity	Range of measurement	Resolution	% Uncertainty
NO_X	0-5000 ppm	1 ppm	± 0.3 %
Smoke (Opacity)	0-100 %	0.1 %	± 0.18 %
CO_2	0-20 % vol.	0.1% Vol.	± 0.4 %
O_2	0-30 % vol.	0.1% Vol.	± 0.36 %
Torque	0-328 Nm	0.1 Nm	± 0.17 %
Fuel vol. flow	0-100 ml	± 1 ml	± 1 %
BTE	-	-	± 1.2 %
BSFC	-	-	± 1.2 %

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