Cleaning the Air of Tehran, One Bus at a Time: retrofit solutions for the ageing diesel bus fleet in Tehran

Technological Assessment, Economic Analysis, and International Best Practices

June 25, 2019

Acknowledgments

This report was prepared by a World Bank (WB) team in close collaboration with counterparts from the Department of Environment (DoE) of the Islamic Republic of Iran, and the Air Quality Control Company (AQCC) of Tehran. From the WB side, the technical analysis and drafting of this report was led by Ranjan Bose, under the guidance of and with input from Martin Heger & Craig Meisner. The task team would like to express its appreciation to Dr. Vahid Hosseini, CEO of AQCC and Associate Professor at Sharif University of Technology, and Dr. Masoud Tajrishi, Deputy Director of DoE.

TABLE OF CONTENTS

Acronyms and Abbreviations

ADB	Asian Development Bank
AECC	Association for Emissions Control by Catalyst (AECC)
ARAI	Automotive Research Association of India
AQCC	Air Quality Control Company
BC	Black Carbon
BAT	Best Available Technology
BEST	Brihanmumbai Electric Supply & Transport
BRT	Bus Rapid Transit
BSII	Bharat Stage II
CARB	California Air Resources Board
CCV	Closed Crankcase Ventilation
CCRT	Catalyzed Continuously Regenerating Trap
CD	Conventional Diesel
CDPF	Catalyzed Diesel Particulate Filter
CMB	Chemical Mass Balance
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRT	Continuously Regenerating Trap
DCF	Discounted Cash Flow
DDC	Detroit Diesel Corporation
DOC	Diesel Oxidation Catalyst
DOE	Department of Environment
DPF	Diesel Particulate Filter
EC	Elemental Carbon
ECD	Emission Control Device
ECMA	Emission Control Manufacturers Association
EEV	Enhanced Environmentally friendly Vehicle
EGR	Exhaust Gas Recirculation
ENR	Environment and Natural Resources
EPA	Environmental Protection Agency
ER	Emission Reduced
EU	European Union
FBC	Fuel Borne Catalyst
FTF	Flow Through Filter
HC	Hydro Carbon
HDDV	Heavy Duty Diesel Vehicle
HDV	Heavy Duty Vehicle
IARC	International Agency for Research on Cancer
ICCT	International Council on Clean Transportation
IRI	Islamic Republic of Iran
IRR	Iranian Rial
LEZ	Low Emission Zone
LNT	Lean NOx Trap
NEDC	New European Driving Cycle
nm	nanometer
µm	micrometer
NO_x	Oxides of Nitrogen
NPV	Net Present Value

NY	New York
OC	Organic Carbon
O&M	Operation and Maintenance
OAPC	Ordinance on Air Pollution Control
OEM	Original Equipment Manufacturer
PAH	Polycyclic Aromatic Hydrocarbons
PB	Pay Back
PM	Particulate Matter
$PM_{0.1}$	PM that have a diameter of less than 0.1 micrometers
$PM_{2.5}$	PM that have a diameter of less than 2.5 micrometers
PMP	Particulate Measurement Program
PN	Particle Number
PNFE	Particulate Number Filtration Efficiency
ppm	Parts Per Million
PV	Present Value
SCAQMD	South Coast Air Quality Management District
SCR	Selective Catalytic Reduction
SOF	Soluble Organic Fraction
SO_2	Sulfur Dioxide
SO_x	Oxides of Sulfur
TCO	Total Cost of Ownership
TERI	The Energy and Resources Institute
TfL	Transport for London
THC	Total Hydro Carbon
TMA	Tokyo Metropolitan Area
TMG	Tokyo Metropolitan Government
TWC	Three Way Catalyst
UBCT	United Bus Company of Tehran
ULSD	Ultra-Low Sulfur Diesel
UPF	Ultra-Fine Particle
USD	United States Dollar
VERT	Verification of Emission Reduction Technologies
VKT	Vehicle Kilometers Traveled
VOC	Volatile Organic Compound
VSL	Value of Statistical Life
WBG	World Bank Group
WHSC	World Harmonized Stationary Cycle
WHTC	World Harmonized Transient Cycle

Executive Summary

According to a report by the World Bank published in April 2018, air pollution in Tehran incurs annual loss of USD 2.6 billion and over 4,000 premature deaths from exposure to fine particles ($PM_{2.5}$) ambient concentrations. Tehran, the capital and largest city in Iran, has grown rapidly in recent decades and its current population is about 8.5 million spread over 800 square kilometers. The study asserts that Tehran is one of the most air polluted cities in the world and indicates that slightly more than 4,000 people die prematurely from ambient $PM_{2.5}$ pollution in the city per year. It estimates that reducing ambient $PM_{2.5}$ concentrations to levels comparable to those of London (20 micrograms per cubic meter) would prevent about 1,300 premature deaths per year; and to levels comparable to those of New York City (15 micrograms per cubic meter) would prevent about 2,000 premature deaths.

Particulate matter (PM), one of the primary pollutants from diesel exhaust, is associated with many different types of respiratory and cardiovascular effects, and premature mortality. $PM_{2.5}$ (particles smaller than 2.5 micrometers), in particular, are a significant health risk as they can pass through the nose and throat and cause lung damage. People with existing heart or lung disease, asthma, or other respiratory problems are most sensitive to the health effects of fine particles as are children and the elderly. Children are more susceptible to air pollution than healthy adults because their respiratory systems are still developing, and they have a faster breathing rate. EPA expects reductions in air pollution from diesel engines to lower the incidence of these health effects, as well as contribute to reductions in regional haze in national parks and cities, lost work days and reduced worker productivity, and other environmental and ecological impacts.

About 85% to PM emissions originate from heavy-duty vehicles (HDVs) even though their share is about 2% of total vehicles in the streets of Tehran. Most $PM_{2.5}$ originates from HDVs powered by diesel engines with outdated technology. There are thousands of ageing diesel vehicles in the streets of Tehran, with HDVs being particularly important (85% of the 70 % of PM emissions from vehicles comes from HDVs). Given the sizeable health and economic costs these vehicles incur on Tehran each year, urgent intervention is necessary. Considering replacement of older with newer vehicles will be (cost) prohibitive, and in view of the current (and for the foreseeable future) macro-economic and fiscal situation of Iran, retrofit programs to control PM emissions will be one of the short-to-medium term solutions for Tehran.

Advanced retrofit control technologies for HDVs in combination with ultra-low sulfur diesel offer hope for dramatic PM pollution reduction into the future. Rapid technological advances have led to a set of important technology and policy solutions to address diesel exhaust emissions. Since 2007, a growing number of national governments in different countries have implemented tailpipe emissions standards that can be met only with the installation of a diesel particulate filter (DPF) when applied to diesel engines. These "soot-free" engines—which is defined as those equivalent to or better than Euro VI for HDVs, or any policies that explicitly require the installation of a DPF—can reduce exhaust emissions of diesel soot by 99% compared with older-technology engines. Implementation of these limits also requires improvements in diesel quality to no greater than 10–15 parts per million (ppm) of sulfur, also called ultra-low sulfur diesel (ULSD), for soot-free engines to operate most effectively.

There is an urgent need to introduce ULSD in Tehran for the implementation and effective operation of old diesel vehicles equipped with retrofit emission control technologies to reduce $PM_{2.5}$ emissions. The combination of cleaner fuels and vehicles will have major health benefits and therefore vehicles and fuels must be treated as a system to achieve the optimum benefits from emission control policy. Near-zero sulfur (50 ppm or less) diesel offer optimum results in diesel vehicles equipped with appropriate DPFs (see Figure 2.2). Reducing traffic emissions alone by half would prevent about 750 premature deaths per year in Tehran according to the World Bank study. In countries without fuel sulfur limits, diesel sulfur content is typically 500 to 2000 ppm, and sulfates make up 15% to 50% of diesel $PM_{2.5}$ emissions. Of the four primary PM retrofit control technologies (namely, crankcase filters, diesel oxidation catalysts, flow-through filters, and DPFs), DPFs are considered the best available control technology for heavy-duty diesel PM control. DPFs help in significantly reducing ultrafine particulates and black carbon which is a component of fine particulate matter.

Although retrofit control technologies can be applied in theory to any appropriate diesel vehicle or engine, it is easier to administer and control a program by targeting Tehran city diesel bus fleet. The advantage of targeting heavy-duty diesel buses (e.g. Tehran City Bus Company) for public transit is two-fold. First, that they are centrally fueled to ensure uniform dispensing of ULSD in a bus and are typically maintained in a more controlled fashion. In addition, training of operators and maintenance personnel is more easily achieved. Second, results from emission inventory studies show Tehran city diesel bus fleet operating for public transit account for 14% to the PM emissions load. This allows local-level policymakers and transit managers to deploy more aggressive strategies on the city bus fleet operating exclusively in their administrative regions than national-level policy makers can on an entire diesel fleet nationwide.

Pilot test results of municipality buses in Tehran retrofitted with several DPF brands using different levels of sulfur diesel have shown significant reduction in PM emissions from diesel exhaust. Different DPF brands supplied by different manufacturers were tested on in-use diesel buses conforming Euro I to Euro 3 standards to evaluate filters' performance. The best test results conform excellent performance of filter operations (mainly Continuously Regenerating Trap, or CRT) with <50 ppm sulfur diesel or ULSD. Following the encouraging test performance results of DPFs under real bus operating conditions, the City Council of Tehran decided to mandate the retrofit of the public bus fleet of the capital. Subsequently, according to a statute passed by the cabinet in 2018, the DPF has been made mandatory in all diesel vehicles (old or new) in 8 metropolises of Iran. However, renovating public transport for Tehran has been put off due to a budget deficit and a sharp increase of prices of DPFs.

The main objective of this study is to evaluate the cost effectiveness of retrofitting existing city diesel bus fleet in Tehran with best available DPFs available in the market. The report provides an updated assessment on the diesel retrofit solutions for an ageing diesel city bus fleet in Tehran based on publicly available information. The economic benefits of DPF installed in buses are evaluated with standard techniques of environmental economics, and technological assumptions about how much PM emissions can be avoided and control costs. The report highlights a number of national, regional and local examples of effective emission control program that exhibit best practices from around the world. Also, it presents important features and global experiences of successful retrofit program on heavy-duty diesel vehicles (HDDVs), including benefit-cost analysis from several case studies to help Tehran city leadership in taking informed economic and policy decisions. Finally, it recommends a set of critical actions to the government both at the national and local level for implementation of an effective emission control programs.

The present value of the total investment cost to install DPFs in all 4,577 city diesel buses in Tehran over a period of seven years (i.e., 2019-2025) will be in the range of USD 22 – 44 million (Table 5.2). Total investment cost for the city bus retrofit program in Tehran (taking both municipal and private operated buses for public transit) will vary depend on the type of DPF technology selected. For Catalyzed Diesel Particulate Filter (CDPF) or Catalyzed Continuously

Regenerating Trap (CCRT) total cost would be USD 22 million; for metal CRT (USD 29 million); and for DPF+Fuel Borne Catalyst (FBC) (USD 44 million).[1] The costs accounted for in the analysis do not include administrative costs, costs of maintenance training and monitoring and reporting. Assuming 99% filter efficiency in each type of DPF, the maximum annual potential of PM load reduction is estimated at 0.48 million tons when all 4,577 buses are equipped with DPFs (see Table 5.2). That means the annual PM abatement cost from a city diesel bus retrofit program in Tehran ranges between USD 46 and USD 91 per ton depending upon the type of DPF selected.

Tehran city transit authorities need only an additional IRR 0.13 billion (or USD 950) towards meeting additional expenses on ULSD assuming a fuel economy penalty by 1% in DPF equipped buses and no change in the diesel fuel price. In view of the lessons learned from international experience, studies have shown fuel economy drops between 0.6% and 1.8% in buses retrofitted with DPFs. Assuming a drop of 1% in fuel economy in city buses equipped with DPFs in Tehran will result in an additional cumulative ULSD demand of 44,883 tons over 7 years (Table 5.3). Considering the price of low sulfur diesel for city buses at IRR 3.5/l (=IRR 2.92/kg) would remain the same for ULSD, the city transit company would need additional IRR 0.13 billion (USD 950) to meet additional fuel expenses. However, the expenditure on ULSD to run DPF equipped buses will go up if the unit price of delivered ULSD increases, which is highly likely.

Estimated annual benefits of a comprehensive DPF program on city buses outweigh costs by a factor of around 8 to 16 depending on the type of retrofit technology used. The annual mean concentration of $PM_{2.5}$ in Tehran was 32 micrograms per cubic meter in 2015-16, more than three times the national standards and the Air Quality Guideline of the WHO, which are 10 micrograms per cubic meter. A 14 percent reduction of $PM_{2.5}$ ambient air pollution to concentration levels from DPF retrofitted heavy-duty city diesel buses for public transit would result in avoided economic costs of about USD 364 million per year (see Figure 5.2). This monetization of annual benefits is many times greater than the present value of the cost associated with retrofitting all city diesel buses (i.e. 4,577 buses) with best available DPFs in Tehran over a period of seven years (2019-2025). In a conservative estimate that assumes no reduction in cost of three types of DPFs recommended over the period, this would cost USD 22.32 million for buses retrofitted with CDPF or CCRT. For the other retrofit technologies, the cost will be higher: USD29.47 million for metal CRT and USD 44.05 million for active DPF+FBC. Estimated annual benefits outweigh costs by a factor of around 8:1 to 16:1.

The analysis presented here demonstrates that on road diesel buses as a captive city bus fleet equipped with DPFs can be a cost-effective way to reduce PM emissions and improve city's air quality considerably and prevent premature deaths each year. It has become increasingly clear from literature review that as regulations in Iran have become more stringent that sulfur content in diesel must be controlled significantly (to <50 ppm S). It is a precondition of introducing advanced emission control retrofit technologies. Clean fuels can be a part of the solution only if there are enough buses on the road to prevent more people from opting personal transport.

1. Introduction

The economic costs associated with air pollution in Tehran are estimated at USD 2.6 billion per year. Concerned with the increasing levels of air pollution in Tehran, the Environment and Natural Resources (ENR) team in The World Bank Group (WBG) produced a discussion paper in 2018 based on a comprehensive air pollution diagnostic study for the capital of the Islamic

---

[1] The local currency conversion rate throughout this study is taken as 1 USD = 136,900 IRR as on 15 April 2019.

Republic of Iran (IRI) (Heger and Sarraf, 2018). The paper identifies mobile sources as the largest contributor (roughly 70%) to ambient Particulate Matter (PM) pollution in Tehran, especially fine particles ($PM_{2.5}$) based on evidence from published literature on source apportionment and emissions inventories in Tehran (Shahbazi et al., 2016).

1.1 Heavy duty vehicles are a major source of PM emissions

Heavy duty vehicles contribute the most to PM pollution. Even though the share of heavy-duty vehicles (HDVs) in the city is about 2% of total motor vehicles in the streets of Tehran, HDVs contribute about 85% to mobile PM emissions. HDVs are the largest contributor to mobile PM source not because of the size of the vehicle fleet, but mainly because of the age of the fleet powered by diesel engines. On average, 30% of HDVs are more than 20 years old, with almost 60% of minibuses being over 20 years old.

What is PM, and how does it get into the air?

PM stands for particulate matter (also called particle pollution): the term for a mixture of solid particles and liquid droplets found in the air. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Others are so small they can only be detected using an electron microscope.

Particle pollution includes:
- PM_{10}: inhalable particles, with diameters that are generally 10 micrometers (µm) and smaller.
- $PM_{2.5}$: fine inhalable particles, with diameters that are generally 2.5 µm and smaller. How small is 2.5 µm? Think about a single hair from your head. The average human hair is about 70 µm in diameter – making it 30 times larger than the largest fine particle.
- $PM_{0.1}$: ultrafine particles of diameters below 0.1 µm or 100 nanometer

Sources of PM
These particles come in many sizes and shapes and can be made up of hundreds of different chemicals. Some are emitted directly from a source, such as construction sites, unpaved roads, fields, smokestacks or fires. Most particles form in the atmosphere as a result of complex reactions of chemicals such as sulfur dioxide and nitrogen oxides, which are pollutants emitted from power plants, industries and automobiles.

What are the harmful effects of PM?
The size of particles is directly linked to their potential for causing health problems. Small particles less than 10 micrometers in diameter pose the greatest problems, because they can get deep into your lungs, and some may even get into your bloodstream.

Exposure to such particles can affect both your lungs and your heart. Numerous scientific studies have linked particle pollution exposure to a variety of problems, including:
- premature death in people with heart or lung disease;
- nonfatal heart attacks;
- irregular heartbeat;
- aggravated asthma;
- decreased lung function;
- increased respiratory symptoms, such as irritation of the airways, coughing or difficulty breathing.

Source: U.S. Environmental Protection Agency. EPA. https://www.epa.gov/pm-pollution/particulate-matter-pm-basics#PM

The age of HDVs vehicle is to blame for their substantial contribution to PM emissions. Given the sizeable health and economic costs associated with air pollution mainly from ageing diesel powered engines in HDV, addressing HDV pollution is critical for improving air quality in communities around the country (Shahbazi et al., 2016). Urgent intervention is necessary in Tehran to control and reduce particulate emissions.

Targeting old HDVs in short to medium term is likely to be more cost-efficient among available options to curb PM emissions. A World Bank report from 2018 – Heger & Sarraf (2018) - identified nine priority transport policy interventions (see Table 1.1). These are listed under first- and second-order priorities taking into consideration the timeframe, financial cost that would be incurred by the government, and the effectiveness of implementing a certain measure (Heger and Sarraf, 2018; Shahbazi et al., 2016).

Table 1.1: Transport policy priorities for the reduction of air pollution in Tehran

Measures	Time-frame	Financial Cost	Effectiveness
First-order priorities:			
1. Heavy Duty Diesel Vehicle (HDV) replacement program with scrappage	Short-term	Very high@	High
2. A comprehensive Diesel Particulate Filter Program for HDVs	Short-term	Low-Medium	High
3. Expand low emission zones including pollution charges	Short-term	Low	Medium
4. Improve Inspection and Maintenance program	Short-term	Medium	Medium
Second-order priorities:			
5. Incentivize electric and hybrid vehicles	Medium-term	Medium	High
6. Incentivize non-motorized transportation	Medium-term	Low	Medium
7. Expand BRT and possibly LRT lines	Medium-term	High	Medium
8. Expand metro lines	Long-term	High	High
9. Strengthening monitoring, measurement and analysis capacity	Medium-term	Low	Low

@updated in consultation with expert from Sharif University of Technology, Iran.

Source: Heger and Sarraf, 2018; p-21.

A comprehensive diesel retrofit program for in-use HDVs is highly recommended for the city in view of current economic situation in the country. The recent economic sanctions imposed on Iran, and the current macroeconomic – monetary & fiscal – situation has changed the feasibility and economics of some of the originally proposed solutions. In view of the current economic conditions of the country, replacing old with newer vehicles will be prohibitive (particularly as the newer vehicles have to be imported). A retrofit program of heavy-duty diesel vehicles (HDDVs) would be one of the most promising solutions under the current circumstances in Tehran. Many of the retrofit technologies are similar to the advanced emission control technologies now available on newer 'clean' diesel engines including diesel oxidation catalysts (DOCs) and DPFs for reducing diesel PM. Several diesel retrofit programs in different geographies have demonstrated their ability to significantly reduce unwanted emissions from older diesel engines at a reasonable cost without jeopardizing vehicle performance.

Among several retrofit technologies available in the market, city diesel buses retrofitted with diesel particulate filter have shown significant PM reduction benefits. To control the PM emissions of in-use diesel engines, several technologies can be used in the short-medium term, including improving the combustion efficiency in the cylinder, optimizing engine control strategies, using renewable and clean fuels and implementing a diesel particulate filter (DPF). Among them, DPF is widely acknowledged as the best diesel after-treatment technology to meet more and more stringent emission standards (Fleischman et al. 2018; Dallmann et al. 2011). Faced with environmental pressure, retrofitting in-use HDVs with DPF is a relatively simple method to make them accord with current emission standards (Mohannadiha, Malakooti, and Esfahanian 2018).

Targeting centrally-managed captive fleets with more aggressive local strategies will significantly help in improving air quality. Thousands of ageing diesel-powered HDVs are running in the streets of Tehran. The control of HDV emissions presents unique challenges for policy makers. First, HDVs exists in thousands of different configurations operating across highly variable duty cycles. This huge scope of application and operation requires the careful design of control programs targeting different classes and types of HDVs, such as the establishment of detailed, specific retrofit certification programs. Second, HDVs play a critical role in virtually every sector within the economy, and older vehicles are often owned and operated by small business owners and/or self-employed individuals. Providing flexibility, fiscal incentives, subsidies, and/or loan assistance programs in parallel with mandatory control programs may be warranted. This is especially true in certain freight and vocational HDV sectors that can be highly fragmented in many regions, and in which vehicle owners may be quite sensitive to capital equipment and operation costs.

Policymakers may take advantage of certain opportunities in the control of in-use HDV emissions relative to passenger vehicles. For example, certain emission control solutions—fuel switching, some retrofit technologies, and advanced technology vehicles—can be well suited for application on specific HDV fleets due to their centralized management and relatively predictable duty cycles (e.g., Tehran City Bus Company). Similarly, local-level policymakers may be able to deploy more aggressive strategies on municipal vehicles operating exclusively in their administrative regions than national-level policymakers can on an entire fleet nationwide.

1.2 Vehicles and fuels should be treated as a system

It has become increasingly clear as emissions regulations have become more stringent that fuel properties and vehicle technologies are closely intertwined. Certain fuel parameters such as sulfur content in diesel must be controlled as a precondition to introducing advanced vehicle technologies. Sulfur in fuel is problematic because it leads to increased air pollution. This occurs directly through emissions of harmful sulfur compounds such as sulfates, and indirectly by inhibiting the effectiveness of modern emission control devices. Sulfur in fuel is also a barrier to dealing with climate pollution from diesel engines. Black carbon associated with diesel combustion can be controlled using DPFs required by Euro 6/VI emissions standards, but these devices are only effective with low, or ideally ultra-low, sulfur fuels.

Emerging retrofit technologies, in combination with intelligent policies, offer hope for dramatic emissions reductions into the future for Iran. Both industrialized and developing nations have taken major steps to control emissions from on road diesel fleet. Strong retrofit programs in several countries have produced impressive emissions reductions over the last thirty years, indicating a similar potential for in countries like Iran with younger programs. An updated global assessment of end-of pipe solutions, especially DPFs, will help authorities in the national and local government in taking an informed decision.

1.3 Scope of the study

This review and outlook report provides an updated assessment on the diesel retrofit solutions for an ageing diesel city bus fleet for public transit in Tehran. The economic benefits of DPF retrofitting in buses are evaluated with standard techniques of environmental economics, and technological assumptions about how much PM emissions can be avoided and control costs. The report highlights a number of national, regional and local examples of effective emission control program that exhibit best practices from around the world. Specifically, the report presents important features and global experiences of successful retrofit program on HDDVs in different geographies to help Tehran city leadership in taking informed economic and policy decisions. At the end, it suggests a set of critical actions that are necessary for the government both at the national and local level to design an effective emission control programs from in-use heavy-duty vehicles in Iran.

This report comprises six sections.

1. A summary of the report with the background context, study area, options and recommendations
2. A global overview of health impacts of HDDV emissions and the benefits of low sulfur diesel that enable advanced emissions technologies.
3. A review of the current state of knowledge on successful diesel retrofit technology options for on-road HDDVs and a summary of beneficial experiences and important lessons from around the world including selected fiscal policy support to improve diesel fuel quality.
4. A cost-benefit analysis framework applied in different geographies with and without emission control technologies to illustrate the cost effectiveness of a retrofit program based on published evidence.
5. A cost-effectiveness analysis of cleaning up the bus fleet for public transit in Tehran with diesel retrofit solutions.
6. The relative roles that national and local decision-makers can play in controlling emissions by local authorities from diesel powered in-use HDVs.

2. Health Impacts of Heavy-Duty Vehicle Emissions

With mounting evidence that diesel exhaust poses major health hazards, reducing diesel pollution has become a public priority. Diesel engines are widely used around the world in commercial applications due to their higher efficiency, better torque at low engine speeds, reliability, and durability. However, diesel exhaust, which is made up of numerous gaseous and solid chemical compounds, is widely recognized to be harmful to human health. Specific emissions of concern include ozone precursors, such as NO_X and volatile organic compounds (VOCs); PM and PM precursors (e.g. NO_X and SO_X); and toxic and carcinogenic compounds such as formaldehyde. The known human health effects of diesel exhaust include cancer (especially lung cancer), heart disease and stroke, asthma, bronchitis, and other respiratory infections and diseases, as well as acute effects such as irritation, lung function changes, headaches, nausea, and fatigue (IARC, 2012; Kagawa, 2002; Sydbom et al, 2001; CARB, 1998). These result in significant societal losses in the form of premature deaths, lost productivity and increased medical spending for hospital admissions and emergency room visits, reduced learning due to school absences, work losses, restricted activities, and more.

Many of the acute health effects caused by diesel exhaust are linked to particle size. Many diesel particles can penetrate the deepest portion of the lungs due to their small size (below 100 nanometer (nm), or 0.1 µm, in aerodynamic diameter also referred to as ultra-fine particles), where they can pass through cell walls and be transported via the bloodstream to other organs of the body (Prasad and Bella, 2010). Smaller particles also provide a large surface area for adsorbing toxic organic compounds. Several studies investigated the relationship between PM emissions and human health and found that 4.2 million premature deaths (7.6% of all global deaths) are caused by outdoor fine particulate air pollution in 2015. $PM_{2.5}$ was the fifth highest ranking risk factor for death (Vidale and Campana, 2018). A study issued in February 2005 states that fine particulate pollution from diesel engines shortens the lives of nearly 21,000 people in the U.S. every year, with health-related damage from diesel PM estimated to total $139 billion in 2010 (CATF, 2005).

2.1 Components of $PM_{2.5}$

Several components make up the total mass of $PM_{2.5}$ emitted by an engine. The components are generally categorized into: (a) solid fraction, including black carbon and ash; (b) soluble organic fraction, including unburnt fuel and oil; and (c) sulfate particles, including sulfuric acid and adsorbed water. The amount of any of these components varies greatly depending on engine technology, engine load, and for sulfates the sulfur content of the fuel. The pie chart in fig. 2.1 shows a composition typical of a HDDV operated in the U.S. in 1998, when diesel sulfur limits were 500 ppm (Kittelson, 1998).

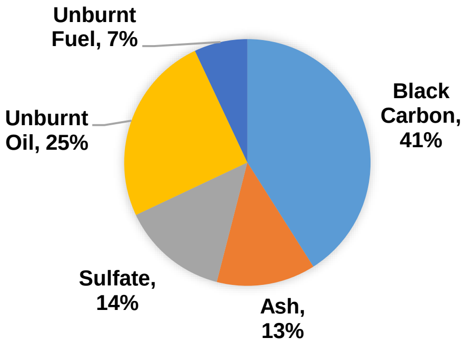

Fig. 2.1: Composition of a typical HDDV (1998 US) with 500 ppm (max) sulfur in diesel

Higher fuel sulfur content increases the mass of sulfates produced, and as a consequence increases total $PM_{2.5}$ as illustrated in Figure 1.2. Lowering sulfur levels decreases sulfate production but does not directly lower production of other components (e.g. black carbon). However, it does enable the use of advanced emission control technologies and engine tuning that reduce the solid and soluble organic fractions of black carbon, and thus indirectly plays a role in reducing climate-forcing emissions (CCAC, 2016; page 17).

Black carbon is a potent climate-warming component of PM formed by the incomplete combustion of carbon rich fuels. In addition to the direct health impacts of PM, the carbonaceous component of PM often referred to as black carbon (BC) has been found to be a significant contributor to the atmospheric warming effect by enhancing the absorption of sunlight. The global warming potential of BC has been estimated to be up to 4500 times higher than that of CO_2 on a per gram of emission basis. Since BC particles only remain airborne for weeks at most compared to carbon dioxide, which can remain in the atmosphere for more than a century, removing BC from diesel exhaust has an immediate benefit to both global warming and public health.

The health and environmental communities have focused on ultrafine particulates from diesel engines exhaust. The extremely high surface area of ultrafine particles provides a favorable support for deposition of volatile toxic compounds that are present in the exhaust upon cooling and dilution in the atmosphere. A combination of these two mechanisms provides a pathway by which air toxics such as polycyclic aromatic hydrocarbons (PAHs) can adsorb onto particles and enter the body efficiently increasing the oxidative stress and inflammation within the cells in other organs (Biswas *et al.*, 2009 and Garshick *et al.*, 2008).

Emissions from diesel-fueled old HDVs are of concern. A single, uncontrolled HDV may emit as much pollution per kilometer as dozens of vehicles meeting a modern, advanced emission standard. For instance, in China in 2009, uncontrolled "pre-Euro vehicles"[2]—vehicles that entered the fleet prior to 2000—accounted for only 17% of the highway vehicle fleet but emitted 56% of PM and 50% of total NO_X emissions (ICCT, 2013). The ICCT study also reports, in Brazil in 2009, 28% of diesel vehicles were certified to the older Pre-Proconve, P1, and P2 standards yet emitted 50% of total particulate matter.

2.2 Health benefits of sulfur reduction

Removing sulfur from vehicle fuel is of two-fold importance in preventing harmful vehicle pollution. First, fuel sulfur directly increases production of fine particulate matter ($PM_{2.5}$) which is considered a dangerous pollutant associated with heart disease, lung cancer, and a range of other harmful health effects (Krewski et al., 2009). When diesel sulfur content is high, sulfate particles, formed from combustion of sulfur in diesel, make up a significant share of total fine particulate emissions. Second, low-sulfur fuels are necessary for cleaner engines (for example high compression diesel engines) and allow for the efficient performance of equipment designed to remove all small particulates and other pollutants from the exhaust stream (including particulate filters and catalysts) (Corro, 2002). DPFs, for example, perform best with a maximum diesel sulfur content of 10 or 15 ppm. These filters control not only $PM_{2.5}$ mass, but also can reduce the emission of ultrafine particles, which are thought to have a greater toxicity than larger particles due to their higher quantity, and ability to penetrate deep within lung tissue and cross into the blood stream (May et al., 2007; HEI, 2013). High-sulfur fuel can also damage some systems that control nitrogen oxides, a pollutant that leads to smog and additional $PM_{2.5}$ formation. While fuel sulfur reduction alone delivers significant health benefits, the full benefits of cleaner fuels are realized when low-sulfur fuel is combined with appropriate vehicle emissions standards.

Vehicles and fuels must be treated as a system to achieve the optimum benefits from emissions control policy. Progressively stringent vehicle emissions standards are linked to matching fuel quality. For instance, the Euro 4/IV[3] standards for light- and heavy-duty vehicles respectively require 50 ppm diesel fuel to be effective. Some more advanced emission control technologies associated with higher standards can also operate with 50 ppm fuels – for instance, DPFs will still deliver benefits with 50 ppm diesel – but the optimal system will pair a stronger vehicle emissions standard with ultra-low-sulfur fuel (maximum 10 or 15 ppm). These stronger emissions standards, including Euro 5 and 6, and U.S. Tier 2 and 3, for passenger vehicles, and Euro VI and the U.S. 2010 standards for heavy duty vehicles, require more advanced technologies to be employed in order for compliance to be achieved, including diesel particulate filters (CCAC, 2016).

Introducing low-sulfur fuels and cleaner vehicles standards will result in major PM reductions. Figure 2.2 shows the impact of Euro I-VI standards in heavy-duty diesel vehicles with reduction in sulfur in diesel. While lowering sulfur in diesel fuel results in direct and proportional reductions in $PM_{2.5}$ emissions in all vehicles (even those without emission controls), cleaner fuel combined with emission controls at Euro IV and above results in drastic reductions in both $PM_{2.5}$ and black carbon emissions. Euro VI standard-level technology combined with 10/15 ppm diesel will result in an approximate 99% reduction in $PM_{2.5}$ as compared to combustion of 2,000 ppm fuel with no control requirement.

---

[2] While the HDV fleet in Tehran today is still largely meeting Euro III standards or less, the majority of vehicles in the country only meet the Euro I standard (Heger and Sarraf, 2018).

[3] The European standards are designated by Arabic numerals (i.e. Euro 1, 2, 3, 4) for light-duty vehicles, and Roman numerals (i.e. Euro I, II, III, IV) for heavy-duty vehicles (ICCT, 2016).

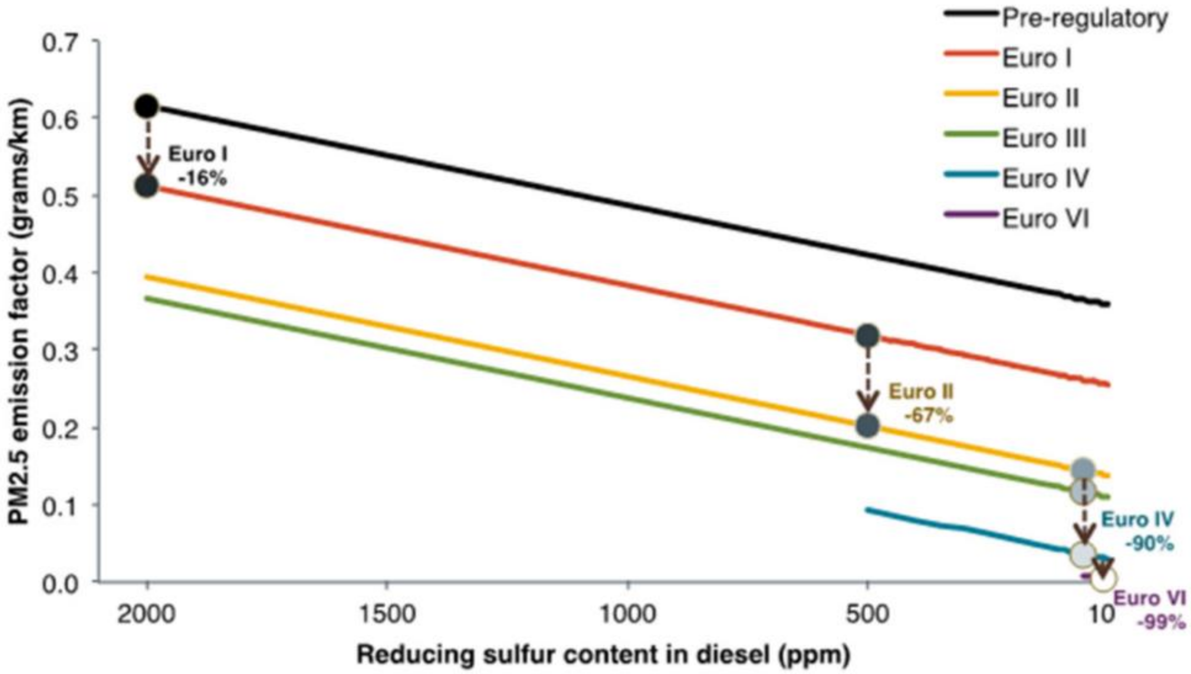

Fig. 2.2: Impact of fuel sulfur levels and emission control standards on $PM_{2.5}$ from HDDVs (g/km)

Source: Reproduced from CCAC, 2016; p-13.

3. Available Retrofit Technologies to Control Emissions

Many retrofit technology options exist to reduce emissions from diesel engines. There are four primary PM exhaust retrofit technologies as summarized below (ICCT, 2013; MECA, 2014).

- **Diesel oxidation catalysts (DOCs).** The retrofit of diesel engines with DOCs has been taking place for well over twenty years in the off-road vehicle sector in several countries. A typical catalyst can reduce PM emissions by 25-50% depending on the composition of the PM being emitted. Over 300,000 oxidation catalysts have been installed in underground mining and materials handling equipment. Diesel oxidation catalysts do not, however, reduce BC emissions; they do have some effect at reducing the organic fraction of diesel PM (UNEP, 2009). Diesel oxidation catalysts can also reduce smoke emissions from older vehicles and virtually eliminate the obnoxious odors associated with diesel exhaust. DOCs can reduce more than 90 percent of the CO and HC emissions and more than 70 percent of the toxic hydrocarbon emissions in diesel exhaust.

- **Wall-flow diesel particulate filters (DPFs).** Installation of DPFs on new and existing diesel engines can achieve up to and, in some cases, greater than a 90% reduction of PM emissions. Over 300,000 on-road and off-road heavy-duty engines worldwide have been retrofitted with passively or actively regenerated particulate filters, with more than 100,000 such retrofits installed on diesel engines in the United States since 2001. The DPFs are extremely effective in controlling the carbon fraction of the particulate known as black carbon (BC). BC has been identified as a significant contributor to global warming with a CO_2 equivalence estimated to be hundreds if not thousands of times that of carbon dioxide. 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. The DPFs incorporating a catalyst function have been shown to decrease the levels of polyaromatic hydrocarbons, nitro-polyaromatic hydrocarbons, and the mutagenic activity of diesel PM.

- **Flow-through filters (FTFs).** In a relatively new method, FTFs or partial filters employ catalyzed metal wire mesh structures, tortuous flow, metal foil-based substrates with sintered metal sheets, or specially designed ceramic filters to reduce diesel PM. FTFs can achieve PM reduction of about 30 to 75 percent, depending on the engine operating characteristics, as well as trapping the sub-micron, ultrafine particles capable of penetrating deep into the lungs. Because of their open structure, these devices are less prone to plugging and may be more suited to older diesel engines with higher engine-out PM levels (MECA, 2014). FTFs can be catalyzed to offer co-benefits of reducing HC, CO, and toxics of up to 80-90%. FTFs require periodic maintenance; they have had some issues of PM build up resulting in failure.

- **Closed crankcase ventilation (CCV).** This technology is meant to be retrofitted on turbocharged diesel engines to eliminate crankcase emissions. For model years 1994 to 2006 heavy-duty diesel engines, crankcase PM emissions reductions provided by crankcase emission control technologies range from 0.01 g/bhp-hr to 0.04 g/bhp-hr.

The NOx emissions from diesel engines also pose a number of health concerns. Once in the atmosphere, the oxides of nitrogen react with volatile organic compounds (VOCs) in the presence of sunlight to form ozone. Ozone is a reactive and corrosive gas that contributes to respiratory problems. Ozone is particularly harmful to children and the elderly. Available retrofit technologies designed to control oxides of nitrogen (NO_x) include,

- **Exhaust gas recirculation (EGR).** EGR systems are retrofitted on heavy-duty diesel vehicles. EGR is capable of achieving a 40 percent reduction in NO_x emissions or more.

- **Selective catalytic reduction (SCR).** SCR system uses urea as a reducing agent and is found effective in reducing NOx emissions by up to 90 percent while simultaneously reducing HC emissions by 50 to 90 percent and PM emissions by 20 to 30 percent.

- **Lean NOx Catalysts or HC-SCR.** HC-SCR systems are installed on heavy-duty on-road and off-road vehicles in combination with a DPF and can achieve 25-40 percent NOx reduction. These devices rely on the use of on-board diesel fuel from the vehicle as the reducing agent.

- **Lean NOx Trap Storage Catalysts (LNT).** LNT systems have been successfully used on new light and medium-duty vehicles with over 80 percent NOx conversion.

The diesel retrofit devices for after-treatment pollution control can be installed on new or existing vehicles and equipment to reduce PM, NO_x, HC, CO as well as other non-regulated air pollutants. Table 2.1 provides a snapshot of estimated emission reductions from different types of emission control after-treatment technologies and typical costs in USD available in the ECMA (Emission

Control Manufacturers Association)[4]. However, it is important to note actual emissions reduction and costs will depend on specific manufacturers, technologies and applications. The costs would be lower with domestic manufacturing.

Table 2.1: Diesel retrofit devices with their emissions reduction potential and typical costs*

Technology	**Typical Emission Reduction (%)**				**Typical Costs ($)**
	PM	**NOx**	**HC**	**CO**	
DOC	20-40	no change$	40-70	40-60	Material: \$600-\$4,000 Installation: 1-3 hours
DPF	85-95	no change$	85-95	50-90	Material: \$5,000-\$8,000 Installation: 6-8 hours
FTF	up to 60	no change$	40-75	10-60	Material: \$4,000-\$6,000 Installation: 6-8 hours
CCV#	varies@		40-70		
EGR#		25-40	40-70		
SCR#		up to 75			\$10,000-\$20,000; Urea \$80/gal
LNT#		5-40	40-70		\$6,500-\$10,000

$almost no change in the ratio NOx emission concentration before and after the installation of DPF (Quan-shun *et al.*, 2017)
#may be combined with DOC or DPF system to reduce PM, HC and CO emissions.
@according to the U.S. verification documents, the combined CCV/DOC system controls PM emissions by up to 33%, CO emissions by up to 23% and HC emissions by up to 66%. (https://www.wrapair.org/forums/msf/projects/offroad_diesel_retrofit/V2-S8_Final_11-18-05.pdf).
*Actual emissions reductions and costs will depend on specific manufacturers, technologies and applications. EPA and the California Air Resources Board (CARB) verify the emissions performance of retrofit devices through specific testing protocols and statistical analysis.

Source: EPA; Extracted from the Emission Control Manufacturers Association (ECMA) website: http://www.ecmaindia.in/retrofit-technology.aspx?mpgid=51&pgidtrail=51

3.1 Impact of sulfur in diesel fuel on catalyst technologies

The sulfur content of diesel fuel is critical to applying catalyst technology. Catalysts used to oxidize the soluble organic fraction (SOF) of the particulate can also oxidize sulfur dioxide to form sulfates, which is considered part of the particulate. This reaction is not only dependent on the level of sulfur in the fuel, but also the temperature of the exhaust gases. Catalyst formulations have been developed which selectively oxidize the SOF while minimizing oxidation of the sulfur dioxide. However, the lower the sulfur content in the fuel, the greater the opportunity to maximize the effectiveness of oxidation catalyst technology for both better total control of PM and greater control of toxic HCs. Lower sulfur fuel (500 ppm sulfur; 0.05% wt.), facilitates the application of catalyst technology to diesel-powered vehicles. For best results, the availability of ultra-low sulfur diesel (ULSD) fuel (15 ppm sulfur; 0.0015% wt.) provide significant enhancements of catalyst performance for retrofit applications.

Sulfur in diesel fuel significantly affects the reliability, durability, and emissions performance of catalyst-based DPFs. Sulfur affects filter performance by inhibiting the performance of catalytic materials upstream of or on the filter. Sulfur also competes with chemical reactions intended to reduce pollutant emissions and creates particulate matter through catalytic

---

[4] ECMA is a non-profit Association made up of the world's leading manufacturers of Emission Control equipment for automobile and non-road engines in India. ECMA is associated with the Association for Emissions Control by Catalyst (AECC), *a non-profit Brussels-based association of European companies,* and the Manufacturers of Emission Controls Association (MECA), *a non-profit Washington, DC-based Association*—from inception.

sulfate formation. 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. The 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 actively regenerated devices, is not affected by fuel sulfur.

Without low-sulfur fuel, many effective diesel pollution control technologies cannot be deployed, either on new vehicles or as retrofits. Sulfur also inhibits the proper operation of many emission control devices, including passively regenerating particulate filters and high-performance SCR systems, in some cases permanently damaging their effectiveness. The European Union, countries such as the United States and Japan, and cities such as Hong Kong and Beijing have reduced diesel sulfur levels for highway vehicles to near-zero levels. In Europe, the Euro III, IV, and V heavy-duty diesel emission standards were accompanied by corresponding fuel standards requiring a maximum of 350, 50, and 10 parts per million (ppm) sulfur in diesel fuel, respectively. This progressive ratcheting down of fuel sulfur levels facilitates the introduction of the advanced emission control devices summarized in Table 3.1.

Table 3.1: Summary of emission control technologies for heavy-duty diesel vehicles

Tech.	New Vehicle Application	Retrofit Application	Control Efficiency	Sulfur level requirement (ppm)	Notes
EGR	Euro IV+	No	20-80% NO_x reduction	<350	NOx reduction depends on load conditions. Higher loads lead to higher reduction
DOC	Euro IV+	Yes	20-50% PM reduction; >80% CO and HC reduction	<350 viable; <50 preferred	Only reduces SOF, not fine particles; NO_2/NO ratio may increase
PFF	Euro IV+	Limited	30-60% PM reduction; >80% CO and HC reduction	<350	Long-term durability and effectiveness still not proven
DPF	Euro VI	Yes	>99% PM (particle number); >90% PM (particle mass)	<50 required for catalyzed DPFs; <10 preferred	Only proven technology for reducing ultrafine particles
SCR	Euro IV+	Limited experience with DPF+SCR combined retrofits; Pilot programs for exclusive SCR retrofits	50–95% NOX reduction	<2,000 for vanadium catalysts (350 preferred); <50 for zeolite catalysts	Systems must be carefully designed and controlled to function properly and prevent secondary emissions; Requires urea supply infrastructure

Source: ICCT, 2013; p-20.

Elevated fuel sulfur levels increase both the number and mass of diesel exhaust particles, as well as emissions of other conventional air pollutants. Reducing the sulfur content of diesel fuel is therefore essential for effective operation of emission control technologies to reducing emissions from conventional diesel engines. Reducing the sulfur level in diesel fuel will result in lower emissions—especially particulate emissions—from any diesel engine regardless of the emission standard to which it is certified (Liu *et al*., 2008).

Although sulfur level is the single most important fuel quality indicator impacting in-use heavy-duty emissions, other fuel characteristics including, polyaromatic content, cetane number, density, distillation, ash, suspended solids content, and viscosity, are also important. Improvements in these characteristics can yield immediate environmental benefits for the entire vehicle fleet (See Table 3.2). Further information about recommended diesel fuel quality specifications can be found for HDVs and engines in the International Council on Clean Transportation (ICCT) publications (Walsh *et al.*, 2007) and its recent retrospective on China's emission control efforts (Fung *et al.*, 2011).

Table 3.2: Impact of various fuel characteristics on HDDV emissions

Diesel fuel characteristic	**Pre-EURO**	**EURO I**	**EURO II**	**EURO IV**	**EURO V**
Decrease sulfur content	Decrease SO_2, PM		Decrease SO_x, SO_2, PM		50 ppm S maximum (if filter) 10 ppm S maximum (if NO_x adsorber)
Increase cetane	Decrease CO, HC, benzene, 1,3-butadiene, formaldehyde, acetaldehyde				
Decrease polyaromatics	Decrease NO_x, PM, HC				

Source: ICCT, 2013, p-21.

3.2 Best practices in using cleaner diesel

Adopting and implementing policies to improve fuel quality and promote the use of low-to-ultra-low sulfur diesel in ageing HDDVs can be a complex process requiring coordination among multiple actors at both the national and local levels from a variety of legislative and regulatory departments (environment, finance, economic planning, state-owned oil companies, etc.). The following international best practices characterize effective setting and enforcing of conventional fuel quality standards (ICCT, 2013):

3.2.1 Adopt a systems approach

The best vehicle emissions performance can only be achieved if vehicles and fuels meet complementary standards in parallel. This "systems approach" phases in vehicle tailpipe emission and fuel quality standards concurrently, ensuring that appropriate fuels are available when advanced and/or retrofitted old vehicles with emission control technologies enter the market. The systems approach avoids potential engine malfunction due to misfueling of vehicles and limits political infighting between automakers and fuel providers—who otherwise tend to blame each other for a lack of technology development—during policy design. The systems approach has been successfully pursued in Japan since 1992, the United States since 1994, and Europe since 2000 (Euro III). Failure to adopt such an approach risks suboptimal emissions performance and the delay of vehicle emission standards vital to protecting human health.

3.2.2 Allow local authorities to set higher standards

Although the environmental policymakers have the authority over both vehicles and fuels, they should allow local authorities leeway to set higher standards. The systems approach described above is commonly implemented by granting a single regulatory agency authority over both vehicle emissions and fuel quality as related to emissions. For example, in the United States the EPA holds authority over both vehicles and fuels under the Clean Air Act. Nationwide requirements for low sulfur diesel fuel are preferable so that vehicles with advanced emission control devices can be operated anywhere within a country. However, in situations where nationwide fuel quality improvement lags, cities or regions may choose to introduce higher quality fuels prior to national requirements. In China, local Environmental Protection Bureau officials in key regions, including Beijing, Shanghai, and Guangdong, have negotiated with local refineries to supply low-sulfur diesel well in advance of the rest of the nation. China's Air Pollution Prevention and Control Law grants them this authority, contingent on approval from the national-level State

Council. In India, according to the recent government's directives, together with 13 megacities the capital city Delhi have joined a premier league of global cities from 1st April 2019 to receive ULSD (max. 50 ppm S) from national oil companies to follow Bharat Stage IV standards while the rest of the country will have Bharat Stage III regulations to combat PM emissions from on diesel engines.

3.2.3 Adopt progressive pricing to encourage cleaner fuels

Appropriate fiscal incentives or subsidies together with mandatory regulations is necessary for refineries to produce higher quality fuel. In many cases, the largest obstacle to the introduction of low- or ultra-low-sulfur diesel fuel is cost. The cost of producing ultra-low-sulfur diesel depends on many factors such as base refinery configuration, local economic conditions, crude slate sulfur levels, and more. However, multiple analyses across a variety of regions have concluded that the cost of producing ultra-low-sulfur diesel is on the order of cents per liter or even less (Hart Energy and MathPro, 2012; ADB, 2008; USEPA, 2000). Still, in countries with fixed fuel prices or large fuel subsidies, this may act as a significant barrier to the introduction of cleaner fuels. International experience suggests refineries require appropriate fiscal incentives or subsidies to justify upgrading capital equipment to refine higher quality fuel. Fiscal policies to encourage the supply of higher-quality fuel—in combination with mandatory regulations—have been used successfully in many places around the world, including Japan, Hong Kong, Germany, the United Kingdom, and the United States. Some examples of fiscal policy precedents to encourage the production and use of low-sulfur fuels are summarized in Table 3.3.

Table 3.3: Examples of fiscal policies used to encourage diesel fuel desulfurization

Policy	Region	Goal	Magnitude	Result
Tax differentials at the pump	Hong Kong	▪ 2000: Accelerate 500 → 50 ppm transition ▪ 2007-2008: Accelerate 50 → 10 ppm transition	▪ 2000: Reduced import duty for 50ppm diesel by Hk$ 0.89/L (USD 0.11/L) ▪ 2007–2008: Concessionary duty on 10 ppm diesel cut in half (to Hk$ 0.56/L (USD 0.07/L)) as compared with 50 ppm	▪ Became the first region to introduce 50 ppm sulfur diesel in Asia ▪ Exclusive availability of 10 ppm sulfur diesel by 2008
	United Kingdom	▪ 1997–1999: Accelerate 200 → 50 ppm transition	▪ 1997–1999: Differential tax of 1~3 pence/L levied (USD 0.016~0.048/L)	▪ Rapid transition to full 50 ppm diesel market in 1999 ▪ Full conversion to 50 ppm six years ahead of most other EU member states
	Germany	▪ 2001–2002: Accelerate 350 → 50 ppm transition ▪ 2003-2004: Accelerate 50 → 10 ppm transition	▪ 2001–2002: 3 pfennigs/L (USD 0.015/L) tax on >50 ppm diesel ▪ 2003–2004: 1.5 pfennigs/L (USD 0.03/L) tax break for ≤10 ppm diesel	▪ Rapid shift to 50 ppm and 10 ppm diesel
Tax Incentive for refineries	Japan (national)	▪ 1990–1997: Accelerate 5,000 → 500 ppm transition	▪ 7% deduction in corporate tax, or a 30% accelerated depreciation on equipment purchase	▪ Nationwide diesel supply desulfurized from 5,000 ppm to 2,000 ppm by 1992, and further to 500 ppm by 1997
	United States	▪ 2003–2009: Accelerate 500 → 15 ppm transition for small refiners	▪ Tax credit of 5 cents per gallon of 15 ppm diesel provided to small refiners	▪ Complete shift to 15 ppm diesel in 2009

Policy	Region	Goal	Magnitude	Result
Direct government subsidy to refiners	Tokyo	▪ 2001–2003: Accelerate 500 → 50 ppm transition ▪ 2003–2005: Accelerate 50 → 10 ppm transition	▪ 10 yen/L (USD 0.13/L) subsidy to refiners	▪ 500 ppm → 50 ppm (2003) → 10 ppm (2005) transition completed 21 months and two years, respectively, ahead of national regulatory schedule

Source: Reproduced from ICCT, 2013, p-26.

3.2.4 Implement an effective compliance program

The introduction of low- and ultra-low-sulfur fuel requires a strong policy framework that includes mandatory standards, regular testing, and strong penalties for non-compliance. In regions where two fuels are supplied in parallel (e.g. on-highway and off-highway diesel fuel in China, India, etc.), a clear system such as color marking may be necessary to prevent misfueling. A system of presumptive liability to maintain consistent fuel quality is a must, as practiced in Japan, when policymakers do not have the ability to check all fuels. An effective compliance program will also help prevent fuel adulteration**. Aftermarket adulteration (for example, the mixing of diesel or gasoline with lower-cost fuels such as naphtha, natural gas liquids, kerosene, waste solvents, byproduct petroleum stream, etc.) can affect vehicles in a variety of ways, including increasing emissions and reducing durability.** One example program of note is in Tokyo. In September 2000, the Tokyo Metropolitan government (TMG) began “Operation No Diesel”, a local campaign to reduce particulate emission from in-use diesel vehicles. Fuel adulteration, which increases fuel sulfur content and therefore impacts the viability of PM retrofits, quickly became an issue. TMG adopted a ban on illicit diesel fuel use by local ordinance and began cracking down on its use through more 11,000 roadside and onsite inspections, worked with 13 other prefectures to identify and eliminate manufacturing bases and distribution pipelines, and engaged end users to voluntarily eliminate fuel use. Of particular use in identifying manufacturing operations was active monitoring of sulfur “pitch,” a hazardous byproduct that is created when chemicals are added to heavy oil and kerosene to remove the fuel marker. Efforts to eliminate illegal fuel mixing met with considerable success in Tokyo. As a result of these efforts, illicit diesel fuel in Tokyo fell from an estimated 14% of the fuel supply in FY 2000 to only 1% in 2002 Similar programs were subsequently adopted by other urban areas in Japan, such as Kobe and Nagoya.

3.2.5 Use captive fleets to create demand for cleaner fuels

Local authorities may consider using public fleets to create early market pull for clean fuels, where national requirements are delayed. In some cases, public fleets may make up a large enough fraction of total diesel use to create enough initial demand to justify the cost of refinery upgrades—for example, diesel fuel purchased for Tokyo metro buses in 2001 and 2002 equaled 8% of local diesel sales (Rutherford, 2006). In East Africa, clean diesel is now a reality for the use of cleaner diesel technology for buses (Smukste, 2015). The Heavy-Duty Diesel Initiative has, since 2013, supported the East Africa Community in its landmark introduction of low sulfur fuels (maximum sulfur content of 50 ppm in diesel). A June 2013 meeting of East African Ministers from Burundi, Kenya, Rwanda, Tanzania and Uganda adopted a regional harmonized low sulfur fuel standard, paving the way for the use of cleaner diesel technology on HDVs. In Tanzania, the whole country went to 50 ppm diesel because of the introduction of a Bus Rapid Transit (BRT) system requiring the fuel in the capital Dar es Salaam. Furthermore, public fleets tend to be centrally fueled, minimizing investments in delivery infrastructure and reducing the risk of misfueling vehicles that can occur when more than one kind of diesel fuel is made available to private fleets at a given station.

3.2.6 Key considerations in designing and operating a diesel retrofit program

It may be easier to administer and control a program by targeting vehicle fleets. Some examples of captive fleets include urban bus fleets, school buses, privately-owned delivery fleets, construction equipment, publicly-owned diesel-powered vehicles, utility fleets, and construction equipment at a given construction site. The advantage of targeting these vehicles is that they are often centrally fueled and are typically maintained in a more controlled fashion. In addition, training of operators and maintenance personnel is more easily achieved.

Diesel engines equipped with retrofit control technologies should receive routine maintenance just as other engines would. Attention must be given to fuel injectors and turbochargers to insure they are operating properly. With particularly dirty engines, periodic cleaning of a DOC or SCR catalyst might be needed. Diesel oxidation and SCR catalysts employing larger cell densities, e.g. 50 to 200 cells per square inch (cpsi), can considerably minimize the risk of plugging and fouling. For engines equipped with DPFs, backpressure should be monitored using monitoring equipment supplied with the DPF. If backpressures become excessively high, the filter should be cleaned according to the procedures specified by the filter supplier (MECA, 2005). Retrofit technologies like closed crankcase filters and low pressure EGR systems have regular maintenance requirements specified by the technology provider. Retrofit systems should be regularly inspected to ensure that exhaust installation hardware remains in good condition. Inspections should include checking for warning lights on the backpressure monitor, inspecting the mounting brackets for looseness or damage, checking for signs of soot on the inside of the exhaust pipe and inspecting backpressure sensor tubing for any signs of condensation. Fleet vehicles are often excellent candidates for retrofit because organizations that operate fleets often have strong preventative maintenance programs in place.

High smoke opacity could be a sign of excessive oil consumption or a bad fuel injector, both of which result in high engine-out PM that may lead to plugging of the filter. Once installed, the importance of proper engine maintenance cannot be overemphasized for the durability and long-term performance of the vehicle and a retrofit filter. Regular maintenance becomes critical once a DPF is installed because the presence of smoke in the exhaust can no longer be used as an indicator of engine operation problems. Once a DPF is installed in the exhaust system, it will capture the PM and mask any signs of high smoke. A recommended regular maintenance practice is to have an opacity-based check of the engine-out exhaust, each time a filter is removed for cleaning.

An opacity test is an inexpensive, simple measurement that should be an integral part of a proactive preventative maintenance program. The SAE standard, J1667, provides a recommended practice for performing an exhaust opacity measurement. Performing an annual, engine-out opacity measurement is a way for fleets to actively monitor the condition of their engines and perform the necessary maintenance to keep their equipment functioning within the engine manufacturers recommended guidelines and minimize the chance of filter plugging. This will have the added co-benefit of better performance and longer engine life.

Finally, the successful operation of an emission retrofit program depends on a number of elements. The program should define:

- Which vehicles are suitable for retrofit?
- What is the appropriate emission control technology for each vehicle?
- Whether the emission reductions that are desired or required?
- What are the fuel quality needs (e.g. percent sulfur, cetane number, etc.)?
- What are the operational and maintenance requirements?
- What are the training needs of vehicle operators and maintenance personnel?

3.3 Real-world performance of buses retrofitted with diesel particle filters

DPF retrofit has led to significant particle emissions reduction, usually above 99% (Mayer, 2008; Tartakovsky *et al.*, 2015). In the effort to mitigate PM emission from the diesel engines several retrofit (after treatment) technologies have been proposed and developed, while the most efficient of them has been shown to be the DPF (Mayer *et al.*, 1998). Due to the relative installation simplicity of this device on in-use vehicles, a massive DPF retrofitting is being performed worldwide, especially in heavy-duty trucks and buses, which can be kept in service for more than 15 years (Boudart and Figliozzi, 2012).

Despite the cleaner exhaust gases, worsening in the fuel economy have been reported when a DPF is used due to the increased backpressure caused by the filter (Alleman *et al.*, 2004; Lapuerta *et al.*, 2012; Lin, 2002; Liu *et al.*, 2011). An increase in fuel consumption due to a DPF retrofit is an important countervailing indirect effect in terms of reducing air pollution and GHGs relative to the positive direct effects of filtering local air pollutants and climate change gases. From the mid-1990s, several studies reported on change in a vehicle fuel economy after DPF retrofitting in real-world usage conditions (LeTavec *et al*., 2002; Richards *et al*., 2003). However, a reliable assessment of the fuel economy penalty in real-world operating conditions caused by DPF added to the engine exhaust system remains to be a challenging task due to a need to separate the effects of vehicle ageing, changes in driving (duration, behavior) and ambient conditions, driving style, driving terrain, etc.

Particle Number (PN) as an additional measurement parameter, especially for the evaluation of ultrafine particle (UPF) fraction is being introduced in vehicles emission legislation. In 1998 the Verification of Emission Reduction Technologies (VERT)[5] has published a list of different DPF technologies that reached 95% PN filtration efficiency in the range from 20 to 500 nm (0.02 to 0.5 µm) (Mayer *et al*., 1998). In 2001, the Particulate Measurement Program (PMP) was formed and resulted in development of the UNECE regulation No. 83 revision 4, which led to the implementation of the first PN legislation by the European Union, the Euro 5B standard, with a limit of particles/km for light-duty diesel vehicles, based on standard cycles (Bischof, 2015). Subsequently, a program for HDDVs was developed. It followed the PMP procedures, and was published in the UNECE Regulation No. 49, introduced in 2011. It established Euro VI emission standards of particles/kWh for the World Harmonized Stationary Cycle (WHSC) and of particles/kWh for the World Harmonized Transient Cycle (WHTC) on engine dynamometer test bed.

Despite the great advance made in regulating vehicle PN emissions, existing legislation is limited to the type approval of new engines and there is no international legislation that controls PN emission levels of in-use vehicles. The only national legislation prescribing PN measurement for periodic inspection of DPF-equipped engines is applied in Switzerland for off-road and construction machinery (Fleischman *et al*., 2018). Bischof (2015) reports that transmission smoke meters and opacimeters also reach their limits and are not suitable for tests of diesel engines meeting Euro V and Euro VI standards. Giechaskiel *et al.* (2014) further confirmed in their comprehensive review that measurement of exhaust gas opacity is not suitable for modern diesel engines because PM emissions are far below the detection limit of conventional smoke meters. In a more recent study of Kadijk *et al.* (2016), total 213 in-use diesel light-duty vehicles with DPF were investigated. The study confirmed the inappropriateness of the smoke

---

[5] VERT Association was founded in 1993 as a non-profit organization under the Swiss law. The VERT Association aims at promoting best available technologies (BAT) for the reduction of emissions from internal combustion engines, with a focus on particulate numbers. For further details visit: https://www.dieselnet.com/vert/.

measurement for roadworthiness tests of vehicles with DPF. PM measurement at low idle regime were performed and found to be beneficial compared to the smoke measurement. In their latest study Kadijk *et al.* (2017) tested 14 light-duty vehicles of Euro 3, 4, 5 and 6 generations with a purpose to propose a new roadworthiness emission test procedure aimed at identifying vehicles with a malfunctioning of removed DPF. The vehicles were tested at low and high idle, as well as at free acceleration regimes. Opacity measurements were performed at the free acceleration and high idle modes. PN measurements were carried out at low idle and chassis dyno (NEDC-New European Driving Cycle) tests. No attempt was made to separate the influence of engine and DPF. No assessment of particulate number filtration efficiency (PNFE) was performed. While most of the authors agree on a need to apply PN measurements in the roadworthiness test, various attempts are still made to develop the improved methods of opacimetry (Kadijk *et al*., 2016; Axmann *et al.*, 2017). For example, Axman et al. (2017) suggested a novel multi-wavelength opacimeter for measurement of both NOx and soot concentrations in the exhaust gas of diesel engines during the periodical inspection tests. Mayer (2014) concluded his presentation with the following key messages in a presentation he delivered at the 18th ETH–Conference on combustion generated nanoparticles held in Zurich in June 2014:

- PM is not sufficient to address health effects
- PM is not sufficient to define Best Available Technology (BAT) emission control
- PM criteria are misleading for filter selection
- PN instrumentation is now available
- PN is indispensable to link emission to air quality
- Air quality must replace or complement PM by PN
- Metrics in emission and AQ must be coherent.

Several wide-scale HDVs retrofit projects were performed worldwide at different engine operating modes (various loads, low idle, high idle, etc.). PM and PN measurements were analyzed over a long period of time under real-world performance of diesel vehicles retrofitted with DPFs in different countries. Summary of key findings in a few countries which are particularly relevant for Iran are highlighted below.

3.3.1 Switzerland

Mayer *et al*. (2004) reported that DPF was technically, operationally and economically feasible in in-use diesel engines under the Swiss diesel engine retrofitting program. In Switzerland, more than 6,000 diesel engines were retrofitted with different particle trap systems from 1998 to 2000. This is in response to the Swiss 1998 Ordinance on Air Pollution Control (OAPC) mandates curtailment of carcinogenic diesel particle emissions at construction sites. Construction machines have much higher PM-emission factors than trucks and are operated more intensely than tractors. Under the Swiss retrofit program, all construction machines were periodically inspected for emissions and functionality. Trap certification was cancelled when more than 5% failure was detected annually. Many traps surpassed 99% filtration efficiency, from the beginning, and secondary emissions were mostly prevented. However, trap failure due to mechanical and thermal damage was initially rather high at about 10%. By the year 2000, the failure rate halved to about 6% and by 2003 yearly failures of about 2%. The work was performed in close collaboration with the regulatory authorities and the trade association AKPF of the trap manufacturers and retrofitters. The experience with this large retrofitted fleet proved the applicability of traps for diesel engines of various design, power range and age for all construction machines - the directive included no exceptions. However, there are several important prerequisites reported, including: comprehensive suitability testing, careful function monitoring and regular field inspection.

3.3.2 United Kingdom

In order to tackle unacceptable air pollution levels in London, the Mayor of London announced on 28 June 2017 an £86.1 million program to retrofit around 5,000 of the capital's bus fleet (over half of the total fleet size) to meet the Euro VI emission standard. DPFs will also be installed alongside Selective Catalytic Reduction (SCR) equipment to reduce city air pollution. The program is due to be completed by September 2020 with Transport for London (TfL) as the nodal agency. TfL is working with bus operators and five companies: Amminex, Baumot Twintech, Eminox, HJS and Proventia to retrofit buses across the capital to fit exhaust systems which are designed to reduce PM and NO_x emissions. More than 40 new apprenticeships have been created to support the program. The apprentices will be employed by the five suppliers and will work across the project in a range of areas, from installation and servicing to management. According to the long-term transport strategy for London, from 2018 all new double-decker buses deployed in the capital will be hybrid, electric or hydrogen. In central London, all double-decker buses will be hybrid by 2019 and all single-deck buses will emit zero exhaust emissions by 2020. By 2037 at latest, all 9,200 buses across London would be zero emission (Air Quality News, 2017).

3.3.3 United States

Among the numerous diesel retrofit demonstration programs taken place in the US in early 2000s, the interest in the DPF based emission control solutions such as the Continuously Regenerating Technology (CRT) have significantly increased. Chatterjee *et al*. (2001) reported the evaluation of CRT filter systems on urban transit buses in NY City. Several NY City transit buses with DDC Series 50 engines were equipped with CRT filters and operated on ultra-low sulfur diesel (< 30 ppm S) in transit service in Manhattan area since February 2000. Emission testing results from this program have shown >90% reduction in PM and CO and > 80% for HC with the CRT system after 12 - 16 months of operation. The on-road operational data demonstrated the filter system to be very durable and near maintenance-free. Under similar test programs in California, CRT systems were successfully evaluated on transit buses and grocery trucks for over 16 months of operation (Chatterjee *et al.*, 2001).

3.3.4 India

In a bilateral initiative involving India and UK in December 1999, The Energy and Resources Institute (TERI) designed and implemented city bus evaluation project in India involving multiple stakeholders (Bose and Sundar, 2005). In this project, eight Euro II compliant buses, using diesel with different levels of sulfur (i.e., maximum 500 ppm, 350 ppm and 50 ppm), and with and without emission control devices (ECDs), and two Euro II compliant CNG buses with three-way catalyst (TWC) were tested in India using Mumbai City Driving Cycle. All 10 buses were tested at ARAI's (Automotive Research Association of India) laboratory in Pune on a chassis dynamometer All the ten buses were tested twice essentially to see whether the ECDs were working satisfactorily; the second test was carried out after running each bus for approximately 40,000 kilometers. This two-year long bus evaluation project was completed in September 2003. The results of the test program on the basis of field trials in Mumbai conducted on eight diesel and two CNG buses supplied by city's bus company, BEST (Brihanmumbai Electric Supply & Transport), came up with the following key findings which provide directions for an auto-fuel policy for India. .

- PM emissions, which are of the utmost concern from the point of view of health, from a CNG bus with a TWC and a ULSD (max 50 ppm S diesel) bus with a CRT are comparable. As for THC and CO, the emissions from a ULSD bus equipped with a CRT are even lower than that from a CNG bus. However, NOx emissions from the diesel bus are higher.
- Progressive reduction of sulfur in diesel from 500 ppm to 350 ppm to 50 ppm and conforming to standards of three different grades of diesel presented could lead to a reduction in PM emissions. However, even the use of diesel with 350 ppm sulfur or diesel with 50 ppm sulfur (or ULSD) by itself did not have PM emissions comparable with CNG

or ULSD with an appropriate ECD. Progressive reduction of sulfur in diesel could, therefore, help to reduce PM but not to the extent of CNG.
- If the sulfur content in diesel is progressively reduced and an appropriate ECD is also used, then the reduction in PM is more significant than with only a reduction in sulfur. The use of an appropriate ECD therefore becomes imperative and must be mandated. Mandating DOCs would result in BS-II standards in India (equivalent to Euro II) diesel buses being supplied as OEM just as CNG buses come with TWC as an OEM and would help to improve air quality.
- The mere use of CNG without a fully-functioning TWC or poorly maintained engine can have emissions which are much above what is expected from a CNG bus, especially for CO and THC. Periodic inspection and maintenance is therefore, of primary importance in bringing down the emissions of regulated pollutants to the optimum level.
- The on-road operational data of diesel buses in Mumbai equipped with RPT over a period of 7–14 months indicated that CRT functioned satisfactorily.

The TERI project has established the feasibility of retrofit devices on HDVs with environmental benefits but have not been followed up for implementation on commercial scale. There are two major obstacles to implementing DPF retrofits in India. First are the fuel sulfur levels. Diesel fuel with maximum 50 ppm sulfur (ideally 15 ppm sulfur or less) is required to achieve reliable passive regeneration. Oxidation of SO_2 competes with oxidation of NO_2 and thus impedes passive regeneration. Oxidation of SO_2 to sulfate also creates sulfate particulate matter composed primarily of sulfuric acid aerosol - a very undesirable result. Even at diesel fuel sulfur levels of only 50 ppm, catalyzed diesel particulate filter (CDPF) systems would oxidize enough SO_2 to sulfate PM to nearly replace the PM emissions originally removed by the system. So virtually sulfur-free fuel should be the first goal. Second, designing retrofit CDPF systems are a greater engineering challenge than engineering the system as part of an overall solution together with the entire powertrain.

Retrofits can be done successfully, but tremendous care must be taken with respect to application engineering. For example, it is particularly important to understand the operational conditions, especially exhaust temperature that a retrofit application will be applied to. For instance, a long-haul truck operating on steep grades with consistent high loads might be a good application. A lightly loaded delivery truck at moderate ambient temperatures and with few grades and only occasional high load operation might be a poor application. Both trucks might even use identical engines.

3.3.5 China

Despite retrofit devices on HDVs provide environmental benefits, China has not followed up their implementation on a commercial scale like in India in the absence of supply of low sulfur diesel. Wu *et al.*, (2017) in their study reports, high sulfur content of China's on-road fuels, for diesel, can be attributed to three factors similar to the experiences in many other oil importing countries in South and Southeast Asia. First, the formulation of national mandatory standards for fuel quality is controlled by the stakeholders of the oil industry, which were reluctant to propose a stringent and mandatory limit (e.g., 350 ppm) of diesel sulfur content before 2010. Further stringent limits on sulfur content of diesel fuels required substantial investments for most existing refineries, such as the hydrodesulfurization and deep hydrodesulfurization technologies to achieve 50 ppm and 10 ppm, respectively. Second, although a sulfur content limit of 350 ppm was formulated by the national mandatory standard of on-road diesel quality in January 2010, the transition period for a nationwide enforcement lasted until July 2011. Later, the transition period of lowering maximum sulfur content from 350 ppm to 50 ppm lasted until the end of 2014. Third, the quality standards for non-road diesel fuels are formulated separately in China. Prior to the national mandatory standard for non-road diesel implemented since July 2013, actual sulfur content of non-road diesel fuels could be up to 2000 ppm. Recognizing the need for a unifying quality standard for on-road and non-road fuels to avoid the issue, in April 2015, the state council gas set a timetable to improve fuel quality by setting sulfur content limits to 50 ppm starting in July 2017, and further to 10 ppm starting in January 2018. In this backdrop, to confirm progressively stringent vehicle emission standards in China, Wu et al., (2017) now expects that DPF will be widely used to reduce $PM_{2.5}$ emissions under China VI standards for diesel trucks in nationwide, while some developed may use DPF for diesel fleets from China V.

3.3.6 Iran

High air pollution in Tehran is of critical concern to authorities in view of public health. Ultrafine particles (UFPs) from internal combustion engines have been identified as the most toxic component of polluting mixture. Regulations on UFPs do not exist for this nanoscale size class of ambient air pollution particles, which are far smaller ($PM_{0.1}$) than the regulated PM_{10} and $PM_{2.5}$ particle classes and are believed to have several more aggressive health implications than those classes of larger particulates. The Iranian government decided to elimination of $PM_{2.5}$ and UFP by retrofitting HDDVs and initiated new emissions legislations for diesel vehicles. Both national and international engine industries and experts are now challenged to comply according to the new upcoming standards. The current type approval limits is the custom-made Euro IV+DPF or EURO V EEV[6] (both have limits on PN).

In January 2014, the City Council of Tehran decided to mandate the retrofit of the public bus fleet of the capital. The mandate pointed out the need of a pilot test followed by a large-scale project. In all 6,000 public buses with almost half diesel buses are affected, while the first step targets 2,000 buses. After this the government plan is to roll out the program to other cities in Iran. The project is organized by the city-owned Air Quality Control Company (AQCC) based in Tehran and supported by the Sharif University of Technology, the Tehran City Bus Company, VERT association, TTM consulting and aurigna consulting. AQCC is the lead contact in Iran to organize this big DPF retrofit project and VERT is to oversee the verification process for which a test engine lab was provided in Tabriz for approval of DPFs in Iran.

With the support of VERT Association, a diesel particulate filter (DPF) retrofit project as a pilot was initiated in Tehran for the public transit bus fleet. A pilot fleet of several buses were retrofitted with VERT certified fuel borne catalysts (FBC)—a DPF technology tolerant of high sulfur fuels that are used in Iran. These retrofitted buses were tested under actual city bus operating conditions in Tehran city. The scope of the VERT-Tehran project comprise all measurements and evaluations as required in diesel engines. The average size and number concentration of the particulates were systematically measured besides the usual engine operating parameters, pollution and PM emissions. Several DPF brands were tested on a Euro II Daimler engine on the engine dynamometer at three levels of sulfur in diesel (<50 ppm, 229 ppm, and >7000 ppm). The key conclusions of the test results are summarized below:

- DPF removed up to 98.3% of the particle counts.
- DPF removed up to 88.7% of the particulate mass
- The efficiency of filter in some operation points is negative, suggesting high condensation effects of S components downstream of the filter.
- DPF system used oxidation catalyst to significantly reduce CO and HC emissions but increased the NO_2/NO_x ratio.

---

[6] Enhanced environmentally friendly vehicle or **EEV** is a term used in the European emission standards for the definition of a "clean vehicle" > 3.5 tonne in the category M 2 and M 3. The standard lies between the levels of Euro V & Euro VI**.**

- For 229 ppm sulfur in diesel, the DPF inlet temperature went up to 280℃ and reached the ‘balance point’ in the passive regeneration cycle.
- The maximum power loss of the engine caused by the back pressure under normal filter conditions was approximately 5 kW.
- A normal silencer has maximum 80mbar backpressure which is about 2.5kW power loss.
- The maximum power loss of the engine is about 2.5kW (about 1% of total power).
- CRT-filter system could only be used for very clean vehicles with <50ppm sulfur (with soot emission lower than 10 mg/m3 – corresponds to Euro IV) running at an average temperature of 280 °C and with guaranteed fuel sulfur < 230 ppm.
- The bus test results conform excellent performance of filter operations in Tehran (mainly CRT) with <50 ppm S diesel or ULSD given ideal pressure and very high temperature data distribution measured under real bus operating conditions.

A two-day workshop was held in Tehran on 15-16 April 2015 to support the implementation of future clean diesel programs in Tehran and other Iranian cities that have some of the highest $PM_{2.5}$ pollution levels in the world. The workshop—organized by the Iran’s Air Quality Control Company (AQCC), Iran Department of Environment (DOE) and by VERT Association—was attended by over 180 participants from Iranian and European engine and vehicle manufacturers (Scania, Isuzu, Iran Kohdro Diesel and Saipa Diesel) and other stakeholders, including Iran Ministry of Industry, Ministry of Oil, Sharif University of Technology, as well as Germany’s TÜV Süd (DieselNet, 2015).

3.3.7 Israel

Fleischman *et al.* (2018), evaluated real-world performance of buses with 9 in-use urban and 9 in-use intercity Euro III compliant buses retrofitted with CRT DPFs. These 18 in-use urban and intercity buses operating in three geographical regions—*Tel Aviv*, *Jerusalem* and *Haifa*—were investigated for a period of 12 months. All the vehicles were produced under the Euro III emission standards and had traveled a distance typical to their age (1.2-1.6 million km for intercity coaches and 450-580 thousand km for urban buses) with DPF retrofit. Every vehicle had an original engine and had been appropriately maintained before and during the experiments by the bus operator. Four different load and non-load engine operating modes were investigated on their appropriateness for roadworthiness tests. The influence of the DPF and of the vehicle natural aging on buses fuel economy revealed the following findings:

- The effect of natural deterioration is about 1.2% to 1.3%.
- The fuel economy penalty is found to be 0.6% to 1.8% depending on the bus type.
- DPF filtration efficiency throughout the study is found to be in average 96% in the size range of 23-560 nm.
- High idle is found to be the most suitable regime for PN diagnostics considering PNFE.

Main results on the one-year program analyzed the impact of DPF retrofitting on PM emissions, engine performance and maintenance aspects of in-use bases. To make the process of retrofitting clear for vehicle owners, a detailed inspection on DPF installation procedure was published by the Israeli Ministry of Transportation. The key findings of the pilot program are summarized below:

- Choice of an appropriate DPF technology is a function of the exhaust gas temperature profile of diesel buses during its real-world operating conditions of intercity and urban buses. The mean measured temperature during engine operation was found to be 258oC. Based on the obtained temperature profiles, three different DPF types were selected in a close cooperation with the VERT-list of Best Available Technology filters.
- The regeneration mechanism used by all three DPF manufacturers is based on the passive regeneration of Continuously Regeneration Trap (CRT) technology developed by

Johnson Matthey (Cooper et al. 1990 and Allansson et al. 2002). The three DPFs from different manufacturers behaved similarly.

- Particulate Number (PN) concentration and size distribution were measured both before and after DPF at different engine operating regimes. Data collected from the measuring equipment included particles with diameters from 5.6 nm up to 560 nm.
- DPFs filtering efficiencies in terms of number (PNFE) were always higher than mass (PMFE). Results from field trials confirm high PNFE of ~97% together with relatively low fuel economy penalty (0.6-1.8%, depending on the bus type). It is important to note that PNFE values higher than 98% were obtained in 2/3 of the total measurement cases.
- Retrofitting the in-use urban and interurban buses of Euro III technologies by the VERT-certified DPF confirmed its high efficiency in reduction of UFP emissions (Tartakovsky et al. 2015).
- Careful monitoring and correct maintenance of DPF-equipped buses are required with an average frequency of filter cleaning as 2-2.5 years in average. The exact need in DPF cleaning is to be determined based on backpressure monitoring results carefully monitored.
- Intercity coaches achieved a better fuel efficiency compared to urban buses. Moreover, drivers did not report on any deterioration in buses drivability.
- The successful pilot also triggered a decision on Low Emission Zones (LEZ) formation in Israel with the first LEZ to be opened in Haifa (the whole city).

Based on the success of the pilot test program, the Israel government decided to invest $6 million (USD) in 2017 to retrofit DPFs in heavy-duty diesel vehicles in Haifa region and in garbage trucks – nationwide (Tartakovsky and Fleischman, 2017; Fleischman et al. 2016).

4. Cost and Benefit Analysis – A Global Review

While the air quality and public health benefits of diesel engine retrofit program for HDVs have been well explored in several studies from around the world, the incremental costs of introducing advanced emission control technologies are less well known. This cost assessment is necessarily indirect because total emission control technology costs are known only to manufacturers, who are understandably unwilling to share this information because of competitiveness concerns. Government agencies may be able to request and obtain specific cost information under confidentiality agreements for regulatory purposes. Usually the regulatory agency hires a consulting company to estimate the cost; the consulting company estimates the technology required and obtains prices from suppliers. Suppliers only know the pricing of their particular components. Beyond that, there are only a few scattered sources of information. It is therefore important to note that while the estimates reflect the best available data, there are limitations inherent in such an assessment.

4.1 Case studies

The benefit-cost analysis from case studies in different geographies carried out at different points of time may not correctly capture the cost effectiveness of a control strategy. Retrofits are best applied toward vehicles with some useful life left in them and for which scrappage is not cost-effective. Retrofits most appropriate to control PM emissions include the installation of DPFs, if ultra-low sulfur diesel (<50 ppm maximum S) fuel is available. Results from a few published case studies in different geographies show the costs for reducing PM emissions through diesel vehicle retrofits are considerable (Voorhees and Uchiyama, 2007; Molina and Molina, 2002; Schrooten, L. et al, 2006; and Cohen *et al*., 2003). Whether the benefits outweigh these costs is therefore an important question to address. Benefits for public health have been calculated and expressed as costs associated with negative externalities. The data presented are based on a selected sampling of projects worldwide carried out at different points of time and therefore may not completely capture the potential cost-benefit relationship of emission control technology and fuel quality standards.

4.1.1 Tokyo

Results of a case study carried out in Tokyo Metropolitan Area (TMA) in the early 2000s show PM pollution control policies is a cost-effective measure to quickly and efficiently reduce PM emissions. The study analyzed the economic costs of environmental policies to control PM emissions from both stationary and mobile sources using the 1998 data and compared to estimates of benefits developed previously (Voorhees and Uchiyama, 2007). The purchasing power parity-adjusted one-year estimates for the costs of PM pollution control and prevention were: (1) $720 million (USD) for stationary source controls, (2) a range of $690 million to $1.1 billion for diesel motor vehicle controls, (3) $4.2 million for governmental employee salaries, (4) $50 million for financial assistance by the government, and (5) a range of $1.5 billion to $1.9 billion of total costs. Overall these cost estimates appear more likely to be over estimates than underestimates due to several conservative assumptions, in particular for mobile source controls. When compared to health and productivity benefits that were estimated in a previous study at $38 billion (Voorhees, 2005), the net benefit-cost ratio was 20:1. All dollar values were converted to yen using a value of 166 yen per dollar of purchasing power parity, then re-converted to dollars using a market exchange rate of 110 yen per dollar. **This case study suggests that Tokyo's PM pollution control policies were economically very effective, and the stricter controls or broader regulatory coverage is justified, including a ban on old diesel vehicles without appropriate after-treatment emission control devices like a DPF.**

4.1.2 Mexico City

In May 2004, a group of Mexican and international experts, chaired by Nobel Laureate Mario Molina, released "Air Quality in México Megacity: An Integrated Assessment" (Molina and Molina, 2002). The report highlighted a three-part plan to achieve clean air in Mexico in the near term:

i. Introduce ultra-low-sulfur fuels, which are required both for new, clean cars, buses and trucks, and also for the retrofit technology that can be used on existing vehicles.
ii. Tighten the tailpipe emissions standards for new cars, trucks and buses sold in Mexico, bringing them up to world-class standards.
iii. Launch a program to retire, replace or retrofit existing heavy-duty vehicles, mainly trucks and buses.

The report estimated the net benefits throughout the country would range from $8 - 11 billion USD annually, once clean fuels and vehicles are fully introduced. The benefits were highest in Mexico City, where the reduction in fine particle concentrations would be almost 30 percent. This level of improvement in air quality was calculated to result in roughly 4,000 fewer premature deaths per year, as well as greatly reduced incidence of illness and fewer lost workdays. The monetary value of these benefits, using values developed specifically for Mexico ranged from $3 - 5 billion USD annually, in Mexico City alone.

A Benefit-Cost analysis study of retrofitting diesel a total of 1,000 vehicles with catalyzed DPFs in the Mexico City Metropolitan Area, resulted in the following either type of diesel particulate filter or an oxidation catalyst is expected to provide net benefits to society (Gretchen, Wilson and Hammitt 2005). Median estimates of costs, benefits, and net benefits are presented numerically in the Table 4.1.

Table 4.1: Median Costs & Benefits of Technologies, in 2010 (Million US$/1,000 Vehicles Retrofit)

Vehicle Type	**Older Vehicles**				**Newer Vehicles**		
	Benefits	**Costs**	**Net Benefits**		**Benefits**	**Costs**	**Net Benefits**
Catalyzed DPF							
Bus					2.0	0.3	1.7
Truck					1.4	0.2	1.1
Tractor Trailer					0.8	0.4	0.4
Active Regeneration DPF							
Bus	8.9	0.8	8.1		2.0	0.6	1.4
Truck	3.0	0.6	2.5		1.4	0.4	1.0
Tractor Trailer	2.9	0.9	1.9		0.8	0.7	0.1
Diesel Oxidation Catalyst (DOC)							
Bus	2.6	0.1	2.6		0.7	0.1	0.7
Truck	1.0	0.1	0.9		0.5	0.1	0.4
Tractor Trailer	0.8	0.1	0.7		0.2	0.1	0.1

Note: “Newer Vehicles” are model-year 1994 and newer, and “Older Vehicles” are model-year 1993 and older. Values may not sum because of rounding.

Source: Gretchen, Wilson and Hammitt 2005; p-891.

Although the results in the Table 4.1 shows slightly greater net benefits for catalyzed rather than actively regenerating filters, the relatively large uncertainty for each of the estimates suggests the best choice among the two options would be made by the fleet manager or agency performing the retrofit, which will have access to precise price information and can account for situation-specific operation and maintenance concerns.

The net benefits of retrofit vary by vehicle type due to three influences, in order of importance: the activity location, the emissions rate, and the annual activity level. The benefits of emission control per kilometer traveled are greater inside the Mexico City area than outside because population density is higher, and therefore the intake fraction is greater. This is why benefits of retrofitting buses or trucks are greater than benefits of retrofitting tractor trailers, which travel outside of the city. A higher baseline emission rate, as found in older vehicles, results in higher benefits per kilometer traveled, at similar total costs. Finally, those vehicles that travel a greater distance per year have higher net benefits. In new vehicles, capital costs are annualized over the time it takes for the vehicle to travel 600,000 kilometers. The device is annualized over fewer years in vehicles that travel a greater distance per year, which leads to lower annualized costs per kilometer, and thus lower annualized costs per unit of benefit. In older vehicles, capital costs are annualized over the time until the vehicle retires. Vehicles with greater annual activity levels travel further before retirement, and therefore the device provides greater benefits at the same cost. In our model, tractor trailers have the highest annual activity level, followed by buses and trucks. Therefore, **benefits are greatest for old buses because these vehicles’ emissions are more likely to result in population exposure than tractor trailers, their emission rate is higher than that of new buses, and they have a greater annual activity level than trucks** (see Table 4.1).

While at current (2000) prices, retrofit with a DOC provides greatest net benefits. However, as capital costs decrease, retrofit with DPFs is expected to provide greater net benefits. In both scenarios, retrofit of older, dirtier vehicles that circulate only within the city provides greatest benefits, and retrofit with oxidation catalysts provides greater health benefits per dollar spent than retrofit with particulate filters. **Uncertainty about the magnitude of net benefits of a retrofit program is significant.** Results are most sensitive to values used to calculate benefits, such as the concentration-response coefficient, intake fraction (a measure of exposure), and the monetary value of health benefits.

Recognizing Mexico City air pollution as a major environmental and social concern, the Mexican government started developing and implementing comprehensive air quality management programs in the 1990s that combined regulatory actions with technological change. Specific actions included the removal of lead from gasoline, implementation of catalytic converters in automobiles, reduction of sulfur content in diesel fuel, closure of an oil refinery, substitution of fuel oil in industry and power plants with natural gas, reformulation of liquefied petroleum gas for cooking and heating, reinforcement of vehicle inspection and maintenance program, and implementation of “no driving day (Hoy No Circula)” rule. Such a comprehensive integrated air pollution control strategy resulted in decreasing ambient air quality concentrations of criteria pollutants over the past decade.

4.1.3 Flanders

In a case study of Flanders, a region of Belgium, a pre-defined set of measures to reduce PM emissions from traffic were analyzed with respect to their costs and benefits (Schrooten, L. et al, 2006), The main purpose of the study was to inform policy makers how great the extra reduction of PM emissions in 2010 could be compared to the baseline scenario, and whether there was a net benefit to society. The study demonstrated that accelerated policies beyond the steady improvement of technologies and the fleet turnover are not always justified by assumptions about health benefits. First, the PM emissions from road traffic in Flanders were calculated without taking any extra reduction measures using the mobility data for the year 2000 and estimated traffic flows for the year 2010 of the Mobility Plan for the Flemish Region to establish a baseline scenario. Thereafter, a range of options presented in Table 4.2 were explored to increase attempts to reduce PM exhaust emission from traffic in 2010. The marginal cost curve tool was used to make a cost-effective selection between different PM reduction measures. The tool helped in taking an informed decision on at what cost an additional emission reduction can be realized.

Table 4.2 presents marginal costs (at a discount rate of 5%) and reduction potential for the different emission reduction measures. The marginal external costs per ton of $PM_{2.5}$ were computed taking into consideration the geographical distribution of different vehicle categories presented in the table. With local buses primarily in urban areas and heavy-duty trucks for the greater part on highways for example, this generates a location-weighted external cost per vehicle category. However, the marginal benefits were taken to be the same on a per ton basis for the same vehicle categories, irrespective of their Euro norm class, because similar vehicle categories have the same geographical distribution of mileage.

Table 4.2: Marginal costs and benefits for the different reduction measures, ranked accordingly

Measure	Vehicle Category	Euro Standard	Reduction Potential (ton)	Marginal Cost (€/kg)	Marginal Benefit (€/kg)	Cost-Benefit ratio
Replace diesel by gasoline	Passenger cars	Euro 3	46	46.5	205	0.23
+Install particle filter	Heavy duty trucks	Euro 1	+11	74.5	140	0.53
+Install particle filter	Heavy duty trucks	Euro 2	+25	125	140	0.88
+Install particle filter	Heavy duty trucks	Euro 3	+63	161	140	1.14

Measure	**Vehicle Category**	**Euro Standard**	**Reduction Potential (ton)**	**Marginal Cost (€/kg)**	**Marginal Benefit (€/kg)**	**Cost-Benefit ratio**
+Install particle filter	Local buses	Euro 3	+1	270	406	0.66
+Install particle filter	Travel buses	Euro 2	+0.3	513	187	2.80
+Install particle filter	Travel buses	Euro 3	+1	602	187	3.20
+Replace diesel by hybrids	Passenger cars	Euro 4	+55	644	205	3.10
+Replace diesel by gasoline	Passenger cars	Euro 4	+75	690	205	3.40
+Replace diesel by hybrids	Vans	Euro 4	+6	721	203	3.60
+Introduce biodiesel	All categories	All	+36	1936	192	10.1
Total			320			

Source: Schrooten, L. et al, 2005; page 908

Both costs and benefits are expressed on an annual basis. For costs, a total discounted cost divided by the lifetime expectancy of the vehicle. For benefits, only impacts in that year are considered. For acute health effects, this is straightforward; for health effects from chronic exposure, the authors of the study used ExternE approach where the reduction of particulate air pollution in a given year is transformed into a few life-years saved in a population (Friedrich and Bickel, 2001).

The cost-benefit ratios presented in the table 4.2 show it is more efficient to equip heavy-duty trucks with a particular filter, starting with Euro 1 heavy duty trucks, before placing particle filters on newer heavy-duty trucks or buses. **Retrofitting older vehicles is more cost effective than newer vehicles because of the higher reduction potential for older vehicles, while annual costs remain approximately the same for new and old vehicles.** For a similar reason, retrofitting buses is less efficient than retrofitting heavy-duty trucks. Buses travel fewer kilometers per year than heavy vehicle trucks; their reduction potential is therefore less, while the annual costs stay approximately the same. This is even more pronounced for travel buses because they drive for even fewer kilometers per year than local buses. To conclude, the study demonstrates that only an enhanced effort to retrofit trucks & buses with particle filters has a net benefit.

4.1.4 Istanbul

Diesel buses were found to be the most economical followed by CNG and then electric. An economic analysis based on actual field data is carried out to determine total cost of ownership (TCO) from well-to-wheel for three groups of transportation, namely, diesel, CNG and electric buses for the public transport in Istanbul city (Topal and Nakir, 2018). The data source used in the study is created by conducting actual field performance tests for diesel, CNG and electric buses under real Istanbul road, time, and trip conditions. The data was collected for 250 buses spread over 300 days and 82% operation efficiency within one year. The pay back value for the diesel bus is calculated as 2.84 years, CNG bus 3.90 years, and electric bus 5.66 years. With 8% discount rate; TCO calculated as €384,187.61 (diesel bus), €378,505.92 (CNG bus) and €404,307.44 (electric bus); and a 10-year time period: the net present value (NPV) of diesel bus is €52,311,540.54, for CNG € 40,129,447.52 and for electric bus € 19,171,212.50. The model results produced same ranking when calculations are repeated for the discount rate of 12%, 14%

and 16%. Under variable cost conditions, the internal rate of return value for the diesel bus is found to be 23.20%, CNG 22.97% and for electric bus 12.95%.

4.1.5 United States

Many public transit agencies have begun to adopt alternative propulsion technologies to reduce urban transit bus emissions associated with conventional diesel (CD) engines. **Among the most popular alternatives are emission-controlled diesel (ECD) buses with continuously regenerating diesel particle filters burning low-sulfur diesel (and not ultra-low sulfur) diesel, and buses burning compressed natural gas (CNG).** Cohen et al. (2003), based on a series of simplifying assumptions arrived at first-order estimates for the incremental cost-effectiveness (CE) of ECD and CNG relative to CD. The CE ratio numerator reflects acquisition and operating costs. The denominator reflects health losses (mortality and morbidity) due to PM and ozone exposure, measured as quality adjusted life years (QALs). Both ECD and CNG substantially decrease total PM emissions; only CNG decreases NO_x emissions. Findings of the study presented in table 4.3 show **CNG provides larger health benefits than does ECD (nine versus six QALYs annually per 1000 buses) but that ECD is more cost-effective than CNG ($270,000 per QALY for ECD versus $1.7 million to $2.4 million for CNG) and their estimates are subject to much uncertainty)**.

Table 4.3: Parameter Contribution to Cost-Effectiveness Ratios

Description	**Univariate impact of parameter on CE Value**	
	ECD	**CNG**
Emissions from vehicle operations (g/mile)		
CD PM	3.9	2.6
CD NO_x	1.5	1.4
CD SO_2	1.0	1.0
ECD PM	1.4	
ECD NO_x	1.4	
ECDSO_2	1.0	
CNG PM		1.2
CNG NO_x		1.5
CNG SO_2		1.0
QALYs lost per year per million people exposed per µg/m^3 of pollutant		
PM (all-cause mortality)	12.4	5.3
Diesel PM (cancer)	1.2	1.3
CNG PM (cancer)		1.0
Ozone (mortality	1.0	1.1
Ozone (asthma)	1.0	1.0
Intake fraction values		
Inhaled PM from near-source PM emissions	1.5	1.3
Inhaled PM from far-source PM emissions	4.0	3.6
Inhaled PM from NO_x emissions	1.0	1.9
Inhaled PM from SO_2 emissions	1.1	1.0
Inhaled ozone from NO_x emissions	1.0	1.5

Source: Reproduced from Cohen et al. 2003; p-1482**.**

4.2 Costs of technology adoption to meet recent HDV emissions regulation

In addition to having the greatest impact on health, the increasingly stringent limits for PM and NO_x are the key drivers of technology adoption conforming progressively stringent emission regulations for HDVs. The costs assessed include both the in-cylinder technologies to control engine-out emissions and the aftertreatment technologies that act on the exhaust stream. Engine-out emissions are reduced by adjusting the temperature and air/fuel balance within the engine, using improvements to fuel injection and air handling and employing exhaust gas recirculation. Aftertreatment systems include selective SCR systems with ammonia as the reducing agent to control NO_x and DOCs and DPFs to control PM.

ICCT (2016) presented in its ‘White Paper’ cost analysis of different technologies to meet recent standards in the European Union (Euro III, Euro IV, Euro V, and Euro VI) and in the United States (US 1998, US 2004, US 2007, and US 2010). The analysis treated Euro II and US 1994 standards, the first in which 500 ppm sulfur diesel was required in each region, as the baseline for technology determination and cost estimation. In the final regulatory stage considered, Euro VI and US 2010, the two regions were well aligned in fuel sulfur levels, emissions limits, and technology pathways. In addition to the United States and Europe, Canada, Japan, South Korea, and Turkey have all begun implementing equivalent standards. Equivalent standards have been proposed or timelines published for Mexico, India, and Beijing, China, which has typically adopted emission standards ahead of the national standards.

While manufacturers occasionally differ in the layout and suite of technologies used, ICCT focused on the prevailing compliance strategy for each regulatory step and considered the costs of technologies that were or are in widespread commercial use. New systems, either under development or recently brought to market, were likely to further reduce costs, as well as offer other potential benefits such as increased durability or greater ease of operation. At the same time, this analysis did not incorporate discounts for process learning or volume sales; thus, cost estimates presented were considered as conservative. The incremental costs of the prevailing technology to meet recent stages of European and U.S. standards are shown in Table 4.4.

Table 4.4: Incremental costs of emission control under U.S and European regulatory standards

	12-liter diesel engine				
	Euro III	**Euro IV**	**Euro V**	**Euro VI**	**Total**
European standards	$426	$3,771	$460	$2,280	$6,937
	US 1998	**US 2004**	**US 2007**	**US 2010**	**Total**
U.S. standards	$50	$1,421	$1,650	$3,816	$6,937

Source: Reproduced from ICCT, 2016; p-v.

While the incremental costs of individual regulatory steps differ, the cumulative costs for compliance with Euro VI or US 2010 (compared to Euro II or US 1994) are the same: $6,937 (in inflation-adjusted 2015 dollars). **As the 2015 fleet average U.S. truck manufacturer suggested retail price was $157,000, the incremental costs of regulatory improvements over the past two decades add up to slightly over 4% of the average price to the consumer.** The strong benefits of full implementation of Euro VI and US 2010 standards, along with some of the downsides and high costs of the interim standards, suggest that other regions should move as quickly as possible to harmonize with these world-class standards.

5. Costs and benefits of Diesel Retrofit Solutions for the City Bus fleet in Tehran

5.1 Sources of mobile PM emissions

The largest share of PM emissions, roughly 70 percent, originates from mobile sources in Tehran (Shahbazi *et al.* 2016). The remainder stems from non-traffic related emissions: 20 percent from energy consumption (including refineries and power plants), 7 percent from industries, 2 percent from household and commercial sources, and 1 percent from gas terminals. Because of their sizeable contribution to PM, this section exclusively focus on mobiles sources.

There are about 4.24 million vehicles in Tehran. Cars are the largest vehicle type, with a total fleet of 3.37 million, or 80 percent of all vehicles. Of all cars, 90 percent are passenger cars, 8 percent are pick-ups, and only 2 percent are taxis (Hosseini and Shahbazi, 2016). The second largest category, in terms of sheer numbers, are motorcycles, amounting to a total of 0.76 million, or 18 percent of total vehicles. The smallest category is HDVs (including both heavy and medium-duty vehicles), which account for a total of 0.1 million vehicles, or about 2 percent of total vehicles in the streets of Tehran.

Even though cars are the most abundant and the most congestion-causing vehicle type on the streets of the capital, they only contribute about 3 percent of the city's mobile PM pollution. Similarly, despite motorcycles being the most pollution intensive vehicle per passenger, they only contribute to about 12 percent of the total mobile PM emissions. In turn, HDVs contribute about 85 percent to mobile PM emissions (Shahbazi *et al*., 2016). Amongst HDVs, private sector buses (35 percent), followed by Tehran municipal buses (28 percent), and trucks (28 percent), contribute the largest shares to the pollution load (85 percent). HDVs mostly run on diesel, which has a much higher PM emissions factor than petroleum or natural gas (see Figure 5.1).

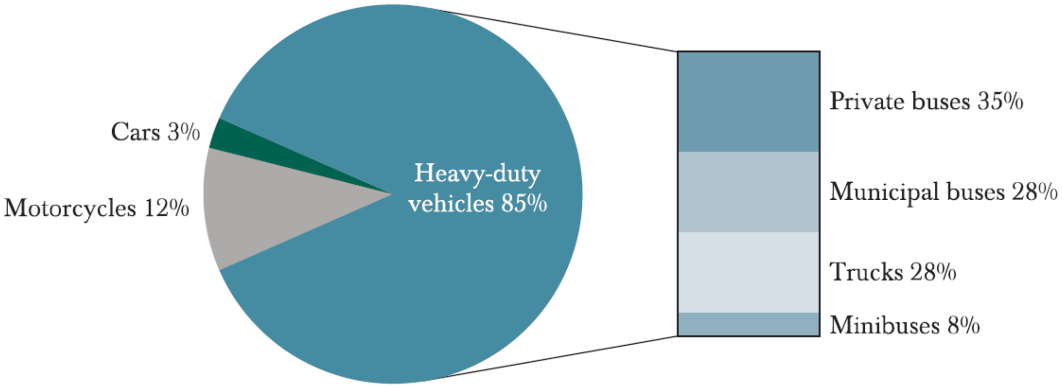

Figure 5.1. Share of PM emissions from mobile sources in Tehran

Source: Shahbazi et al. 2016.

The age of HDVs is the main determinant in its contribution to PM air pollution. On average, 30 percent of heavy-duty vehicles are more than 20 years old, with almost 60 percent of minibuses being more than 20 years old.

Concerned with the increasing levels of air pollution caused by mobile sources, Iran introduced Euro I standards in 2003, Euro II standards in 2005, and Euro IV standards in 2014. Even though Euro IV was introduced, the HDV fleet in Tehran is still largely meeting Euro III standards or less. In fact, most vehicles only meet the Euro I standard. At Euro III standard and lower, there is no requirement for after-treatment technology in the exhaust. As such, all of Tehran's HDV diesel fleet consists of vehicle that have received no after-treatment technologies such as diesel particulate filters (DPF), selective catalytic reduction (SCR), and diesel oxidation catalyst (DOC).

In 2015, the Iranian government increased the emission standards for heavy-duty diesel vehicles to Euro IV, including the use of DPF technology. Euro IV requires engines to use ultra-low sulfur diesel (ULSD) containing less than 50 ppm of sulfur, which is not widely available in the country.

Reducing air pollution from thousands of ageing diesel vehicles in Tehran, especially from ageing heavy-duty city diesel buses, could produce significant health benefits. According to the latest update of emission inventory in Shahbazi *et al.* (2019), the share of PM emissions account for 21% from municipality buses.[7] Considering the share of mobile sources to total PM emissions is roughly 70% (Shahbazi *et al.,* 2016) and that of municipality buses alone contributing roughly 21 percent of PM emissions (Shabazi *et al.* 2019), the contribution of Tehran city bus fleet (for public transit) to total PM is estimated at 14% (=0.70 x 0.21).

Recognizing the importance of carrying out a cost effectiveness analysis of retrofitting Tehran city bus fleet for public transit and the avoided PM emission control costs, the following sections provide an estimate of: (a) economic costs of PM abatement through retrofitting Tehran city diesel bus fleet; (b) total investment required over seven years for rolling out a diesel bus retrofit program in the city bus fleet; (c) the total reduction in PM loading over seven years and the monetary value associated with avoiding PM emissions; and (d) monetary value of avoided PM emissions from mobile sources or the avoided cost for controlling PM pollution from diesel public transit buses.

5.2 Cleanup costs of city diesel fleet through diesel retrofits

Tehran has experimented with DPF retrofitting pilot projects extensively on its city buses. However, there has been no widespread adoption due to a budget deficit and sharp increases of prices. Although based on a statute passed by the cabinet in 2018, the DPF has been made mandatory so all in-use diesel vehicles in 8 metropolises of Iran must be equipped with the filters and new models should already have the filter (Tehran Times, 2018). Given the availability of bus test data on both the applicability to the current fleet and the challenges to implementation combined, a careful cost analysis could push a wider-scale adoption of a diesel bus retrofit program.

Retrofitting city buses powered by diesel engines will allow significant and immediate emission reductions that would not otherwise be addressed as the results of the field trials suggest (see section 3.3.6). Based on a series of simplifying assumptions, a first-order estimate is presented here to understand the incremental cost of retrofitting DPFs in all 4,577 city diesel public transit buses. An attempt is made to estimate the PM abatement cost and impact on fuel consumption and PM emissions. The purpose of this economic analysis is to evaluate the cost effectiveness of retrofitting existing city diesel buses to reduce PM emissions.

In general, two types of costs are accounted for in cost-effectiveness analysis, capital and operation and maintenance (O&M) costs. It is important to note that since most of these costs are predictive, they could vary significantly depending on the state of the economy, demand, competition, and unknown factors. The costs of retrofit technology typically decline over time. Several sources of information are available on the price of retrofit technologies which ranges from CDPF prices of $3,000 to $7,500 depending on size, expected product sales volumes, and configuration (i.e., in-line or muffler replacement) (EPA, 2006). Similarly, these sources suggest DOCs will range in price from $425 to $1,750 depending on size, sales volume and configuration. While these ranges are reflective of 2005 prices of PM retrofit technologies applied on HDDVs of different categories (including trucks and school buses in the United States), future retrofit costs are likely to drop substantially as a result of the most recent new HDDV emission standards (European or United States).

The Mechanical Engineering Department at the Sharif University of Technology, Iran closely working with the Tehran Air Quality Control Company (AQCC) supplied the following sets of information for cost analysis, and table 5.1 summarizes the data collected and key assumptions.

---

[7] Municipality buses are operating for public transit in city bus lines; private sector and municipality owned.

- Most recent city bus fleet operational data by the public and private sectors (i.e. number of operating diesel buses, average daily utilization and fuel economy).
- Average PM mass emission factors of buses with and without retrofits based on results of the field trials with VERT's certified BATs under real city driving conditions.
- Types of VERT certified BATs the city is considering for bus retrofit and the annual consumption of diesel fuel.
- Capital and installation cost of each type of retrofit device if purchased in bulk for all 4,577 diesel buses to get the least unit cost of each type of equipment.
- Annual operation and maintenance cost of each equipment.
- Iranian Rial (IRR) exchange rate in US dollars (USD) as on 15 April 2019.

Table 5.1: Operational and cost data for the city bus fleet in Tehran (2018)

Description	Unit	Value	Notes
Total buses in operation	number	6,538	Total number of buses reduced from 7,390 in year 2007 to 6,538 in 2018 due to economic sanctions and scrappage of old buses
▪ Government owned and operated	number	3,923	
▪ Privately owned and operated	number	2,615	
Total diesel buses in operation	number	4,577	70% of the total buses are diesel and 30% CNG
▪ Government owned and operated	number	2,746	
▪ Privately owned and operated	number	1,831	
Average daily utilization of a bus			
▪ Government owned and operated	kmpd	160	Taking into account real city driving condition
▪ Privately owned and operated	kmpd	200	
Total supply of low sulfur diesel in bus depots	10^6 ton	84	Only for city buses operated by the United Bus Company of Tehran (UBCT)
Selling price of diesel for city buses	IRR/l	3,500	-
Average fuel economy of a typical bus (w/o retrofit)			
▪ Government owned and operated	kmpl	1.5	-
▪ Privately owned and operated	kmpl	2.0	
Average PM emission factor of a typical bus			
▪ Without retrofit	g/km	2016	▪ 99% filter efficiency ▪ Based on engine tests' results and DPF manufacturer's data
▪ With BAT retrofits	g/km	20	
Capital & installation cost to retrofit a bus			
▪ Catalyzed Diesel Particulate Filter (CDPF) or Catalyzed Continuously Regenerating Trap (CCRT)	10^6 IRR/bus	547.60	Bulk purchase price of converting the entire diesel bus fleet of 4,577 buses
▪ Metal Continuously Regenerating Trap (CRT)	10^6 IRR/bus	821.40	
▪ Active Diesel Particulate Filter (DPF)+Fuel Borne Catalysts (FBC)	10^6 IRR/bus	752.95	
Operational & maintenance cost of a retrofit bus			
▪ CDPF or CCRT	10^6 IRR/bus	20.00	Periodicity of cleaning filters as per manufacturer's specifications
▪ Metal CRT	10^6 IRR/bus	10.00	
▪ Active DPF+FBC	10^6 IRR/bus	94.00	
Local currency conversion rate	IRR/USD	136,900	As on 15 April 2019

Source: Based on personal communication with researchers at the Sharif University of Technology, Iran.

The DPF market is highly competitive with many suppliers in the global market with a limited number of well-established vendors. DPF has not been produced locally in Iran yet. Following recent legislation, a few companies have started working on DPF prototype manufacturing and a few Iranian filters are under test. Normally, the core is imported from China and the canning and electronics are done in Iran. Major manufacturers that can export to Iran in Europe (Switzerland and Germany), and South Korea.

A brief summary of each of the three diesel retrofit technologies considered for Tehran is given below as per the information contained in DieselNet website (https://www.dieselnet.com/):

- CDPF or CCRT: In this filter, a catalyst is applied onto the filter media to promote chemical reactions between components of the gas phase and the soot (carbon) collected in the filter. The main purpose of the filter is to facilitate passive regeneration of the filter by enabling the oxidation of diesel particulate matter under exhaust temperatures experienced during regular operation of the engine/vehicle, typically in the range 300-400^{o}C range. In the absence of the catalyst, particulates can be oxidized at appreciable rates only at temperatures around 550-650^{o}C, which can occur at full load conditions in the diesel engine and in most cases are rarely seen during real-life operation. For further details visit: https://www.dieselnet.com/tech/dpf_cat.php/.
- CRT: In this filter, a two-stage passive diesel particulate filter system is used, where an un-catalyzed filter is regenerated using nitrogen dioxide (NO_2) generated over an oxidation catalyst positioned upstream of the filter. By using NO_2 to oxidize diesel soot, filters can be regenerated at relatively low exhaust temperatures. The CRT requires ultra-low sulfur diesel and a certain minimum NOx/PM ratio for proper operation and is capable of regenerating at temperatures as low as 250-300°C. For further details visit: https://www.dieselnet.com/tech/dpf_crt.php.
- FBC: In this filter, both passive and active diesel filter systems can be used to enhance filter regeneration. The catalysts act to lower the soot combustion temperature, thus making regeneration possible over a wider range of the engine operating range, and due to the intimate mixing of the catalyst and the soot can lead to a more rapid and complete regeneration. The most common FBCs include compounds of iron, cerium, or platinum, either singularly or in combination. For further details visit: https://www.dieselnet.com/tech/dpf_fbc.php.

Due to the highly competitive DPF market with only a few established vendors, it becomes important that selected filter devices are properly certified to avoid the risk of using cheaper counterfeits that do not produce the desirable results.

In accordance with vehicle Inspection/Maintenance (I/M) program of Iranian fleet, there is a national system in place in which for all heavy duty diesel commercial vehicles annual inspection for emission and safety is required. Based on the legislation, the heavy duty diesel vehicle inspection centers are operating under the Ministry of Road and Transportation, but the data is collected in the central database of SIMFA under the Ministry of Interior to be unified with light duty database.

The current limit value of emission for all heavy duty diesel vehicle is K<2 a/m which is obtained by commercial opacity meters. Such a value is only good for diesel vehicles without any exhaust after-treatment device. For vehicles equipped with DPF and/or any other aftertreatment device in the exhaust system, a new limit value must be used. The current emission limit value for such vehicle is K<0.2 1/m which is in effect since April 2019. The effectiveness of the new limit value for DPF-equipped vehicles is yet to be determined by collecting data from I/M program of heavy duty commercial diesel vehicles.

5.2.1 Estimation method

To measure control costs in USD per ton of PM emissions reduced from retrofitting the entire city diesel bus fleet in Tehran, the difference in cost and emissions between a proposed control measure and an uncontrolled (baseline) case is considered. In other words, the average cost of PM abatement through appropriate DPF retrofit is obtained by dividing the present value (PV) of the control costs with the PM emission reduced (ER) over equipment life using a phased implementation approach.

The discounted cash flow (DCF) method is used to calculate the PV of the emission control costs over the life of DPF. PV is calculated by adding the capital cost to the present value of all annual costs and other periodic costs over the life of emission control equipment considered in this analysis. The DCF method is used by the South Coast Air Quality Management District (SCAQMD), California to measure cost effectiveness measured in terms of control costs (dollars) per air emissions reduced (tons) (SCAQMD, 2019).

Mathematically,

$$PV = C + A * PVF \qquad \text{........ (1)}$$

where,
PVF = $(1-1/(1+r)^n) / r)$
n = Equipment or DPF Life (years)
r = Annual rate of Interest (%)
C = Capital cost
A = Annual operating costs

Estimating the annual emissions reduction (ER) is simple and can be viewed as the difference of the product of the annual vehicle kilometers traveled (VKT) with the baseline emission rate (EF_{bl}) of vehicle without a retrofit and with the emission rate of retrofitted vehicle (EF_{ct}) expressed in gm/km.

Mathematically,

$$ER = VKT * (EF_{bl} - EF_{ct}) \qquad \text{........ (2)}$$

where,
VKT = N * U
N = Total number of diesel buses in the city fleet
U = Average effective utilization of one bus in a year (km/yr)

In practice, the estimation of ER is more complicated since we must account for vehicle scrappage, variations in VKT as the vehicle ages, remaining years of vehicle life, type of vehicle emission class, and the relative value of emission reductions realized in the current year versus a future time. Furthermore, estimates of the lifetime emission reductions for retrofit technologies must address the age of the vehicle when the retrofit is installed (i.e., retrofitting a one year old vehicle would be expected to result in a larger emission reduction compared to a ten year old vehicle).

In the absence of such detailed bus inventory for Tehran, following simple assumptions are made to derive the results using the two equations (1) and (2).

- Three types of VERT certified DPFs are considered namely, CDPF or CCRT; Metal CRT; and Active DPF+FBC.
- Real annual interest rate of 4% adopted from the Best Available Control Technology (BACT) Guidelines used in South Coast Air Quality Management Plan in California (SCAQMD, 2019).
- Minimum warranty period seven years for each type of DPF.
- It would take a total of 7 years starting from 2019 to retrofit all 4,577 city diesel buses with the selected DPF's.
- The penetration level of DPF retrofit over seven years would be: 10% (2019); 20% (2020); 30% (2021); 45% (2022); 60% (2023); 75% (2024) and 100% (2025).
- Filter efficiency of 99% irrespective of the type of BAT installed in a diesel bus.
- Fuel economy to drop by 1% after retrofit.

The cost-effectiveness analysis presented below considers deployment of each DPF technology in a phased manner during the period of 7 years (2019-2025). It assumes that the technology once installed in a bus does not have to be replaced or even updated. That also means the DPFs will have the same lifetime as the retrofitted old diesel buses.

5.2.2 Estimated costs of PM reduction through retrofit

Table 5.2 gives the PV of annual average cost of implementing the DPF retrofit program in Tehran under three alternative choices of emission control technologies to reduce PM emissions from city diesel bus fleet over 7 years (2019 to 2025). The annual PM abatement cost is determined by dividing the total PV of the control cost of a retrofit technology by the associated total ER.

The annual PM abatement cost from a city diesel bus retrofit program with BAT, ranges between USD 46 and USD 91 per ton of PM depending upon the type of DPF selected (Table 5.2). The actual cost of implementation will depend on the type of BAT the city government decides to choose in cleaning up its existing operational bus fleet on road (4,577 buses in 2018) with diesel retrofit solutions.

Table 5.2 also gives the total investment required for retrofitting all 4,577 diesel buses in a phased manner over a period of 7 years starting 2019. **The present value of the total investment cost of cleaning up the entire city diesel bus fleet is estimated at USD 22.32 million for buses retrofitted with CDPF or CCRT. For the other retrofit technologies, the cost will be higher: USD29.47 million for metal CRT and USD 44.05 million for active DPF+FBC.** The total cumulative PM emissions loading that can be avoided through bus retrofit over seven years (i.e., from 2019 to 2025) is estimated to be 1.64 million tons (Table 5.2). Total emissions loading remains same for each equipment considering very high filtration efficiency (99%) assumed in each case.

It is important to note that the costs accounted for in the analysis do not include administrative costs. Under general practice, transit agencies must already make annual reports, and the reporting required and thus not accounted for. Similarly, reporting and additional administrative costs are not expected to result in any significant cost to transit agencies – government or private. The cost of maintenance training is also not included in the analysis. Again, the general practice is the ECD manufacturers would provide maintenance training at no additional charge.

Table 5.2: Present value of annual average cost of PM reduction: 2019-2025

Year	No. of DPF buses	Capital & Installation Cost per /bus	O&M cost/ bus	Present Value Formula	Present Value of total annual investment cost	Diesel PM reduction	Cost per ton PM reduced annually
	N	C	A	PVF[#]	PV[##]		
	(number)	(USD)	(USD)		(USD)[###]	(t/yr)	(USD/t)
I. CDPF or CCRT retrofit							
2019	458	4,000	146	6.00	2,233,345	48,232	46
2020	915	4,000	146	6.00	4,461,814	96,464	46
2021	1,373	4,000	146	6.00	6,695,160	144,696	46
2022	2,059	4,000	146	6.00	10,040,302	217,044	46
2023	2,746	4,000	146	6.00	13,390,320	289,391	46
2024	3,432	4,000	146	6.00	16,735,462	361,739	46
2025	4,577	4,000	146	6.00	22,318,825	482,319	46
Total						**1,639,885**	**46**
II. Metal CRT retrofit							
2019	458	6,000	73	6.00	2,948,673	48,232	61
2020	915	6,000	73	6.00	5,890,907	96,464	61
2021	1,373	6,000	73	6.00	8,839,580	144,696	61
2022	2,059	6,000	73	6.00	13,256,151	217,044	61
2023	2,746	6,000	73	6.00	17,679,160	289,391	61
2024	3,432	6,000	73	6.00	22,095,731	361,739	61
2025	4,577	6,000	73	6.00	29,467,413	482,319	61
Total						**1,639,885**	**61**
III. Active DPC+FBC retrofit							
2019	458	5,500	687	6.00	4,407,522	48,232	91
2020	915	5,500	687	6.00	8,805,422	96,464	91
2021	1,373	5,500	687	6.00	13,212,944	144,696	91
2022	2,059	5,500	687	6.00	19,814,604	217,044	91
2023	2,746	5,500	687	6.00	26,425,888	289,391	91
2024	3,432	5,500	687	6.00	33,027,548	361,739	91
2025	4,577	5,500	687	6.00	44,046,355	482,319	91
Total						**1,639,885**	**91**

[#] PVF = $(1-1/(1+r)^n) / r$), where n = 7 years and r = 4%.
[##] PV = N*(C+A*PVF).
[###] Assuming 1 USD = 136,900 IRR as on 15 April 2019

5.2.3 Estimation of fuel demand and anticipated penalty

Sulfur content in diesel must be controlled and must be a precondition to introducing advanced emission control vehicle technologies to get the desirable results as described in section 3.1. It is therefore important to understand diesel requirement of a specific quality to get desired results from retrofitted city buses. **Currently, the city uses 119 thousand tons (or 143 million liters) of diesel to run its 4,577 diesel buses** both by public and private operators (Table 5.3). However, for the proposed DPF retrofit implementation plan in phases over next seven years, the city transit authorities (both public and private companies) need to ensure dedicated supply of low-sulfur diesel (max 350 ppm S) and ultra-low sulfur diesel (max 50 ppm S) for refueling these buses daily.

Several best practices as discussed in section 3.3, based on results of field trials of DPF retrofitted buses, have shown increase in fuel consumption in vehicles and the fuel penalty is in the range 0.6% to 1.8% with retrofit buses depending upon the bus type (Fleischman *et al.* (2018). However, according to researchers at the Mechanical Engineering Department in Sharif University of

Technology, Iran, closely associated with field trials of buses retrofitted with BATs in Tehran, “*We did not find out any fuel consumption penalty, at least considerable enough to be measured. We also have not received any complain about it. One reason is the highly subsidized fuel, so nobody notices it, the other reason is the condition of Euro II and Euro III engines in which the fuel consumption fluctuations during normal operations without filter is also high, depending on driving cycles, routes, and engine maintenance conditions.*”

Table 5.3: Low- and ultra-low sulfur diesel to run the current city bus fleet: 2019-2025

Year	Baseline		Cleaning up the bus fleet with BAT				Fuel Penalty (1% drop in fuel economy with DPF retrofit)
			No. of diesel buses		Total diesel demand		
	No. of diesel buses	Total diesel demand	without DPF	with DPF	ultra-low sulfur diesel (max 50 ppm) with DPF	low sulfur diesel (max 350 ppm) w/0 DPF	
	number	ton/year	Number	number	ton/year	ton/year	ton/year
2019	4,577	118,801	4,119	458	13,200	106,921	1,320
2020	4,577	118,801	3,662	915	26,400	95,041	2,640
2021	4,577	118,801	3,204	1,373	39,600	83,161	3,960
2022	4,577	118,801	2,518	2,059	59,401	65,341	5,941
2023	4,577	118,801	1,831	2,746	79,201	47,521	7,921
2024	4,577	118,801	1,145	3,432	99,001	29,700	9,900
2025	4,577	118,801	-	4,577	132,002	0	13,201
Total							**44,883**

In view of the lessons learned from international experience, and to come up with a conservative estimate, it is assumed that fuel economy will drop by one percent in retrofitted buses. The impact of 1% drop in fuel economy will result in an additional demand of 44,883 tons of low sulfur diesel over 7 years (Table 5.3). Considering the price of low sulfur diesel for city buses at IRR 3.5 per liter (=IRR 2.92 per kg), **the city transit authorities need an additional IRR 0.13 billion (or USD 950) towards meeting fuel expenses between 2019 and 2025**. The study assumes the cost data for supply of ULSD (max 50 ppm S) to be the same as that of current diesel used in city buses. In practice, the cost of supplying ULSD will be much higher due to the additional costs associated with setting up separate distribution, storage and supply facilities. The higher cost of ULSD supply could not be taken into account in absence of any ULSD price data in Tehran.

It is also important to recognize that the municipal bus fleet is a captive fleet and is only fueled at controlled stations, which all have high quality fuels. Therefore, the condition of having sufficiently clean fuels like, ULSD, supplied from these controlled stations for filter retrofitting technology is guaranteed. Moreover, Euro 4 diesel fuel with ULSD (sulfur <50 ppm) is guaranteed for all Tehran fleet by many pieces of legislation and several monitoring programs.

5.3 Benefits (avoided costs) from diesel retrofit of city buses

Frequent air pollution episodes have been reported for Tehran mainly because of critically high levels of $PM_{2.5}$. The composition and sources of these particles are poorly known (Arhami *et al*., 2017). The same study came up with the following findings based on an analysis of 24-hour $PM_{2.5}$ samples collected at a main residential station every 6 days for a full year from February 2014 to February 2015: (a) major $PM_{2.5}$ mass components were found to be organic matter and sulfate, (b) factors dominated by dust oxides and toxic metals explained 70 percent of $PM_{2.5}$ variances, (c) dust's contribution to $PM_{2.5}$ reached up to 56 percent in summer, while minimum 7 percent in winter, and (d) contrary to the dust oxide trend, toxic metals increased significantly in the cold season.

In 2014, the Tehran Air Quality Control Company (AQCC), a subsidiary of Tehran Municipality, ran an emission inventory model for Tehran. The model results are likely to be updated in 2019 by the Department of Environment (DOE). On the basis of the available information from published sources and using simple assumptions, researchers at the Mechanical Engineering Department in Sharif University of Technology, Iran, produced **a cost estimate of USD 158 to reduce one kg of PM emissions from mobile sources** (Table 5.4).

Table 5.4: Calculation of PM cost in Tehran

Description	Unit	Amount	Source
Annually economic cost of PM	USD	2,600,000,000	Heger and Sarraf, 2018 (WBG)
Mobile sources share in PM emissions	%	71	Annual Report of AQCC-2017
Primary pollutant portion in PM	%	51	Arhami *et al*., 2017
Primary pollutant of mobile source cost	USD	934,830,000	
Amount of PM of mobile source	kg	5,930,000	Tehran emission inventory-2014
PM cost of mobile source per kg	**USD**	**158**	

Source: Information received from Sharif University of Technology, Iran

5.3.1 Impact of the reduction in PM emissions from HDVs on city's air pollution

This section addresses how to best convert the reduction of PM mass (tons) emissions and pollution concentration values (µg/m^3) due to installed DPFs on all city buses and estimates the economic benefits from the abatement technology in terms of avoided costs. To quantify the impact of PM mass emissions load reduction on the ambient PM concentration value, a two-step approach is followed as presented below.

1. *Reduction in PM air pollution concentrations with DPF retrofit city buses*
   First, the relative contribution of PM emissions loading from mobile sources using an emissions inventory (bottom-up) approach in Tehran is analyzed and then compared to the results from source apportionment (top-down) studies using published literature. Findings from both types of studies help in establishing the ratio between the observed contribution to overall PM concentration and the inventory contribution to PM from mobile sources (see details below). The ratio is the used to estimate the reduction in PM concentration from PM mass reduction corresponding to a retrofitting of city diesel buses with DPF technology.

2. *Avoided costs of reducing $PM_{2.5}$ concentrations with DPF retrofit in city buses*
   The standard concentration-response curves and value of statistical life (VSL) approach is used to determine the economic costs that could be avoided with a reduction in $PM_{2.5}$ concentration as estimated in step 1. A cost curve (see figure 5.2) was established as part of the earlier 2018 study for Tehran and is used for this analysis (Heger and Sarraf, 2018).

Reduction Sin PM air pollution concentrations with DPF retrofit in city buses

Taghvaee *et al.*, (2018) in their study used the positive matrix factorization (PMF) model for the source apportionment of ambient $PM_{2.5}$ in two locations in central Tehran from May 2012 through June 2013. Factors taken into consideration include vehicular emissions, industry, secondary aerosol, biomass burning, soil and road dust. The average $PM_{2.5}$ mass concentrations were 30.9 and 33.2 µg/m^3 in the two locations. **Results indicated that almost 50% of the $PM_{2.5}$ concentration can be attributed to vehicular emissions at both locations.**

In another seasonal study for Tehran by Arhami *et al.,* (2018), the composition and sources of $PM_{2.5}$ and carbonaceous aerosol were determined. The source apportionment was performed using organic molecular marker-based Chemical Mass Balance (CMB) receptor modeling. Carbonaceous compounds were the major contributors to fine particulate mass in Tehran, as Organic Carbon (OC) and Elemental Carbon (EC) together comprised on average 29% of $PM_{2.5}$ mass. The major contributing source to particulate OC was identified as vehicles, which contributed about 72% of measured OC. Among mobile sources, gasoline-fueled vehicles had the highest impact with a mean contribution of 48% to the measured OC. **Mobile sources were also the largest contributor to total $PM_{2.5}$ (40%)**, followed by dust (24%) and sulfate (11%). In addition to primary emissions, mobile sources also directly and indirectly played an important role in another 27% of fine particulate mass (secondary organics and ions), which highlights the impact of vehicles in Tehran. Results highlighted and quantified the role of motor vehicles in fine PM production, particularly during winter time.

The third study by Arhami, *et al.,* (2017), looked at the major and heavy metals in $PM_{2.5}$ along with the seasonal trends and associated sources in Tehran. **OC and EC together comprised 44% of $PM_{2.5}$ on average (increased to over 70% in the colder season), which reflects the significance of motor vehicles**.

Thus, available published literature for Tehran have attributed varying contributions from mobile sources to $PM_{2.5}$ ambient concentration levels to be from 40 percent (Arhami et al., 2018) to nearly 50 percent in Tehran (Taghvaee et al, 2018). $PM_{2.5}$ emissions from mobile sources are generated from three general processes: (1) it is directly emitted from the tailpipes of mobile sources (buses, cars, trucks and other on-road vehicles), (2) it is re-entrained from materials found on the roadway (typically known as fugitive dust), and (3) it is created by secondary formation from precursor emissions such as SO_2, NO_x, VOCs and ammonia. Items 1 and 2 are primary emissions of $PM_{2.5}$. Secondary formation occurs due to chemical reaction in the atmosphere generally downwind some distance from the original emission source. Efforts to determine the contribution of each of these $PM_{2.5}$ mechanisms have shown a great deal of variability, especially across seasons with a high share in the colder season as Arhami *et al,* reported in their study.

A more recent study by Shahbazi *et al.*, (2019) shows municipality buses contribute 21 percent to mobile PM emissions. With the share of mobile sources to total PM emissions as 70 percent by Shahbazi et al. (2016) implies that municipality buses in the city bus fleet without any emission control device, contribute roughly 14% (=0.70 x 0.21) of PM emissions load. Also, based on the evidence accumulated, 99% of PM can be filtered out in buses if retrofitted with DPFs (see Table 5.1). **Hence, roughly 14% (=0.14 x 0.99) of PM emissions loading can be filtered out with DPF installed buses.**

According to CARB (1998), "Almost all of the diesel particle mass is in the fine particle range of 10 microns or less in diameter (PM_{10}). Approximately 94 percent of the mass of these particles are less than 2.5 microns in diameter. Because of their small size, these particles can be inhaled and a portion will eventually become trapped within the small airways and alveolar regions of the lung".

The emissions inventory results show the largest share of PM emissions, roughly 70%, originates from mobile sources (Shahbazi, 2016). When comparing PM emissions loading with concentrations from all motor vehicles the ratio is roughly 2:3. It is important to recognize that the two emissions inventory studies by Shahbazi *et al.* (2016 and 2019) do not take into account: (i) the secondary organic aerosols unlike in source apportionment studies (as they are the product of secondary formation and this only detected in particle for by concentrations) and (ii) fugitive dust. However, as per the Arhami *et al.* (2017) study, the share of dust component in mass emissions is roughly 25%. Once 25% dust is added to the emissions inventory result, the 2:3 ratio changes to 1:1 for the mass-concentration relationship.

Considering the 1:1 the ratio established between observed contribution to overall PM and inventory contribution to PM from mobile sources in Tehran means, and almost all of the diesel particle mass are less than 2.5 microns in diameter or $PM_{2.5}$, a 1% drop in PM emissions loading (tons) into the atmosphere from city diesel buses will result in 1% reduction in $PM_{2.5}$ mass concentration ($\mu g/m^3$). **Based on this rationale, a 14% reduction of PM mass emissions reduction from retrofitting all city diesel buses with DPF, would reduce the city's $PM_{2.5}$ pollution concentration by 14%.**

Avoided costs of reducing $PM_{2.5}$ concentrations with DPF retrofit in city buses

The avoided economic costs of reducing PM concentrations with DPF retrofit program in all city diesel buses is presented below. The World Bank study published in April 2018 estimated the economic costs associated with air pollution in Tehran at USD 2.6 billion per year as shown in figure 5.2 (Heger and Sarraf, 2018).

A 14% reduction in PM ambient concentration value from DPF-retrofitted heavy-duty diesel buses would mean approximately be USD 364 million (= 2.6 billion x 0.14) in benefits per year. This cost does not include the direct exposure benefit to passengers sitting in the bus, which is much higher than the average ambient exposure. **This means about USD 364 million per year in health costs can be avoided in Tehran when all 4,577 city diesel buses are equipped with DPFs and reducing $PM_{2.5}$ ambient air pollution to concentration levels comparable levels in Seoul (see Figure 5.2).** This avoided cost can be used as a low estimate for the benefits of pollution reduction, which may be compared to the costs of pollution policy actions.

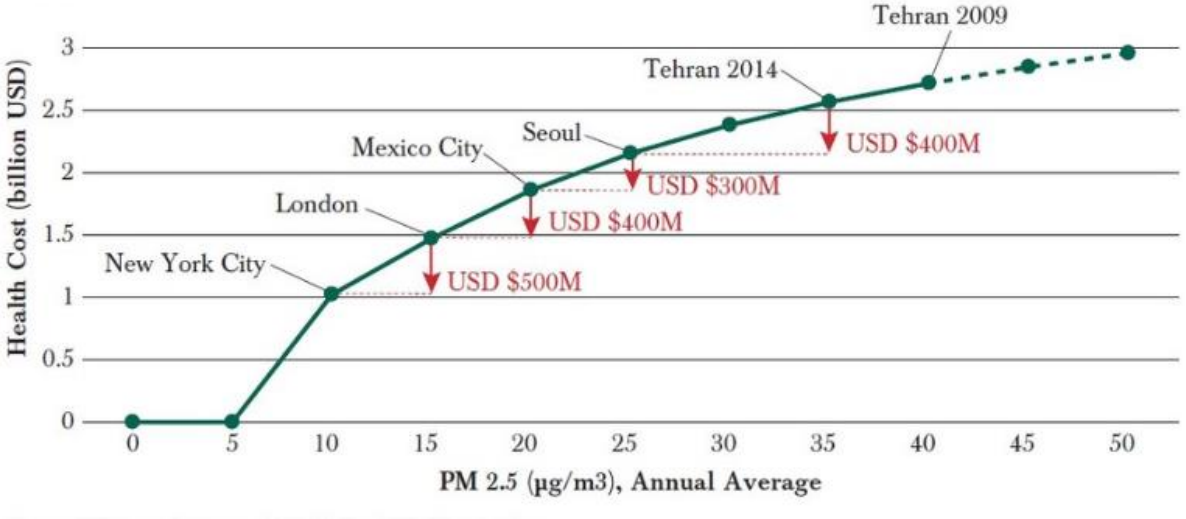

Fig 5.2. Avoided annual economic costs associated with reducing $PM_{2.5}$ concentrations in Tehran

Source: Reproduced from Heger and Sarraf (2018); p-8.

At current prices, retrofitting all city diesel buses with VERT-certified DPFs is expected to provide substantial net benefits to society beginning immediately and through 2025.[8] The study analyzed the economic costs of environmental policies to control PM emissions from in-use city diesel buses using the 2018 data and compared to estimates of benefits. **The present value of the total costs of implementing DPFs in all 4,577 city diesel buses over 7 years (2019 to 2025) is estimated at USD 22.32 million to USD 44.05 million depending on the choice of retrofit technology**. When compared to the health and productivity benefits from a reduction of $PM_{2.5}$, this would result in avoided economic costs of USD 364 million with a net benefit-cost ratio in the range 16:1 and 8:1. **This suggests that Tehran's proposed diesel bus DPF retrofit program is cost-beneficial.S**

6. Roles of Policy Makers to Control In-Use Vehicle Emission Reduction

This concluding section summarizes the critical actions the national and local government need to consider before going ahead with installation of world-class emission control programs from in-use heavy-duty vehicles. Based on how legal authority is generally distributed in most nations, it is important to highlight the relative roles that national and local decision makers can play in controlling emissions from in-use vehicles.

6.1 National Level Roles

The national level actions generally concern industry-wide regulations for engine and vehicle emission manufacturers and for fuel providers. Federal entities—typically environment, energy, transport—have a critical role in establishing a comprehensive source-emission inventory, as well as providing guidelines for evaluation and guidance on in-use, remote sensing, fuel inspection, scrappage, and other programs that many local governments may independently implement. Federal guidance and evaluation in such areas ensures that various local authorities are learning from efforts already undertaken elsewhere. National-decision making agencies can gain greatly from strong technical and data exchange with local actors, leading to better understanding of how local circumstances influence priority setting and policy outcomes. Many complementary fiscal programs (e.g., fuel taxation, vehicle taxation, technology subsidies) would especially benefit from joint national-local decision-making that link the fiscal policies to in-use emission control strategies.

Table 6.1 summarizes list of action areas identified at the national level to reduce emissions from in-use HDVs based on survey of best global practices (ICCT, 2013). The areas identified are recommended for consideration by the national government in Iran.

Table 6.1: National actions to reduce in-use heavy-duty diesel emissions

Action areas	Program(s)	Roles for national (or regional) decision-makers
Identify and prevent high-emitting vehicles	Inventory modeling	▪ Characterize vehicle population, activity, emission inventory model to quantify mobile pollution sources. ▪ Develop emissions inventory model structure for national and local use to quantify mobile pollution sources. ▪ Issue guidance and defaults for use of the inventory model.
	Prevent gross emitters	▪ Establish national regulatory provisions for appropriate full useful life vehicle emission compliance and for in-use compliance testing.

---

[8] The net benefits to society begin immediately considering the city diesel public transit buses are retrofitted with DPFs in a phased manner over a period of seven years starting 2019 as presented in table 5.2.

Action areas	Program(s)	Roles for national (or regional) decision-makers
		▪ Provide inspection and maintenance (I/M) and remote sensing program guidance and evaluation.
Cleaner fuels	Low-sulfur fuels	▪ Set minimum fuel quality requirements, and, if necessary, provide fiscal or other policy support to refineries to begin producing higher-quality fuels. ▪ Establish and oversee fuel quality inspection programs.
	Alternative fuels	▪ Establish national-level alternative fuel use requirements or targets with clear guidelines for fuels' lifecycle emission performance.
Accelerated retirement of high-emitting vehicles	Voluntary or mandatory scrappage	▪ Design overall program or implementation guidance that links scrappage program to highest-emitting vehicles and emission reduction results. ▪ Determine metrics for calculating emissions reductions. ▪ Provide national subsidies to support local programs with demonstrated need.
Vehicle retrofits for emission control	PM, NO_x emission control	▪ Consider developing retrofit technology verification guidelines to target highest-emitting vehicles. ▪ Work to ensure supply of low-sulfur fuels to enable a broad spectrum of retrofit technology options. ▪ Consider policies/measures to foster domestic retrofit device manufacturing capabilities.
	Fuel efficiency and CO_2 improvement	▪ Establish guidelines, publish information resources, and utilize voluntary programs to disseminate best technology practices for in-use fuel efficiency technologies (e.g., aerodynamics, low rolling resistance tires). ▪ Consider pilot and research programs with public funding to measure and demonstrate real-world benefits of aftermarket technologies.
Complementary strategies	Vehicle and fuel taxation	▪ Issue standardized guidelines for low-emission vehicle zones for local implementation, including linkage to national vehicle environmental labeling and regulatory policy as applicable. ▪ Promulgate progressive tax policy discouraging the use of high emission vehicles.
	Demand, mode shifting	▪ Implement national programs to encourage freight and transit shift to lower emission modes.

Source: ICCT, 2013, p: 50-51.

6.2 Local Level Roles

Ultimately, local authorities have to play the critical role to implement national policies. While the actions at the local levels tend to be closely connected with those highlighted above for national actors, but in many cases, the local authorities will have the critical on-the-ground role. Developing robust emissions inventories that reflect the local vehicle population, activity, and real-world emissions factors depending on driving cycles typically require local involvement. Regularly collecting additional information (via inspection, spotting of gross emitters, vehicle compliance testing, available fuel quality, weighing stations for overloading, etc.) on high emitters is a fundamental responsibility of local authorities, typically in urban areas. Ultimately, local policy makers' benefit by coordinating their efforts with federal actions mentioned above to implement a series of cost-effective pollution control policies that carefully target the highest emitting sources and leverage the most directly relevant technology.

Table 6.2 summarizes actions to reduce emissions from in-use heavy-duty vehicles that are generally implemented by local decision-makers based on survey of best global practices (ICCT, 2013). The areas identified are recommended for consideration by the local government in Iran.

Table 6.2: Local actions to reduce in-use heavy-duty diesel emissions

Action areas	Program(s)	Roles for national (or regional) decision-makers
Identify and prevent high-emitting vehicles	Inventory modeling	▪ Develop and utilize standard emission inventory models. ▪ Gather local data for inventory models, run the models, and report the result to national authorities. ▪ Conduct in-use testing to develop real-world emission factors.
	Prevent gross emitters	▪ Design and implement inspection and maintenance (I/M), remote sensing, and spotter programs consistent with national guidance. ▪ Issue and enforce anti-overloading regulations.
Cleaner fuels	Low-sulfur fuels	▪ Implement local-level fuel quality requirements when national fuel quality requirements are insufficient for local air quality needs. ▪ Support and participate in fuel quality inspection programs.
	Alternative fuels	▪ Deploy local fleets of alternative fuel vehicles. ▪ Provide incentives (parking, lane access, etc.) for very-low-emission vehicles with advanced alternative fuel technology.
Accelerated retirement of high-emitting vehicles	Voluntary or mandatory scrappage	▪ Award subsidies based on competitive bid process and cost-effectiveness. ▪ Implement program, including scrappage verification. ▪ Implement supplemental subsidies and/or complementary policies to increase incentives and maximize effectiveness of program.
Vehicle retrofits for emission control	PM and NO_x emission control	▪ Carefully implement retrofit programs that match a given device to vehicle/engine type, location, duty cycle, etc., to ensure effectiveness of the program. ▪ Carefully police systems to make sure that requirements are being met. ▪ Develop incentive programs for retrofits, with a focus on fostering the participation of capital-constrained owner/ operators. ▪ Establish retrofit demonstration projects using public and/or publicly contracted captive fleets to determine the appropriateness of existing technologies. ▪ Enforce mandatory retrofit programs.
	Fuel efficiency and CO_2 improvement	▪ Establish guidelines, publish information resources, and utilize voluntary programs to disseminate best available technology for in-use fuel efficiency technologies (e.g., aerodynamics, low rolling resistance tires). ▪ Consider pilot and research programs with public funding to measure and demonstrate real-world benefits of aftermarket technologies.
Complementary strategies	Vehicle and fuel taxation	▪ Designate and enforce low-emission zones that restrict high-emission vehicles and encourage advanced very-low-emission vehicles. ▪ Conduct driver training programs.
	Use of idling reduction technologies	▪ Issue and enforce anti-idling regulations that encourage operators to use technologies such as truck stop electrification, auxiliary power units, fuel operated heaters,

Action areas	**Program(s)**	**Roles for national (or regional) decision-makers**
		battery air conditioners, thermal storage systems, and automatic shutdown/startup systems to reduce idling of the main propulsion engine.
	Demand, mode shifting	▪ Optimize traffic patterns to resolve congestion and reduce emissions. ▪ Implement local programs to encourage modal shift to lower emission modes.

Source: ICCT, 2013, p: 52.

6.3 Conclusion

Motorized transport, and the use of diesel-powered vehicles, particularly diesel-powered city buses, continues to pollute Tehran's air. Advanced emission control retrofit technologies are a promising short-to-medium term solutions, particularly in circumstances of constrained fiscal space, if the pre-requisite fuel quality is a guaranteed. The analysis presented in this report demonstrates that diesel buses retrofitted with appropriate Diesel Particulate Filter (DPF) technology can be a cost-beneficial and cost-effective way to reduce Particulate Matter (PM) emissions and improve city air quality.

The present value of the total costs of implementing the DPFs in all its 4,577 city diesel buses over 7 years (2019 to 2025) is estimated at USD 46 million to USD 91 million depending on the type of retrofit technology. In terms of economic benefits, about USD 1 billion per year in health costs can be avoided in Tehran when all its city diesel buses are equipped with DPFs and reduce $PM_{2.5}$ ambient air pollution to concentration levels comparable levels in London. The net benefit-cost ratio is thus in the range 16:1 and 8:1 suggesting the proposed diesel bus DPF retrofit program makes economic sense.

It is important to note that, while the cost effectiveness estimates are based on simple assumptions, there is a significant amount of variability in both the costs and the emissions reductions from retrofit technologies in the field. A detailed techno-economic feasibility analysis is required for a DPF bus retrofit program for Tehran with a clear, committed roadmap in consultation with relevant stakeholders.

Lastly, cleaning the existing bus fleet is an important step in the right direction, one which preferably is also met by more and more people switching to public transportation. It is up to the government and the citizens of Tehran to make public transport a model of efficient, equitable and attractive city transport to the rest of the country.

References

ADB. (2008). *A road map for cleaner fuels and vehicles in Asia.* TA 6144 (REG): Better Air Quality Management in Asia. Prepared for the Asian Development Bank (ADB). November. Available at: http://cleanairasia.org/wp-content/uploads/portal/files/documents/Road_Map_for_Cleaner_Fuels_and_Vehicles_in_Asia_2008.pdf. Last Access on 3 May 2019.

Air Quality News. (2017). £86.1 million London bus retrofit program announced, 28 June. Available at: https://airqualitynews.com/2017/06/28/86-1-million-london-bus-retrofit-programme-announced/. Last Access on 7 May 2019.

Allansson, R., Blakeman, P. G., Cooper, B. J., Phillips, P. R., Thoss, J. E., & Walker, A. P. (2002). The use of the continuously regenerating yrap (CRTTM) to control particulate emissions: Minimizing the impact of sulfur poisoning. *SAE paper 2002-01-1271*. Available at: http://tdl.libra.titech.ac.jp/journaldocs/en/recordID/article.bib-02/ZR000000171400. Last Access: 15 April, 2019.

Alleman, T., Eudy, L., Miyasato, M., Oshinuga, A., Allison, S., Corcoran, T., *et al.* (2004). Fuel property, emission test, and operability results from a fleet of class 6 vehicles operating on gas-to-liquid fuel and catalyzed diesel particle filters. *SAE Technical Paper 2004-01-2959*. Available at: https://www.sae.org/publications/technical-papers/content/2004-01-2959/. Last Access on 4 May 2019.

Arhami, M., Hosseini, V., Shahne, M.Z., Bigdeli, M., Lai, A., Schauer, J.J. (2017). Seasonal trends, chemical speciation and source apportionment of fine PM in Tehran. *Atmospheric Environment*, *153 (2017): 70-81.* Available at: https://www.sciencedirect.com/science/article/pii/S1352231016310226. Last Access on 11 May, 2019.

Axmann, H., Bergmann, A., Eichberger, B. (2017). Determination of NO_x and soot concentrations using a multi-wavelength opacimeter. In *Smart Sensors, Measurement and Instrumentation (Vol. 23, pp. 1-19)*. Available at: https://graz.pure.elsevier.com/en/publications/determination-of-nosubxsub-and-soot-concentrations-using-a-multi-. Last Access on 5 May 2019.

Bischof, O.F. (2015). Recent developments in the measurement of low particulate emissions from mobile sources: A review of particle number legislations from mobile sources. *Emission Control Science Technology 1 (2015):203-212*. Available at: https://link.springer.com/article/10.1007/s40825-015-0016-9. Last Access on 5 May 2019.

Biswas, S., Verma,V., Schauer, J.J., Cassee, F.R., Cho, A.K., Sioutas, C. (2009). Oxidative potential of semi-volatile and non-volatile particulate matter from heavy-duty vehicles retrofitted with emission control technologies. *Environ. Sci. Technol., Vol. 43 (2009), No. 10, pp. 3905-3912*. Available at: https://www.ncbi.nlm.nih.gov/pubmed/19544906. Last Access on 3 May 2019.

Bose, R.K., Sundar, S. (2005). Emissions test results from diesel buses, with and without oxidation-catalyst and regenerating particle-trap, and CNG buses with three-way catalyst in India. *SAE International 2005-01-0477.* Available at: https://www.sae.org/publications/technical-papers/content/2005-01-0477/. Last Access on 3 May 2019.

Boudart,J., Figliozzi, M. (2012). Key variables affecting decisions of bus replacement age and total costs. *Transportation Research Record: Journal of the Transportation Research Board 2274 (2012):109-113.* Available at: https://journals.sagepub.com/doi/abs/10.3141/2274-12. Last Access on 4 May 2019.

CARB. (1998). *Findings of the scientific panel on the report on diesel exhaust. Retrieved - July 21, 2015*. California Air Resources Board (CARB). Available at: https://www.arb.ca.gov/toxics/dieseltac/de-fnds.htm. Last Access on 11 June 2019.

CATF. (2005). *Diesel and health in America: The lingering threat.* Clean Air Task Force, February 21, 2005. Available at: https://www.catf.us/wp-content/uploads/2019/02/CATF_Pub_Diesel_Health_America.pdf. Last Access on 3 May 2019.

CCAC, 2016. *Cleaning up the global on-road diesel fleet – A global strategy to introduce low-sulfur fuels and cleaner diesel vehicles*. Climate Clean Air Coalition (CCAC). August. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/21552/Cleaning_up_Global_diesel_fleet.pdf?sequence=1&isAllowed=y. Last Access on 30 April 2019.

Chatterjee, S., Conway, R., and Walker, A. (2001). Emission reduction in on-road heavy duty diesel applications with the continuously regenerating technology (CRT®) diesel particulate filter. *SAE International 2001-28-0049*. Available at: https://www.sae.org/publications/technical-papers/content/2001-28-0049/. Last Access on 7 May 2019.

Cohen, J.T., Hammitt, J.K., and Levy, J.I. (2003). Fuels for Urban Transit Buses: A Cost-Effectiveness Analysis. *Environmental Science Technology, 37 (2003), 1447-1484.* Available at: https://pubs.acs.org/doi/abs/10.1021/es0205030. Last Access on 7 May 2019.

Cooper, B. J., Jung, H. J., & Thoss, J. E. (1990). *US Patent 4,902,487.* Available at: https://patents.justia.com/inventor/barry-j-cooper. Last Access on 15 April 2019.

Corro, G. (2002). Sulfur impact on diesel emission control—a review. *Reaction Kinetics and Catalysis Letters, 75(1):89-106*. Springer Link. Available at: https://link.springer.com/article/10.1023/A:1014853602908. Last Access on 30 April 2019.

Dallmann, T.R., Harley, R.A., Kirchs, T.W. (2011). Effects of diesel particle filter retrofits and accelerated fleet turnover on drayage truck emissions at the port of Oakland. *Environmental Science & Technology 45 (2011) no. 24: 10733-79*. Available at: https://www.ncbi.nlm.nih.gov/pubmed/22039954. Last Access on 2 May 2019.

DieselNet, (2015). Iran considering measures to reduce diesel emissions. Posted on 27 April. Available at: https://dieselnet.com/news/2015/04vert.php. Last Access on 5 May 2015.

EPA. (2006). *Diesel Retrofit Technology: An analysis of the cost-effectiveness of reducing particulate matter emissions from heavy-duty diesel engines through retrofits.* United States Environmental Protection Agency (EPA). EPA420-S-06-002, March. Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi/900N0800.PDF?Dockey=900N0800.PDF. Last Access on 8 May 2019.

Fleischman, R., Amiel, R., Czerwinski, J. Mayer, A., and Tartakovsky, L. (2018). Buses retrofitting with diesel particle filter: Real-world fuel economy and roadworthiness test considerations. *Journal of Environmental Sciences 6 (2018): 273-86.* Available at: https://europepmc.org/abstract/med/29778161. Last Access on 2 May 2019.

Fleischman, R., Amiel, R., Czerwinski, J., Mayer, A. and Tartakovsky, L. (2016). Performance of in-use buses retrofitted with diesel particle filters. *Journal of Earth Sciences and Geotechnical Engineering, vol.6 (2016), no. 4, 255-27*. Available at: www.scienpress.com/Upload/GEO/Vol%206_4_16.pdf. Last Access on 15 April 2019.

Friedrich, R. and Bickell, P. (2001). *Environmental external costs of transport*, Springer, Heidelberg. Available at: https://link.springer.com/book/10.1007/978-3-662-04329-5. Last Access on 29 April 2019.

Fung, F., Hui, H., Sharpe, B., Kamakate, F., and Blumberg, K. (2011). *Overview of China's vehicle emission control program*. The International Council of Clean Transportation: 2010.12. Available at: https://www.theicct.org/sites/default/files/publications/Retrosp_final_bilingual.pdf. Last Access on 3 May 2019.

Garshick, E., Laden, F., Hart, J.E., Rosner, B., EnvironDavis, M.E., Eisen, E.A., Smith, T.J. (2008). Lung Cancer and Vehicle Exhaust in Trucking Industry Workers. *Environmental Health Perspectives, Volume 116 (2008), Number 10, 1327-1332*. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2569090/. Last Access on 3 May 2019.

Giechaskiel, B., Maricq, M., Ntziachristos, L., Dardiotis, C., Wang, X., Axmann, H., Bergmann, A., Schindler, W. (2014). Review of motor vehicle particulate emissions sampling and measurement: from smoke and filter mass to particle number. Journal of Aerosol Science, 67 (2014): 48-86. Available at: https://www.sciencedirect.com/science/article/pii/S0021850213001961. Last Access on 5 May 2019.

Gretchen, S., Wilson, A. and Hammitt, J.K. (2005). A benefit-cost analysis of retrofitting diesel vehicles with particulate filters in the Mexico City metropolitan area. *Risk Analysis, Vol. 25 (2005), No. 4, 883-899.* Available at: https://www.academia.edu/18586588/A_Benefit-Cost_Analysis_of_Retrofitting_Diesel_Vehicles_with_Particulate_Filters_in_the_Mexico_City_Metropolitan_Area. Last Access on 16 April 2019.

Hart Energy and MathPro, Inc. (2012). *Technical and economic analysis of the transition to ultra-low sulfur fuels in Brazil, China, India, and Mexico.* Prepared for the International Council on Clean Transportation. October. Available at: http://www.theicct.org/sites/default/files/publications/ICCT_ULSF_refining_Oct2012.pdf. Last Access on 3 May 2019.

Heger, M. and Sarraf, M. (2018). *Air pollution in Tehran: health costs, sources, and policies*. Environment and Natural Resources Global Practice Paper# 06. The World Bank Group. Available at: http://documents.worldbank.org/curated/en/160681527012587818/pdf/126402-NWP-PUBLIC-Tehran-WEB-updated.pdf. Last Access on May 1, 2019.

HEI. (2013). *Understanding the Health Effects of Ambient Ultrafine Particles*. Boston, MA: Health Effects Institute Review Panel on Ultrafine Particles. Available at: https://www.healtheffects.org/publication/understanding-health-effects-ambient-ultrafine-particles. Last Access on 30 April 2019.

Hosseini, V. and Shahbazi, H. (2016). Urban air pollution in Iran. *Iranian Studies 49 (2016), no.6: 1029-1046*. Available at: https://www.tandfonline.com/doi/abs/10.1080/00210862.2016.1241587. Last Access on 8 May 2019.

IARC. (2012). *Diesel Engine Exhaust Carcinogenic*. Press Release No. 213, 12 June 2012. International Agency for Research on Cancer (IARC). Available at: http://www.iarc.fr/en/media-centre/pr/2012/pdfs/pr213_E.pdf. Last Access on 2 May 2019.

ICCT. (2016). *White Paper – Costs of emission reduction technologies for heavy-duty diesel vehicles*. International Council on Clean Transportation, February. Available at: https://www.theicct.org/sites/default/files/publications/ICCT_costs-emission-reduction-tech-HDV_20160229.pdf. Last Access on 7 May 2019.

ICCT. (2013). *Survey of best practices in emission control of in-use heavy-duty diesel vehicles.* International Council on Clean Transportation, February. Available at: https://www.theicct.org/sites/default/files/publications/ICCT_HDV_in-use_20130802.pdf. Last Access on 2 May 2015.

Kadijk, G., Spreen, J.S., van der Mark, P.J. (2016). *Investigation into a periodic technical inspection test method to check for presence and proper functioning of diesel particulate filters in light-duty diesel vehicles.* TNO Report 2016 R10735v2, Delft, The Netherlands.

Kadijk, G., Elstgeest, M., Ligterink, N.E., van der Mark, P.J. (2017). *Investigation into a periodic technical inspection (PTI) test method to check for presence and proper functioning of diesel particulate filters in light-duty vehicles – part 2.* TNO Report 2017 R10530 | 1.0, The Hague, The Netherlands (85 pp, May 1, 2017).

Kagawa, J. (2002). Health effects of diesel exhaust emissions – a mixture of air pollutants of worldwide concern. *Toxicology: 181-182 (2002): 349-353.* Available at: https://www.sciencedirect.com/science/article/pii/S0300483X02004614. Last Access on 2 May 2019.

Kittelson, D.B. (1998). Engines and nanoparticles: a review. *J. Aerosol Sci, 29, 575-588.* Available at: http://dns2.asia.edu.tw/~ysho/YSHO-English/1000%20CE/PDF/J%20Aer%20Sci29,%20575.pdf. Last Access on 1 May 2019.

Krewski, D., Jerrett, M., Burnett, R., Ma, R., Hughes, E., Shi, Y., Tempalski, B. (2009). *Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality*. HEI Research Report 140 No. 140. Boston, MA: Health Effects Institute. Available at: https://westrk.org/CARBdocs/Krewski_052108.pdf. Last Access on 30 April 2019.

Lapuerta, M., Rodríguez-Fernández, J., Oliva, F. (2012). Effects of soot accumulation in diesel particle filter on the combustion process and gaseous emissions. *Energy 47(2012), no. 1:543-552.* Available at: https://www.sciencedirect.com/science/article/abs/pii/S0360544212007335. Last Access on 4 May 2019.

LeTavec, C., Uihlein, J., Vertin, K., Chatterjee, S., Hallstrom, K., Wayne, S., *et al*. (2002). Year-long evaluation of trucks and buses equipped with passive diesel particulate filters. *SAE Technical Paper 2002-01-0433*. Available at: https://www.sae.org/publications/technical-papers/content/2002-01-0433/. Last Access on 4 May 2019.

Lin, C. (2002). Reduction of particulate matter and gaseous emission from marine diesel engines using a catalyzed particulate filter. *Ocean Engineering, 29(11):1327-1341.* Available at: https://www.sciencedirect.com/science/article/pii/S0029801801000865. Last Access on 4 May 2019.

Liu, Z., Shah, A.N., Ge, Y., Ding, Y., Tan, J., Jiang, L., Yu, L., Zhao, W., Wang, C., Zeng, T. (2011). Effects of continuously regenerating diesel particulate filters on regulated emissions and number-size distribution of particles emitted from a diesel engine. *Journal on Environmental Sciences, 23 (5):798-807*. Available at https://www.sciencedirect.com/science/article/pii/S1001074210604524. Last Access on 4 May 2019.

Liu, H., He, K., He, D., Fu, L., Zhou, Y., Walsh, M.P., and Blumber, K.O. (2008). Analysis of the impacts of fuel sulfur on vehicle emissions in China. *Fuel, Volume 87 (2008): 3147–3154*.Available at: https://www.sciencedirect.com/science/article/pii/S0016236108001221. Last Access on 3 May 2019.

May, J., Bosteels, D., Nichol, A., Andersson, J., and Such, C. (2007). *The Application of Emissions Control Technologies to a Low-Emissions Engine to Evaluate the Capabilities of Future Systems* *for European and World-Harmonised Regulations*. Available at: http://www.aecc.eu/wp-content/uploads/2016/08/AECC_PAPER_for_Aachen_Final_20070716.pdf. Last Access on 30 April 2019.

Mayer, A. (2014). *PM versus PN*. Presented at the 18th ETH-Conference on combustion generated nanoparticles, Zurich, June 2014. Swizerland. Available at: http://www.nanoparticles.ch/2014_ETH-NPC-18/6a-06_Mayer.pdf. Last Access on 5 May 2019.

Mayer, A. (2008). *Particle filer retrofit for all diesel engines*. 18 August. Expert-Verlag GmbH. Available at: https://www.bookdepository.com/Particle-Filter-Retrofit-for-all-Diesel-Engines-Andreas-Mayer/9783816928508. Last Access on 4 May 2019

Mayer, A., Czerwinski, J., Petermann Jean-Luc, Wyser, M., Legerer, F. (2004). Reliability of DPF-systems: Experiences with 6000 applications of the Swiss retrofit fleet. 2004-01-08. *SAE 2004-01-0076*. Available at: https://www.sae.org/publications/technical-papers/content/2004-01-0076/. Last Access on 5 May 2019.

.

Mayer, A., Czerwinski, J., Matter, U., Wyser, M., Scheidegger, Kieser, D., Weidofer. (1998). VERT: diesel nano-particulate emissions: properties and reduction strategies. *SAE Technical Paper 98053, 1998-02-23.* Available at: https://www.sae.org/publications/technical-papers/content/980539/. Last Access on 5 May 2019.

MECA. (2014). *Retrofitting Emission Controls for Diesel-Powered Vehicles. Revised November 2014,* Manufacturers of Emission Controls Association (MECA). Available at: http://www.meca.org/resources/MECA_diesel_retrofit_white_paper_1114_FINAL.pdf. Last Access on 2 May 2019.

MECA. (2005). *Diesel Particulate Filter Maintenance: Current Practices and Experience*, Manufacturers of Emission Controls Association (MECA). June. Available at: http://www.meca.org/galleries/files/Filter_Maintenance_White_Paper_605_final.pdf. Last Access on 3 May 2019.

Mohammad, A., Shahne, M.Z., Hosseini, V., Roufigar, H.N., Lai, A.M., Schauer, J.J. (2018). Seasonal trends in the composition and sources of $PM_{2.5}$ and carbonaceous aerosol in Tehran, Iran. *Environmental Pollution, 239 (2018): 69-81*. Available at: https://www.ncbi.nlm.nih.gov/pubmed/29649761. Last access on May 22, 2019.

Mohammadiha, A., Malakooti, H., and Esfahanian, V. (2018). Development of reduction scenarios for criteria air pollutants emission in Tehran traffic sector, Iran. *Science of the Total Environment 622:17-28.* Available at: https://www.ncbi.nlm.nih.gov/pubmed/29202365. Last Access on 1 May 2019.

Molina, L.T. and Molina, M.J. (2002). *Air Quality in the Mexico Megacity: An Integrated Assessment*. Publisher - Dordrecht; Boston : Kluwer Academic Publishers. Available at: https://www.worldcat.org/title/air-quality-in-the-mexico-megacity-an-integrated-assessment/oclc/49844144. Last Access on 16 April 2019.

Prasad, R., and Bella, V.R. (2010). A review on diesel soot emission, its effect and control. *Bulletin of Chemical Reaction Engineering & Catalysis. 5(2): 69-86.* Availble at: https://www.researchgate.net/publication/49608531_A_Review_on_Diesel_Soot_Emission_its_Effect_and_Control. Last Access on 2 May 2019.

Quan-shun, Y., Jian-wei, T., Yun-shan, G., Li-jun, Hao., Zi-hang, P. (2017). Application of diesel particulate filter on in-use on-road vehicles. *Energy Procedia 105 (2017) 1730-1736*. Available at: https://www.sciencedirect.com/science/article/pii/S1876610217305374. Last Access on 21 May 2019.

Richards, P., Terry, B., Pye, D. (2003). Demonstration of the benefits of DPF/FBC systems on London black cabs, *SAE Technical Paper 2003-01-0375*. Available at: https://www.researchgate.net/publication/290812605_Demonstration_of_the_Benefits_of_DPFFBC_Systems_on_London_Black_Cabs. Last Access on 4 May 2019.

Rutherford, D. (2006). *Policy change in Japan: The Tokyo Metropolitan Government's regulation of diesel emissions.* Dissertation, Stanford University. Available at: https://searchworks.stanford.edu/view/6714436. Last Access on 3 May 2019.

SCAQMD. (2019). *Cost Effectiveness Values and Calculations*. South Coast Air Quality Management District, California. Available at: https://www.aqmd.gov/home/permits/bact/cost-effectiveness-values. Last Access on 9 May 2019.

Schrooten, L. Vlieger, I.D., Lefebre, F. and Torfs, R. (2006). Costs and benefits of an enhanced reduction policy of particulate matter exhaust emissions from road traffic in Flanders. *Atmospheric Environment 40 (2006): 904-912*. Available at: https://www.sciencedirect.com/science/article/pii/S1352231005009817. Last Access 29 April 2019.

Shahbazi, H., Hassani, A., Hosseini, V. (2019). Evaluation of Tehran clean air action plan using emission inventory approach. *Urban Climate*. 27 (2019). 446-456. Available at: https://www.sciencedirect.com/science/article/pii/S2212095518301251. Last Access: 12 June 2019.

Shahbazi, H., Reyhanian, M., Hosseini, V. and Afshin, H. (2016). The relative contributions of mobile sources to air pollutant emissions in Tehran, Iran: An emission inventory approach. *Emission Control Science and Technology 2 (2016), no. 1:44-56.* Available at: https://link.springer.com/content/pdf/10.1007%2Fs40825-015-0031-x.pdf. Last Access: 1 May 2019.

Smukste, K. (2015). *East African clean diesel now a reality: Low sulfur diesel fuel and the life-saving filter to improve people's lives*. Appeared as News in the Climate & Clean Air Coalition (CCAC), 10 March. Available at: http://www.ccacoalition.org/en/news/east-african-clean-diesel-now-reality. Last Access on 3 May 2019.

Sydbom A., Blomberg A., Parnia S., Stenfors N., Sandström T., Dahlén S.E. (2001). Health effects of diesel exhaust emissions. *European Respiratory Journal. 17 (2001): 733-746*. Available at: https://erj.ersjournals.com/content/17/4/733. Last Access on 2 May 2019.

Taghvaee, S., Sowlat, M. H., Mousavi, A., Hassanvand, M.S., Yunesian, M., Naddafi, K. and Sioutas, C. (2018). Source apportionment of ambient PM2.5 in two locations in central Tehran using the Positive Matrix Factorization (PMF) model. *Science of the Total Environment, 628-629 (2018): 672-686*. Available at: https://www.sciencedirect.com/science/article/pii/S0048969718304868#ab0005. Last Access on 22 May 2019.

Tartakovsky, L. and Fleischman, R. (2017). DPF retrofit program in Israel – effects of diesel particle filters on performance of in-use buses. *Combustion Engines, 2017, 170(3), 176-178*. DOI: 10.19206/CE-2017-330. Available at: http://www.combustion-engines.eu/entityfiles/files/articles_published/ptnss-2017-330.pdf. Last access on 14 April 2019.

Tartakovsky L., Baibikov V., Comte P., Czerwinski J., Mayer A., Veinblat M., Zimmerli Y. (2015). Ultrafine particle emissions by in-use diesel buses of various generations at low-load regimes. *Atmospheric Environment, Volume 107, April 2015, Pages 273-280.* Available at:

https://ticel.net.technion.ac.il/files/2012/12/Tartakovsky-et-al_Atmospheric-Environment_2015_final-published-article.pdf. Last Access 15 April 2019.

Tehran Times. (2018). *Diesel particulate filter best option to cut PM2.5*. December 28. Available at: https://www.tehrantimes.com/news/431246/Diesel-particulate-filter-best-option-to-cut-PM-2-5. Last Access on 8 May 2019.

Topal, O. and Nakir, I. (2018). Total cost of ownership based economic analysis of diesel, CNG, & electric bus concepts for the public transport in Istanbul city*. Energies, 2008,11,2369.* Available at: https://www.researchgate.net/publication/327521632_Total_Cost_of_Ownership_Based_Economic_Analysis_of_Diesel_CNG_and_Electric_Bus_Concepts_for_the_Public_Transport_in_Istanbul_City. Last access on 12 May 2019.

USEPA. (2000). Regulatory impact analysis: Heavy-duty engine and vehicle standards and highway diesel fuel sulfur control requirements. U.S. Environmental Protection Agency EPA420-R-00-026. Available at: https://nepis.epa.gov/Exe/ZyNET.exe/P100K576.TXT?ZyActionD=ZyDocument&Client=EPA&Index=2000+Thru+2005&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C00thru05%5CTxt%5C00000033%5CP100K576.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL. Accessed on 3 May 2019.

Vidale, S., and Campana, C. (2018). Ambient air pollution and cardiovascular diseases: From bench to bedside. *European Journal of Preventive Cardiology 25 (2018), no. 8: 818-25.* Available at: https://journals.sagepub.com/doi/abs/10.1177/2047487318766638?journalCode=cprc. Last Access: 1 May 2019.

Voorhees, A. S. and Uchiyama, I. (2007). Cost Analysis of Particulate Matter Control Programs – A Case Study of Tokyo. *Journal of Risk Research, 2007, Vol. 10, No.6, pp. 759-772.* Available at: https://www.tandfonline.com/doi/full/10.1080/13669870701342561?needAccess=true. Last access: 12 April 2019.

Voorhees, A.S. (2005). Benefits Analysis of Particulate Matter Control Programs – A Case Study of Tokyo. *Journal of Risk Research, 2015, Vol 8, Issue 4, pp. 311-329, 2005*. Available at: https://www.tandfonline.com/doi/abs/10.1080/1366987042000265065?journalCode=rjrr20. Last Access on 15 April 2019.

Walsh, M., Kodjak, D., Rutherford, D. (2007). *A model regulatory program for reducing exhaust and evaporative emissions from HDVs and engines*. ICCT. Available at: https://www.theicct.org/sites/default/files/publications/ICCT_HDVmodelrule_2007.pdf. Last Access on 3 May 2019.

Wu, Y., Zhang, S., Hao, J. Liu, H., Wu, X., Hu, J., Walsh, M.P., Wallington, T.J., Zhang, K.M., Stevanovic, S. (2017). On-road vehicle emissions and their control in China: A review and outlook. *Science of the Total Environment, 574 (2017) 332-349.* Available at: https://www.ncbi.nlm.nih.gov/pubmed/27639470. Last Access on 12 May 2019.