Background Paper on

Cleaner Liquid Fuels and Improved Vehicular Technologies

May 31, 2011

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

1. Introduction

The transportation sector is an important source of air pollution in terms of carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM), volatile organic compounds (VOCs), and greenhouse gases emissions. Many of these emissions undergo further reactions in the atmosphere, which increases ground level ozone (O_3) and smog levels. The resulting effects of increased air pollution on human and environmental health are substantial. An evaluation of traffic-related air pollution by the Health Effects Institute (HEI) concluded that there is sufficient evidence that exposure to traffic can cause exacerbation of asthma, especially in children, and suggestive evidence for other health effects such as premature mortality, lung function, and respiratory symptoms (HEI, 2010).

To mitigate the air pollution impact of vehicles, the Auto Fuel Policy of 2003 laid down a roadmap for vehicular emission and fuel quality standards. This roadmap on vehicular emission standards and fuel quality has been largely implemented. Starting year 2010, Bharat IV standards have been implemented in 13 major cities, while Bharat III standards are in effect in the rest of the country. This first phase of emission reductions from vehicular sources represents a great deal of progress as shown in Figure 1[1].

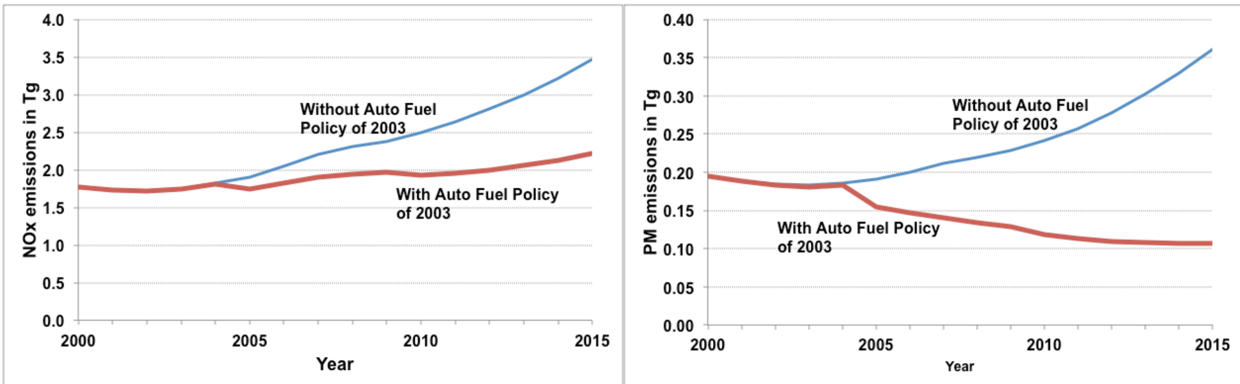

Figure 1: Projected total NOx and PM emissions with and without the 2003 Auto Fuel Policy (2000-2015).

Although some progress has been made, air quality in many urban areas continues to be worse than the national ambient air quality standards (Walsh, 2011). As a result of rapid economic growth, the sales of motor vehicles in India have nearly tripled between 2001 and 2010. During the fiscal year 2010-11 the sales of new vehicles rose by 26%, compared to the previous year and double-digit sales growth is expected across the board in 2011-2012 (SIAM, 2011). As the Indian clean air program (ICAP) has demonstrated, vehicular emissions continue to be one of the main sources of urban air pollution in India. Continued growth in vehicle population will negate the gains of the past decade in the absence of further policy action as shown in Figure 2.

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[1]Assuming existence of a perfect inspection and maintenance regime where there are no gross emitters in the fleet. The actual on-road emissions are likely to be higher due to a significant number of gross emitters.

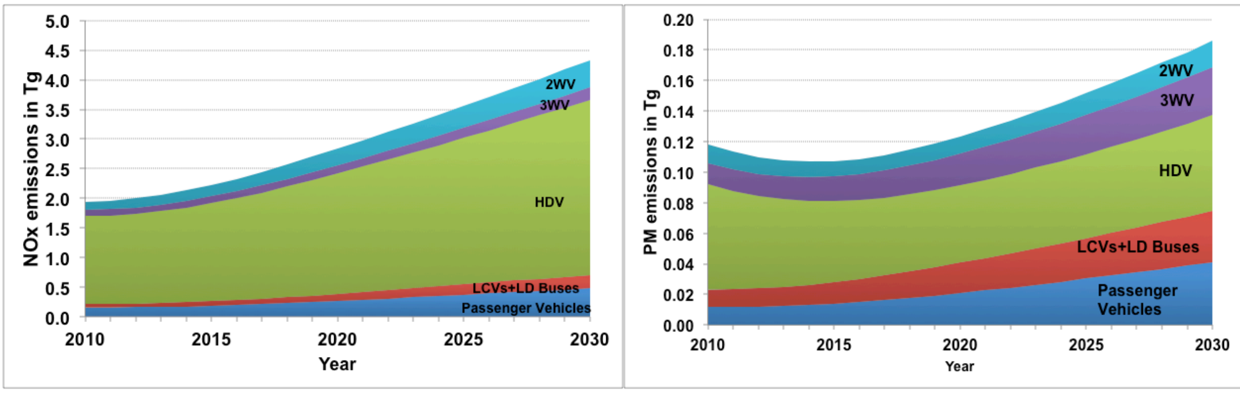
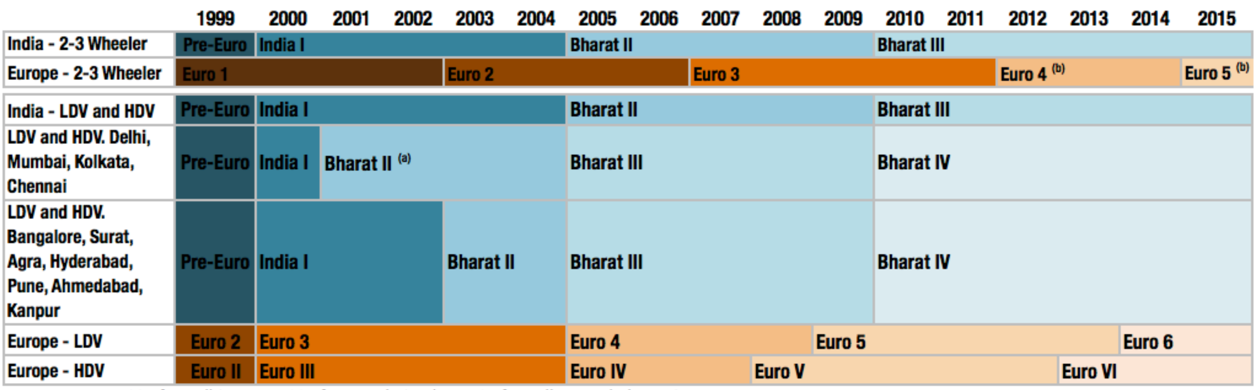


Figure 2: Projected total NOx and PM emissions in the absence of further policy action (2010-2030).

Thus, further efforts are necessary to reduce the impact of transport vehicles on air quality. From the point of view of vehicle emission standards and fuel quality, there is still a time lag between the European and Indian schedules. The time gap between standards for two- and three-wheelers in India and the European Union is currently three years; while for four-wheelers and heavy-duty vehicles the time gap varies, with major metropolitan areas in India about five years behind the latest Euro standards and the rest of the country almost a decade back as shown in Figure 3. Harmonizing emissions standards nationwide and moving to standards that use the best available emission control technologies would enable India to catch up to advanced countries and yield significant environmental and public health benefits.



a - LDV: Apr 1, 2000 for Delhi, Jan 1, 2001 for Mumbai, Jul 1, 2001 for Kolkata and Chennai
HDV: Oct 24, 2001 for Delhi, Oct 21, 2001 for Mumbai, Kolkata and Chennai
b - Proposed implementation dates

Figure 3: Two/Three-Wheeler, Light/Heavy-Duty vehicle standard adoption timeline in India and the EU

The next phase of the auto fuel policy in India will therefore have to decide a roadmap for implementation of Bharat V and VI standards similar to those implemented in Europe and elsewhere in the world.

2. Challenges in front of the vehicular air pollution control program

The *European emission standards program, unlike the US program, have different requirements for diesel and gasoline light-duty vehicles regarding NOx and PM*, as can be observed in Annexure I. NOx emission standards for Euro 3, 4 and 5 diesel vehicles are three times more lenient than the NOx standards for gasoline vehicles, but only one third more lax for the upcoming Euro 6 standards. Due to inherently lower PM emissions from port-fueled gasoline engines, PM emission standards were not required for gasoline vehicles until gasoline direct injected (GDI) engines started entering the market. As a result, PM emission limits have now been introduced for GDI vehicles with the implementation of Euro 5 standards. Never the less, emission limits for petrol and diesel vehicles do not converge until implementation of Euro 6 emission standards. In contrast, the US Tier II program has set the same standards for all fuel types, and several diesel vehicles have been certified at Tier 2 –Bin 5 levels, including a light-duty truck manufactured by Mahindra (EPA, 2011).

It should be noted that *Bharat regulations differ from European regulations* at various levels. As an example, major differences for light-duty vehicle tests are: maximum test speed of 90 km/h for India compared with 120 km/h for Europe; the low temperature (-7°C) HC/CO test is not required in India as the average temperature is well above freezing conditions for most of the country; vehicle inertia weight includes 150 kg in addition to the kerb weight as opposed to 100 kg used in Europe. Major differences for two and three-wheeler regulations include the use of combined limits for HC and NOx in India and a maximum test speed of 50 km/h for India, compared to 60 km/h for Europe. It should be noted that India is an active participant in the World Forum on Harmonization of Vehicle Regulations. While India is making an effort to adopt World-wide Motorcycle Testing Cycle (WMTC) starting 2015, a move towards World Harmonized Stationary and Transient Cycles (WHSC and WHTC) for heavy duty vehicles and engines does not yet appear on the cards.

As noted already, *lack of a comprehensive inspection and maintenance program, and existence of dual emission norms in the country* continue to be a challenge in reducing air pollutants from vehicles. Separate emission norms for major cities and the rest of the country means that majority of buses and almost all heavy-commercial vehicles continue to have emission norms and fuel quality equivalent to Bharat III. As many cities are discovering, it is also proving difficult to prevent the registration of vehicles in Bharat III regions outside the city limits, even though the vehicles largely ply within the Bharat IV cities (Maharashtra Times, 2011).

Further, *fuel sulfur limits in the rest of the country are much higher as compared with Bharat IV cities (350 ppm vs. 50 ppm for diesel)*. This means vehicles that are designed to meet Bharat IV emissions standards, particularly diesel-powered ones, may not be in compliance if they are refueling in areas with higher fuel sulfur content. In coming years, after treatment control devices, such as Selective Catalytic Reduction (SCR) system and the Diesel Particulate Filters (DPFs), might operate below optimum conditions and not provide the designed coverage for control of pollutants, or could fail. These dual fuel quality and emission norms – especially fuel sulfur – continue to present logistical challenges for vehicle manufacturers.

Since the refining sector will need to make substantial investments in improving fuel quality country wide to make the next stage of vehicle emission standards possible, it needs to be adequately incentivized to make these investments.

Finally, the report of the Mashelkar committee on which the Auto Fuel Policy of 2003 was formulated had made an important recommendation with respect to *institutional mechanism for addressing vehicular emissions and fuel quality* as shown in Figure 4. Some elements of such a mechanism exist independently today, and a standing committee on implementation of emission standards (SCOE) exists within the Ministry of Road Transport and Highways (MoRTH). A National Automobile Pollution and Fuel Authority (NAPFA), as recommended by the Mashelkar committee, will bring about a greater level of co-ordination and forward looking vision.

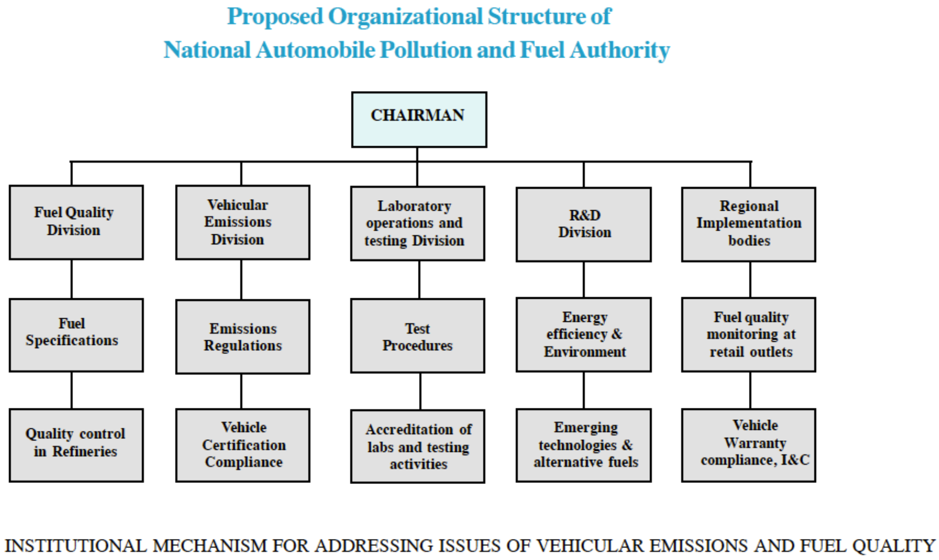


Figure 4: Structure of the National Automobile Pollution and Fuel Authority as recommended by the Mashelkar committee

3. Emission Control Technologies required to meet Euro V/VI standards

The emission standards limit values in the EU, as well as in other mature programs such as the United States, California, and Japan, are set primarily based on the reductions achievable by the best available technologies in the period considered. The set of technologies required to meet each European regulatory step, and correspondingly each Bharat step, is summarized in Table 1, and described in detail in **Annexure – I**.

Table 1. Key Technologies to meet Euro V/VI equivalent Standards

Vehicle Category	Key Technologies to meet Euro V/VI equivalent standards
Gasoline 2/3 wheelers	Closed loop oxygen sensor and three way catalyst
Diesel 3-wheelers	Oxidation catalyst to reduce PM emissions
Gasoline Light-duty vehicles	Continued improvements in air-fuel management systems and three-way catalyst performance
Diesel Light-duty vehicles	High pressure fuel injection systems, Diesel Particulate Filters (DPFs), and Lean NOx Traps (LNTs) or SCR
Diesel Heavy-duty vehicles/equipment	Exhaust gas recirculation (EGR), selective catalytic reduction (SCR), and Diesel Particulate Filters (DPFs)

It should be noted that many of the technologies used to reduce air pollutants will also have a beneficial impact on vehicle fuel economy. As engines are upgraded to include technologies such as variable valve timing (VVT) and variable geometry turbochargers (VGTs), they will yield a side benefit in terms of lowering the fuel consumption, thus increasing cost effectiveness of using these technologies.

The Indian automotive industry has strong technical capacity to meet these future emission standards through development and customization of these technologies for the Indian market. Almost all major manufacturers in India have strong R&D programs themselves, but also have international collaborations that grant them access to the best available technology. Examples of these include high-pressure common-rail diesel engines used by TATA in passenger cars, success of Mahindra in getting a pick-up truck certified to US Tier II standards which are more stringent than Euro VI, and setting up of a joint manufacturing plant by Eicher and Volvo in India to export Euro VI engines for heavy trucks in EU.

4. Fuel quality required to meet Euro V/VI emission standards

4.1 Importance of Improving Fuel Sulfur Quality

Extensive studies have been carried out in the US, EU and Japan to understand the linkage between vehicle technology, fuel quality and emissions level.[2] These studies have shown that sulfur in gasoline and diesel fuel negatively affects the performance of catalytic aftertreatment devices used in passenger and commercial vehicles and also contributes to particulate sulfate (a PM component) and sulfur oxides emissions (SOx). Studies of fuel sulfur effects on gasoline and diesel vehicles' emissions distinguish the benefits of sulfur reduction in two categories, namely enhancement and enablement benefits (Hochhauser et al., 2006). First, lower sulfur enhances the performance of emission control devices by improving their efficiency, as is the case of the three-way catalyst (TWC) for gasoline vehicles. Second, lower sulfur fuel enables the adoption of certain emission control technologies that otherwise would render unacceptable performance and risk damage, as is the case of DPF for diesel vehicles. These findings highlight that the best vehicle emission performance can only be achieved if fuel and vehicle standards are treated as a system and implemented in parallel and a strong compliance program is established to enforce both fuel and vehicle standards.

In general, the sulfur content is one of the greatest barriers to further progress on emission standards, especially for diesel vehicles. **Annexure II** describes the impact of gasoline and diesel fuel quality on meeting Euro V/VI emission standards in detail, whereas **Annexure III** provides a comparison of fuel quality standards in different parts of the world. The best available emission control technologies, including three-way catalysts for petrol fueled vehicles, diesel particle filters (DPFs) and zeolyte SCR catalysts are sensitive to sulfur. To achieve Euro V/VI level emission standards, it would be important to reduce the sulfur content of fuels to 10-15 ppm as soon as possible.

An overview of current Indian refinery situation and readiness to meet ultra-low sulfur fuels (ULSFs) is provided in **Annexure IV**[3]. The desulfurization technologies capable of reaching ULSF level are medium- and high-pressure hydrotreating, and hydrocracking. The total installed capacity in India for hydrotreating and hydrocracking is equivalent to 6% and 5%, respectively, of the total crude refining capacity, which is 184 MMTPA. The installed refining capacity is expected to increase above 260 MMTPA by 2014, including expansion projects for low-sulfur refining.

Capital investments for hydroprocessing technologies can vary depending on the baseline refining technology available at the time of implementation. The specific cost depends on the assumptions made with regard to crude sulfur levels, refinery configuration and the desired levels of sulfur reductions. **Annexure V** summarizes the technologies and costs of achieving ULSF supply nationwide. The incremental cost of ultra-low sulfur diesel (ULSD) as compared with the 350 ppm sulfur level nationwide at present, is estimated at not more than 0.9 Rs/liter. Gasoline desulfurization is less expensive, with incremental costs of no more than 0.3-0.4Rs/liter when reducing the sulfur levels from 150 to 10 ppm.

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[2] For example, the Auto/Oil Air Quality Improvement Research Program (AQIRP) established in the US in 1989 included major oil companies, automakers and four associate members. A test program called the European Program on Emissions, Fuels and Engine Technologies (EPEFE) was initiated by the European Commission and joined by the auto and oil industry. The Japan Clean Air Program (JCAP) was formed by the Petroleum Energy Center as a joint research program of the auto and oil industries and supported by the Ministry of Economy, Trade and Industry.

[3] Ultra-low sulfur fuels (ULSFs) are defined as fuels containing less than 15 ppm sulfur content.

4.2 Experience of Other Countries in the Introduction of Ultra-low Sulfur Fuels

All industrialized countries currently mandating ultra-low sulfur fuels (ULSF) used a combination of regulations and incentives for ULSF penetration. Japan mandated 10-ppm gasoline and diesel starting in 2007, but provided incentives to refineries ahead of that date in the form of tax breaks and subsidies (Gallagher & Hoyer, 2005).

In the United States (US) no direct tax breaks and subsidies were given to refineries, but other incentives were introduced. Ultra-low sulfur diesel (ULSD) (diesel with <15 ppm sulfur) was phased in from 2006-2009, which gave refineries time to acquire the technology and machinery necessary for ULSD production. Refineries were allowed to trade sulfur credits among each other during this period to reward those ahead of schedule and to incentivize those lagging behind to catch up. Small refineries were also offered the option of extending their compliance with the 80-ppm gasoline standard in exchange for meeting ULSD standards early (Gallagher & Hoyer, 2005). Similar policies are in place now as the US phases in near-zero sulfur gasoline.

Like in the US, Europe did not give direct financial incentives to refineries, but created policies that gave refineries time and flexibility to produce ULSF. 50-ppm sulfur gasoline and diesel were mandated in 2005 and the next four years served as transition time before 10-ppm gasoline and diesel were mandated. During this period, many European countries adopted a provision that ULSF be made *widely available*, which encouraged refineries to set themselves up for ULSF production early on. Newer European Union (EU) countries were allowed to switch to ULSF later than older EU countries, and much leeway was given to individual localities to adopt their own strategies to implement ULSF (Gallagher & Hoyer, 2005).

The experience of Europe provides the best example for India, since Bharat emission and fuel quality standards are based on the European model. Two sets of emission standards persist in India at present: Euro IV equivalent standards in 13 major cities and Euro III equivalent standards in the rest of the country. As was done in Europe, India can first mandate 50-ppm sulfur fuel nationwide with the provision that major cities move to ULSF. ULSF can then gradually be made available throughout the rest of the country during a phase-in period, starting with all national highways for example. Flexibility in transitioning to ULSF can be granted to outlying areas to lower economic and logistical burdens.

5. Conclusions and considerations of policymakers

Having implemented the vehicle emission standards and fuel quality standards from the Auto Fuel Policy of 2003, policymakers now need to turn their attention to the next round of emission reductions from the transport sector. Developing a comprehensive roadmap soon will not only create regulatory certainty for the oil and auto sectors and their supplier base, but would also realize key air pollutant reductions that can help many cities achieve better ambient air quality. This is certainly in the spirit of the Auto Fuel Policy of 2003, which recommended revisions to the policy every five years.

As an example, consider two scenarios of implementation of improved emission standards and fuel quality. In the first scenario, India would continue to adopt dual emission and fuel quality standards with a five to ten year lag behind EU policies. In the second scenario, India could leapfrog to the best EU standards available i.e. Euro VI in 2015. The resulting impact on NOx and PM emissions is shown in Figure 5.

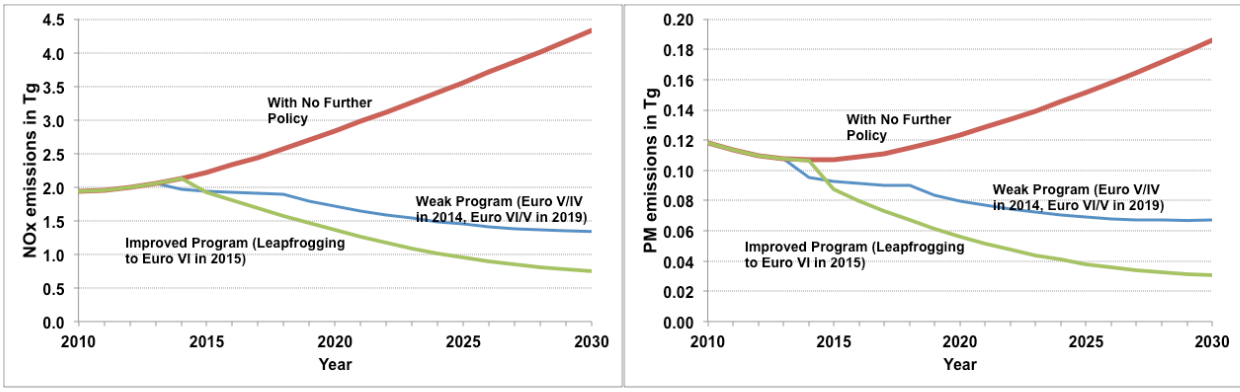

Figure 5: Projected total NOx and PM emissions with further policy action (2010-2030).

As shown in Figure 5, the implementation of Bharat V/VI standards across the country could reduce net emissions of NOx and PM emissions by as much as 65-85% in spite of quadrupling of vehicle sales between now and 2030. Such major reductions can reduce mortality by tens of thousands per year while also reducing chronic as well as acute illnesses across the board.

With market share of diesel passenger cars expected to rise up to 50% over the next few years, concern about diesel vehicle emissions may continue to persist (Times of India, 2011). By implementing Bharat V and VI emission standards as soon as possible, the country would be able to take full advantage of the fuel savings offered by diesel technology without raising concern about air pollution.

The technology analysis shows that 50-ppm or less sulfur fuels are required countrywide for the next generation of emission standards, and proper functioning of present Bharat IV vehicles. Further, the availability of 50-ppm sulfur countrywide may also aid in leapfrogging to the strictest emission standards such as Euro VI, since the after-treatment devices would function properly with 50-ppm sulfur, although at a lower efficiency. A subsequent introduction of 10-ppm sulfur fuels countrywide could improve emission reduction performance further.

The technological know how needed to achieve these reductions is already available in the marketplace, although it will take a determined effort from all stakeholder and adequate lead-time to implement these technologies effectively. Therefore, it is imperative for the policymakers to start stakeholder consultations and formulate a plan to draw up the next phase of Auto Fuel Policy in India.

Annexure – I. Emission Control Technologies required to meet Euro V/VI standards

A.I.I EU and Bharat Emission Standards for Light-Duty Vehicles

The European regulation for passenger cars and light commercial vehicles is structured by vehicle weight and fuel type. The regulation applies to vehicles with a gross vehicle weight (GVW) not exceeding 3500 kg. The following table presents the emission standards for Passenger cars (M1, up to 9 passengers) and light commercial vehicles (N1). The upper weight limit for passenger cars (M1) has been extended since Euro 5 to 2610 kg to include larger vehicles (SUVs). More details can be found in the DieselNet website http://www.dieselnet.com/standards/eu/ld.php.

Table 1. EU Emission Standards for Passenger Cars* (ECE + EUDC chassis dynamometer test)

		Grams per Kilometer (g/km)					
Standard	**Date**	**CO**	**HC**	**HC+NOx**	**NOx**	**PM**	**PN**
Gasoline							
Euro 3	Jan-2000	2.30	0.2	-	0.15	-	-
Euro 4	Jan-2005	1.00	0.1	-	0.08	-	-
Euro 5	Sep-2009[a]	1.00	0.1[b]	-	0.06	0.005[c,d]	-
Euro 6	Sep-2014	1.00	0.1[b]	-	0.06	0.0045[c,d]	TDB
Diesel							
Euro 3	Jan-2000	0.64	-	0.56	0.50	0.050	-
Euro 4	Jan-2005	0.50	-	0.30	0.25	0.025	-
Euro 5a	Sep-2009[a]	0.50	-	0.23	0.18	0.005[d]	-
Euro 5b	Sep-2011	0.50	-	0.23	0.18	0.0045[d]	$6x10^{11}$
Euro 6	Sep-2014	0.50	-	0.17	0.08	0.0045[d]	$6x10^{11}$

* Category M1 vehicles. For Euro 1 through 4, vehicles greater than 2,500 kg were type approved as Category N1 vehicles
a – Sep 2010 for all M and N vehicle weight categories
b – NMHC limit = 0.068 g/km
c – applicable only to vehicles with DI engines
d – 0.0045 g/km using the PMP measurement procedure
e – After Sept 30 1999, vehicles with DI engines had to meet the IDI limits

The Indian regulation for passenger cars is very similar to the European and applies to vehicles with GVW not exceeding 3500 kg and less than 6 passengers (instead of 9). The following table presents the emission standards for Passenger cars (M1, up to 6 passengers) and light commercial vehicles (N1).

Table 2. India Emission Standards for Passenger Cars* (Modified NEDC test cycle)

		Grams per Kilometer (g/km)				
Standard	**Date**	**CO**	**HC**	**HC+NOx**	**NOx**	**PM**
Gasoline						
India I	2000	2.72	-	0.97	-	-
Bharat II	2001[a]	2.20	-	0.50	-	-
Bharat III	2005[b]	2.30	0.20	-	0.15	-
Bharat IV	2010[c]	1.00	0.10	-	0.08	-
Diesel						
India I	2000	2.72	-	0.97	-	0.14
Bharat II	2001[a]	1.00	-	0.70	-	0.08
Bharat III	2005[b]	0.64	-	0.56	0.50	0.05
Bharat IV	2010[c]	0.50	-	0.30	0.25	0.025

a - From Apr 1, 2000 in Delhi, Jan 1, 2001 in Mumbai, Jul 1, 2001 in Kolkata and Chennai, Apr 1, 2003 in Bangalore, Hyderabad, Ahmedabad, Pune, Surat, Kanpur and Agra, Apr 1, 2005 in rest of country.
b - From Apr 1, 2005 in Delhi, Mumbai, Kolkata, Chennai, Bangalore, Hyderabad, Ahmedabad, Pune, Surat, Kanpur and Agra, Apr 1, 2010 in rest of country.
c - From Apr 1, 2010 in Delhi, Mumbai, Kolkata, Chennai, Bangalore, Hyderabad, Ahmedabad, Pune, Surat, Kanpur and Agra.

A.I.II Two- and Three-Wheelers

The two- and three-wheeler category is composed of mopeds, scooters, motorcycles and three-wheelers. Under Bharat III emission regulations, the test cycle for emission and fuel economy is the Indian Driving Cycle for 2- and 3-Wheelers. The progression of technical solutions applied to Indian gasoline 2- and 3-wheelers to meet the current emission standards–the BSIII introduced in the year 2010–and the expected progression for Bharat IV and V are presented in Table 3. Diesel engines are only used for 3-wheeler applications. PM emissions from three-wheeler diesel vehicles are controlled through the oxidation catalyst (OC).

Table 3. Gasoline Two- and Three Wheeler Technology Requirements for Controlling Conventional Pollutants

Gasoline	Regulation		
	Bharat III (2010)	Bharat IV [(a)]	Bharat V [(a)]
Regulated pollutants	CO/HC+NOx/PM	CO/HC+NOx/PM	CO/HC+NOx/PM
Emissions standard, g/km	G2W: 1.0/1.0/- G3W: 1.25/1.25/- D3W: 0.5/0.5/0.05	G2W: 1.4/0.81/- [(b)] G3W: 0.94/0.94/- [(b)] D3W: 0.38/0.38/0.038 [(b)]	G2W: 0.84/0.53/- [(b)] G3W: 0.66/0.66/- [(b)] D3W: 0.26/0.26/0.026 [(b)]
Engine -out emissions A/F control	*Most 2-3 wheelers have carbureted engines (2S and 4S) *Engine/lubrication optimization for all 2-3 wheelers (2S and 4S) G2W-4S Air-Fuel control: *A few high-end models with Port Fuel Injection (PFI) G2W-4S Engine Optimization: *Variable ignition timing (some high-end models only)	*Most 2-3 wheelers have carbureted engines (2S and 4S) * A few 2-3 wheelers models with electronic carburetors [(c)] (2S and 4S) G2W-2S Air-Fuel control: * A few models with Air Assisted Direct Injection G2W-4S Air-Fuel control: * A few models with PFI G2W-4S Eng. Optimization: * Wider use of variable ignition timing	*Some 2-stroke engines replaced by 4-stroke G2W-2S Air-Fuel control: * Some models with Air Assisted Direct Injection * Electronic carburetor for most GSW-4S Air-Fuel control: *Most models with PFI * Some models with Closed Loop System + Three-Way Catalytic Converter *Some high end models with Gasoline Direct Injection
After-treatment system	Oxidation Catalytic (OC) Converter for all 2-3 wheeler models (2S and 4S) G2W-4S Aftertreatment * Secondary Air Injection in a few models * Three-Way Catalytic Converters used in high-end models with PFI D3W: OC for PM control	*Improved OC converter for all 2-3 Wheeler models (2S and 4S) G2W-4S Aftertreatment * Close Coupled Catalyst / Start-up Catalyst / Quick Warm-up Catalyst * Exhaust Insulation (double exhaust pipes) –on selected model D3W: OC for PM control	*Improved OC converter for all 2-3 Wheeler models (2S and 4S) G2W-4S Aftertreatment * Closed Loop System (O2 sensor) + Three-Way Catalytic Converter required in some models D3W: OC for PM control

G2W: Gasoline 2-wheelers; G3W: Gasoline 3-wheelers; D3W: Diesel 3-wheeler; 4S: 4-stroke; 2S: 2-stroke

(a) These two sets of standards have not been officially proposed or defined. The standards presented here for Bharat IV and V are not official and were estimated assuming that the test cycle used is the World Motorcycle Test Cycle (WMTC), and that the future Indian standards would be numerically equivalent to the percentage reduction expected from Euro 4 and 5 with respect to Euro 3-GTR2 standards.

(b) Emission limit values are based on the WMTC cycle after transposing European standards into Indian conditions.

(c) The electronic carburetor air-fuel ratio control operates a solenoid valve that receives signals from the ECU, replacing most mechanical actuators used in the conventional carburetor. The ECU receives air-fuel ratio readings from a lambda sensor (O2 sensor). Its main utility is in start-up and idling situations.

It should be noted that Three-Way Catalytic Converters (TWC) have not come into use so far on Indian two- and three- wheeled vehicles because the combined HC and NOx emission standard allows for focusing the reduction on HC emissions, which required only an oxidation catalyst (OC). A TWC would require an accurate control on air-fuel ratios, which can be achieved only with an electronic fuel injection or an electronic carburettor along with a closed loop system using an oxygen sensor as in passenger cars (Iyer, 2011).

A.I.III Light-Duty Vehicles

This category includes passenger cars, vans and light cargo trucks (M1 and N1). Regulated emissions include hydrocarbon (HC), carbon monoxide (CO), oxides of nitrogen (NOx), and particulate matter (PM) and are tested using a modified version of the NEDC[4].

Table 4. Gasoline LDV Technology Requirements for Controlling Conventional Pollutants

Gasoline	Regulation		
	Euro 4	Euro 5	Euro 6
Regulated pollutants	CO/NOx/HC	CO/NOx/HC/(PM)[b]	CO/NOx/HC/(PM)[b]
Emissions standard, g/km	1.0/0.08/0.1	1.0/ 0.06/ 0.1/ (0.005)	1.0/ 0.06/ 0.1/(0.005)
Emissions reduction vs. previous standard	57% / 50% / 50%	0 / 25% / 0 / -	0 / 0 / 0 / -
Engine -out emissions A/F control	* Stoichiometric combustion *Electronic Injection, *Electronic ignition, *Multi-point fuel injection (MPFI) *Improved controller and Hardware *Improved fueling strategy for proper closed coupled (CC) catalyst operation[a] * Use of EGR for NOx control	-Same as Euro 4 vehicles plus: * Air-Fuel management system improvements *Variable valve timing (VVT) in large vehicles -Stoichiometric GDIs require: *Improved injectors *Higher press. Injection *Linear range O2 sensor for A/F control.	-Same as Euro 5 vehicles plus: * Conventional pollutants control same as Euro 5 technologies. - Improvements focused on fuel economy (FE): Turbocharging, downsizing and Hybridization
After-treatment system	* Three way catalyst (underfloor) *A secondary O2 sensor is required for OBD * Closed coupled (CC) catalyst is required in some models[a]	* Improvements in the TWC system *GDIs might require specially formulated TWCs	Same as Euro 5 vehicles

a- The elimination of warm up period during the test cycle and increased restriction on HC and CO emissions required the addition of a closed coupled (CC) cold start catalyst. In addition, fueling strategy is improved for keeping closed coupled (CC) catalyst at the right temperature range for cold start emissions control

b- Increased use of gas direct injection (GDI) -stoichiometric combustion- forces regulations to include PM emissions levels for GDI vehicles

Table 5. Diesel LDV Technology Requirements for Controlling Conventional Pollutants

Diesel	Regulation		
	Euro IV	Euro V	Euro VI
Regulated pollutants	NOx/PM/CO/HC	NOx/PM[a]/CO/HC	NOx/PM[a]/CO/HC
Emissions standard, g/km	0.25/0.025/0.5/0.05	0.18/0.005/0.5/0.05	0.08/0.0045/0.5/0.09
Emissions reduction vs. previous standard	50% / 50% / 22%	28% / 80% / 0 / -	66% / 10%/ 0 / -
Engine -out emissions A/F control	-Euro 3 diesel technology deals with cold start challenges. -Rotary pumps and common rail share the market but Euro 4 is dominated by common rail systems. -Technologies: * Rotary pump injection timing control improved (for cold start and fast idle) * Common rail systems became available for Euro 3 vehicles. * DI combustion + high-pressure	-Based on Euro 4 technologies -Emission control heavily focused on: * Air-fuel management and combustion improvements * Engine tuning and mapping -Technologies: * High pressure fuel injection 1600-1900 bar * Tumble and swirl control (electronic operated valve) * Variable geometry turbo. (VGT) for improved air-fuel	-Based on Euro 5 technologies. -Improvements on Air-Fuel management, combustion and engine tuning and mapping. -Technologies: * High pressure fuel injection 1800-2100 bar *Variable geometry turbocharger (VGT) may be used in most passenger cars and commercial vehicles.

[4] The New European Driving Cycle (NEDC) is a combination of the ECE 15-cycle urban driving cycle and the EUDC (Extra Urban Driving Cycle)

Diesel	Regulation		
	Euro IV	Euro V	Euro VI
	fuel injection (HPFI). * Pressure 700-1300 bar *Cooled EGR	management for large vehicle * Variable fuel injection timing for DPF regeneration * Variable valve timing (VVT). This may also be used for DPF regeneration and improved FE.	VGT use Improves fuel economy (FE)
Aftertreatment System	* Diesel Oxidation Catalyst (DOC) for PM reduction (SOF fraction)	* DOC + DPF * DPF is regenerated through active or passive techniques with high-temperature exhaust downstream from the DOC. * LNT may be required in large engines (Vd~3.0 liters)	*DOC+DPF +LNT 1.2 < Vd < 2.5 L *DOC+DPF+SCR, Vd~3.0L Choosing LNT vs. SCR depends on costs and FE approach

a- The introduction of particulate matter control by number ($PN \leq 6x10^{11}$) starting for Euro 5 since 2011, mandates the use of wall-flow DPF besides in-cylinder PM emission control measures.

The Euro standards, unlike the US program, have different requirements for diesel and gasoline vehicles, with a less stringent NOx requirement for diesel vehicles—even in the upcoming Euro 6 standards. In contrast, the US program has set the same standards for all fuel types.

A.I.IV Heavy Duty Vehicles

The heavy-duty vehicle category is comprised of large passenger and commercial vehicles with a gross vehicle mass (GVM) over 3,500 kg (categories M2, M3, N2 and N3). Table 6 summarizes the technologies that have been utilized to achieve Euro III to VI standards. Note that engines—not entire vehicles—are subject to testing, and the limits are given in grams of pollutant per work output of the engine (grams/kilowatt-hour or g/kWh). While these limits apply to both compression ignition (diesel) and spark ignition (gasoline, natural gas, or liquefied petroleum gas) engines, this table covers only diesel vehicle technologies, as diesel is the dominant power plant in the heavy-duty sector. It should be noted that European standards for spark ignition HD engines are different from compression ignition engine standards.

Table 6. Heavy-duty diesel vehicle emission control technology developments

Diesel	Regulation		
	Euro IV	Euro V	Euro VI
Regulated pollutants	NOx / PM / HC / CO	NOx / PM / HC / CO	NOx / PM / HC / CO
Emissions target, g/kWh[a]	3.5 / 0.02 / 0.46 / 1.5	2.0 / 0.02 / 0.46 / 1.5	0.4 / 0.01 / 0.13 / 1.5
Emission reduction vs previous standard[a]	30% / 80% / 30% / 29%	43% / 0% / 0% / 0%	80% / 50% / 72% / 0%
Engine-out emissions and air/fuel (A/F) controls	* High-pressure fuel injection * Electric fuel timing and metering, including timing retard for low NOx * Electric EGR, with cooling system * Improvements in engine combustion and calibration for PM control * Turbocharging with intercooling * NOx control[b]: EGR cooled	* Improvements in engine combustion and calibration * Multiple injection fuel system (pilot-main-post) Variable geometry turbocharger (VGT) * NOx control[b]: EGR cooled	* Variable geometry turbocharger (VGT) * Combustion research * PCCI[c], LTC[d]
Aftertreatment system	* NOx control[b]: -SCR systems (open loop) * PM control:	*NOx control[b]: -SCR systems (closed loop)	* NOx control: SCR systems (closed loop) * PM control: DOC +

Diesel	Regulation		
	Euro IV	Euro V	Euro VI
	-DOC in some vehicles. Most rely on in-cylinder control -DOC+Partial Flow Filter (PFF) used in Europe	* PM control: - DOC in some vehicles. Most rely on in-cylinder control -DOC+PFF	DPFs – wall flow filters

a – Emissions measured over the ESC engine dynamometer test cycles.
b – NOx control through EGR or SCR is manufacturer's choice.
c – PCCI: premixed charge compression ignition. Includes multiple fuel timing and metering, allowing for a multimodal combustion engine.
d – LTC: Low temperature combustion. Air-fuel management improvements aim to avoid high temperatures that led to NOx formation.

As presented in Table 6, Euro VI PM limits will require the use of DPFs and low sulfur fuel. As in the light-duty case, near-zero (< 10-ppm) sulfur levels will enable DPFs to perform at their maximum potential, although fuels with 50-ppm will allow the DPF to function, albeit with somewhat higher PM emission levels. To accelerate the environmental and health benefits beyond what can be achieved by strictly following the Bharat III→IV→V→VI pathway, DPFs can be introduced early through incentives as was done in some European countries through road tax pricing schemes (e.g. Germany) or the establishment of Low Emission Zones. This is a viable strategy in urban areas where lower sulfur fuels are already available, however its practical implementation may be limited to city transit buses.

Accelerated benefits could also be achieved through adopting standard limits that require DPFs ahead of the Bharat III→IV→V→VI schedule (e.g. Bharat VI PM limits adopted with Bharat V when Bharat V may come into force in Indian cities). Such requirements could focus on the vehicles types likely to remain within the lower sulfur diesel zone. For example, the Santiago Metropolitan Region in Chile requires all new buses to meet a PM standard that requires Euro III vehicles to be outfitted with DPFs verified by the California Air Resources Board (CARB) or the European VERT (Verminderung der Emissionen von RealmaschinenimTunnelbau) program. In addition, the availability of ULSF would allow leapfrogging from current standards to Bharat 6/VI (Euro 6/VI), provided that a nationwide supply is in place to avoid durability issues with sulfur sensitive technology.

As seen in Europe, meeting the NOx limits for Euro IV and V will require the use of Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR). SCR provides fuel efficiency advantages but requires the use of urea as a reagent to ensure NOx emissions are reduced. Development of an adequate urea infrastructure is a critical step for enabling SCR technology so that urea is widely available to truck operators. Another key consideration is that SCR systems need to be coupled with failsafe measures to ensure that urea is used and the tank is replenished. Options for driver inducements range from warning lights for tank levels, urea quality sensors to make sure tank is filled with urea and not other substances, and limiting the performance of the vehicle if the vehicle is operated when the tank is empty (e.g. drastically reduced speeds or inability to start the engine).

Annexure – II. Impact of fuel quality on emission control technologies

A.II.I Gasoline (Petrol)

While India has made progress in improving gasoline standards, the higher sulfur content in non-Bharat IV areas will have to be addressed in the future if India decides to adopt Bharat IV emissions standards nationwide. The current gasoline standards took effect on Apr 1, 2010 and are 150 ppm for the whole country and 50 ppm for cities where Bharat IV is in effect. Both these standards are marked improvements from Bharat II levels of 500 ppm.

The main concern with sulfur levels in gasoline-powered vehicles is the performance of the three-way catalytic converter (TWC). The TWC is in charge of controlling HC, CO and NOx emission from spark ignited, gasoline vehicles. According to Hochhauser (2009), sulfur concentration in gasoline impacts the operation of the TWC and sensors, without changing fuel octane, engine performance or fuel economy. After analyzing numerous studies on this issue, Hochhauser concluded that reducing the sulfur levels of gasoline lowers emissions of HC, CO and NOx, and that the effect of the reduction is linear, especially for levels below about 150 ppm. The effect of sulfur on PM emissions from gasoline vehicles, while possible, was not detected with 2003 measurement technologies. Table 7 shows some results from the Auto/Oil Air Quality Improvement Research Program (Rutherford, et al., 1995), the CRC Project E-60 (Durbin, et al., 2003) and the European Program on Emissions Fuels and Engine Technologies (Petit, Jeffrey, Palmer, & Steinbrink, 1996). This small sample of studies show that significant benefits can be achieved across all vehicles and cycles when the gasoline sulfur content is reduced to low levels. The results on the US06 test cycle, the most aggressive test cycle, suggest that sulfur reduction significantly lower NOx and non-methane hydrocarbons (NMHC) emissions, which are associated with high-power engine operational conditions.

The sulfur effects on non-regulated emissions were also studied during the CRC Project E-60 for NH_3 and N_2O(Durbin, et al., 2003). Reducing sulfur from 150 ppm to 30 ppm reduced NH_3 emissions from 38 mg/mi to 34 mg/mi, and reduced N_2O emissions from 17 mg/mi to 7 mg/mi.

The significance of sulfur content for 2- and 3- wheelers is the same as that for 4-wheelers, namely the adverse effect on the performance of the catalytic converter. The importance of sulfur content will increase once use of TWC with closed-loop systems are required to meet the proposed BS IV and BS V emission standards as size and performance can be optimized for low-cost provided that ultra-low sulfur is available. Oxidation catalyst and TWC for two- and three-wheeler are very constrained regarding backpressure, size and cost, which make them extremely vulnerable to fuel quality (Meszler, 2007).

Table 7. Sulfur Effects on Gasoline Passenger Vehicle Emissions

Study	Vehicles	Sulfur level, ppm	Test Cycle	NMHC/HC, %	CO, %	NOx, %	Reference
AQIRP	Tier 1	320 -> 35	US FTP	NMHC: -18.5	-16.4	-8.9	Rutherford et al. (1995)
EPEFE	Euro 2	382 -> 18	NEDC	HC: -8.6	-9.0	-10.4	Petit et al., (1996)
CRC E-60	LEV and SULEV	150 -> 5	FTP	NMHC: -2.2	-6.4	-31.0	Durbin et al. (2003)
			US06	NMHC: -64.1	-10.2	-70.8	

A.II.II Diesel

Diesel fuel quality is perhaps more important in India than in other countries because of the high use of diesel compared to gasoline in the country: 51.7 million metric tons of diesel and 11.2 million metric tons of petrol were consumed in India during the FY 2008-09, a ratio of almost 5:1 (MoPNG, 2010). This ratio of diesel to petrol consumption has been maintained over the last

6 years, as reported by the MoPNG (2010). This is at least partly due to government subsidies for diesel, including lower taxes compared to petrol, but also due to the importance of diesel fuel in agriculture and freight.

India has reduced its diesel sulfur content from 10,000 ppm in most of the country in 1999 to a maximum content of 350 ppm today. In major metropolitan areas the level has fallen from 2500 ppm to 50 ppm in the same time period.

The main issues with sulfur content on diesel fuel are the impact on engine-out PM emissions and its effect on aftertreatment devices. The effect of diesel sulfur content on HC, CO and NOx engine-out emissions is insignificant in most conditions. The impact on PM emissions can be explained as follows: During combustion, the sulfur compounds present in diesel fuel burn to form SO_2. A small fraction of SO_2 is later oxidized into SO_3 and sulfuric acid. SO_2 in the exhaust can be later oxidized over some catalysts to form sulfate particles, which, added to sulfuric acid droplets acting as a nucleation site for particle formation and growth, increasing the PM mass emissions (Hochhauser, Schleyer, & Yeh, 2006).

Engine-out PM emissions of any diesel engine and the performance of aftertreatment devices are affected by the diesel sulfur level. As engine-out PM is reduced through improvements in air-fuel management and combustion, the sulfate amount tends to remain constant, increasing its share on PM emissions. Engine-out effects studied in older engines show reductions of 7% in PM when reducing sulfur level from 3000 to 500 ppm for late 80's model engines (Bartlett, et al., 1990). Better reductions were obtained in newer vehicles. Alam et al. (2004) found up to 20% PM reductions when reducing sulfur from 325 ppm to 15 ppm in a model year 2000 diesel engine. Tests performed on heavy-duty vehicles show that in the absence of aftertreatment, fuel sulfur only affected the sulfate portion of PM emissions (Lee et al., 1998). The Diesel Emission Control Sulfur Effects Project (DECSE) report shows that engine-out PM emissions increased linearly by 29% when the sulfur level was increased from 3 ppm to 350 ppm under the European steady state cycle (ESC). For a diesel vehicle with no emission control, sulfur-related PM emissions are directly related to the fuel sulfur content. Therefore, reducing sulfur in fuels can result in lower PM emissions from any diesel engine regardless of the vehicle standard the engine could reach.

The performance of aftertreatment devices with respect to sulfur levels was studied under the DECSE program for diesel particulate filter (DPF), diesel oxidation catalyst (DOC) and lean NOx traps (LNT) (NREL, 2001). Results are presented in Table 8. The study showed that diesel sulfur levels have a strong effect in PM emissions, given that approximately 40%-60% of sulfur in fuel is converted into PM sulfates when tested under the ESC. Sulfates might accumulate on the DPF substrate, increasing its loading rates, or bypass the DPF and continue interacting with water and other species to form PM. As a consequence, PM emission rates, regeneration temperature and exhaust backpressure are affected. The regeneration temperature required for burning the PM accumulated in the DPF increased as the sulfur level was increased from 3 ppm to 30 ppm, but remained steady after that (NREL, 2001). During the Japanese Clean Air Program, Oyama and Kakegawa(2003) found that reducing diesel the sulfur level from 443 ppm to 46 ppm produced an increase in fuel economy of 7.5% due to reduced filter backpressure from slower PM accumulation.

The DECSE program also studied the effect on DOC performance. The DOC oxidizes HC, CO and the soluble organic fraction of PM over a catalyst surface. It might also oxidize SO_2 into SO_4, which ends up as PM. In the DECSE study, when the DOC was tested at high exhaust temperatures, during steady state tests, PM emission increased if $S \geq 150$ ppm, which was attributed to the increased SO_4 fraction. Under transient tests, which generate colder exhaust temperatures, the S level did not impact the PM emissions or the DOC capacity for soluble organic fraction (SOF) oxidation. HC emissions were slightly increased by S levels, while CO emissions were not affected.

The lean NOx trap (LNT) removes NOx in a lean exhaust environment by oxidizing NO into NO_2, storing the NO_2 into alkaline earth, and finally reducing the stored NO_2 in a hydrocarbon-rich environment, as the LNT works. According to the Manufacturers Emission Control Association (MECA), the compounds that trap NOx are more active with sulfur compounds, occupying the storage spaces reserved for NOx trapping. For this reason LNT requires ULSD, reaching 90% efficiency for NOx conversion (MECA, 2007). The durability of the LNT is highly dependent on desulfurization regeneration, an active field of study for LNT development. Engine control strategies for desulfurization include higher exhaust temperature under rich engine operation for short periods of time, which implies fuel penalties and increased deterioration rates (Heck, Farrauto, & Gulati, 2009). In conclusion, LNT devices are particularly sensitive to sulfur compounds, and lose efficiency and deteriorate if $S \geq 15$ ppm (Hochhauser, Schleyer, & Yeh, 2006).

SCR systems are less sensitive to fuel sulfur levels than LNT and DPF technology, although their sensitivity varies by catalyst formulation. There are two types of commercial catalyst used for mobile SCR applications: vanadium based and zeolites based. Vanadium based catalysts have been used for Euro IV and V applications, while zeolites (typically iron or cooper) have been used for Japan 2005, US2010 and are expected for Euro VI. Zeolite catalysts are more thermally durable than vanadium catalysts (Girard, Montreuil, Kim, Cavataio, & Lambert, 2008).

Vanadium catalysts are known for their robustness to sulfur poisoning, which allows surviving exposure at sulfur levels up to 2000 ppm (Girard, 2008). Copper-zeolite catalysts are inappropriate for use with fuel sulfur levels above 50 ppm due to their vulnerability to poisoning by SO_2 and SO_3 (Johnson 2009; Cheng 2009). Since Cu-zeolite SCR catalysts display the best cold-start performance characteristics, this suggests that developing countries without access to low-sulfur fuels may have disproportionately large problems with urban in-use emissions. Iron zeolites can be used with 350-ppm sulfur fuel, albeit with significantly reduced deNOx efficiency, provided the catalysts are periodically regenerated above 600 degrees Celsius (Johnson 2010). Note that this condition is unlikely to be met under urban driving conditions in India.

For these best available technologies to be used under the right operational conditions and obtain the best emission benefits, the vehicles should be operated with the appropriate fuel quality, especially sulfur content. The sulfur content is one of the greatest barriers to further progress on emission standards, especially for diesel vehicles. The best available emission control technologies, including three-way catalysts for SI vehicles, diesel particle filters (DPFs) and zeolyte SCR catalysts are all sensitive to sulfur. If India wishes to implement Bharat IV standards nationwide soon and move beyond that in the future, DPFs for heavy-duty vehicles will be necessary and will require fuels with a sulfur level of 50-ppm or less (10-ppm is preferable for further reduction of PM emissions).

Table 8. Sulfur Effects on Diesel Vehicle Aftertreatment Devices

Aftertreatment	Study	Test conditions	Effects	S level -> efficiency	Max. Sulfur
DPF – PM reduction	DECSE (NREL, 2001)	ESC – 13 mode on Caterpillar I-6, 7.2 L, 275 hp	• Increasing sulfur level reduces DPF efficiency with respect to engine-out values. • Filter regeneration temperature increases with S levels	PM reduction eff. 3 ppm -> 95% 30 ppm -> 73% 150 ppm -> 0% 300 ppm -> -130%	S≤50 ppm
	JCAP (Oyama & Kakegawa, 2003)		• No deterioration in PM control • Fuel economy was reduced by 7%.	No effect on DPF efficiency	S≤50 ppm
DOC – HC, CO, PM reduction	DECSE	FTP 75 on Cummins ISM370, I-6, 11 L, 280 hp	• PM emissions increase if S≥150 ppm at high load • HC oxidation capacity is reduced for some DOCs (depending on catalyst formulation) • CO emissions are not affected	HC reduction efficiency. 3 ppm -> ~100% 350 ppm -> 91%	S≤ 500 ppm
LNT – NOx Reduction	DECSE and MECA (2007)	Engine Prototype – I-4, 1.9 L, 81 hp	• Sulfur compounds interfere with NOx storage function	3 ppm -> 90%	S≤10 ppm
SCR – NOx reduction	Girard, 2009. Chatterjee, 2008	Simulated diesel exhaust gases	• Vanadium SCR systems can operate at S levels of 50-500 ppm • Zeolite SCR systems are susceptible to S>50 ppm levels.	For zeolite SCR: Exposure at 600 ppm reduced the NOx conversion efficiency from ~90% to ~50%. Conversion ~70% after sulfur regeneration	S<500 for vanadium SCR syst S≤ 350 ppm for Iron-Zeolites and S≤ 50 ppm for Copper-zeolites

Annexure – III. Selected Fuel Properties in India and other Countries

A.III.I Gasoline Fuel Properties

Fuel Property	India Bharat Stage III	India Bharat Stage IV	Euro III 98/70/EC	Euro IV 98/70/EC	Euro V 2003/17/EC	EPA RFG average (2005)[1]		EPA conv. gasoline average (2005) [2]		Worldwide Fuel Charter Category 4 [4]
						Summer	Winter	Summer	Winter	
Research Octane (RON), min	88	91	95-91	95-91	95-91	NS				91-95-98
Motor Octane (MON), min	81	81	85-81	85-81	85-81	NS				82.5-85-88
Anti-Knock Index (AKI), min	NS	NS	NS	NS	NS	Recommended: 87-87-91 with seasonal and altitudinal variations ASTM D4814				NS
Aromatics, vol%, max	42	35	42	35	35	20.7 [5]	19.5 [5]	27.7	24.7	35
Olefin, vol%, max	21	21	18	18	18	11.9	11.2	12	11.6	10
Benzene, vol%, max	1	1	1	1	1	0.66 [6]	0.66 [6]	1.21 [6]	1.15 [6]	1
Sulfur, ppm, max	150	50	150	50	10	71 [7]	81 [7]	106 [7]	97 [7]	10
Gum Content, max	NS	NS	NS	NS	5	5				5
Density 15C, kg/m3	720-775	720-775	NS	NS	720-775	NS	NS	NS	NS	715-770
RVP, kPa	60	60	60/70 max	60/70 max	60/70 max	47.6 [9] (6.91 psi) Max	82.0 (11.89 psi) max	57.2 [9] (8.3 psi)	83.6 (12.12 psi)	Temp > 15 C: 45-60 15 C>=T>5 C: 55-70 5 C>=T> -5 C: 65-80 -5 C>=T>-15 C: 75-90 Temp < -15 C: 85-105
Lead, mg/l, max	5	5	5	5	5	13				NS

Fuel Property	India Bharat Stage III	India Bharat Stage IV	Euro III 98/70/EC	Euro IV 98/70/EC	Euro V 2003/17/EC	EPA RFG average (2005)[1]		EPA conv. gasoline average (2005) [2]		Worldwide Fuel Charter Category 4 [4]
						Summer	Winter	Summer	Winter	
Manganese, mg/liter, max	NS	NS	NS	NS	MMT<6 (by 2011) MMT<2 (by 2014)	NA [11]	NA [11]	NA	NA	ND
Oxygen, % m/m	NS	NS	2.7 (max)	2.7 (max)	2.7 (max)	2.49	2.37	0.95	1.08	2.7

NS = Not specified; NA = Not available; ND = Non-detectable; NAP = Not applicable

Notes:

1. National average of the 2005 RFG survey data are shown here. Even though EPA establishes limits on sulfur, summer RVP, aromatics and benzene for reformulated gasoline (RFG), compliance is determined based on the complex model estimates of VOC, toxic and NOx emissions relative to the emissions of the 1990 baseline gasoline.
2. Presented here are national average in 2005 based on conventional gasoline survey data. EPA sets limits on benzene and sulfur content as well as summer RVP, but not for other parameters. Individual producer or importer demonstrates compliance with the conventional gasoline standard by showing that emissions of VOC, CO, NOx and toxic air pollutants from conventional gasoline produced or imported do not increase over levels from the gasoline it produces or imports in 1990. If a producer or importer is unable to develop adequate 1990 data, it must use a "statutory baseline", which is the average quality of all 1990 U.S. gasoline.
3. Refiners and fuel importers could choose to comply with the maximum (flat) limit, or the averaging limit coupled with a cap limit. Refiners and importers could also certify alternative specification by using the predictive model to demonstrate that emissions are equivalent to those of a gasoline meeting the flat limits or the averaging limits plus cap values.
4. Applicable to markets requiring Euro 4, Euro 5 heavy duty, US EPA Tier 2 or 2007/2010 Heavy Duty On-Highway or equivalent emission standards.
5. The reformulated gas provision of the Clean Air Act (CAA) **limits the aromatic content of RFG to 25% by volume**.
6. **CAA limits benzene content of RFG gasoline to 1% by volume**; the Mobile Source Air Toxics final rule further tightens the benzene limit to 0.62% for all gasoline (reformulated and conventional) on an annual average basis beginning Jan. 1, 2011. While the 0.62% limits could be met through an averaging, banking and trading program, the actual annual average of gasoline produced or imported by any refiner or importer must not exceed 1.3% by volume beginning Jul. 1, 2012.
7. Effective from 2006, the gasoline sulfur limit for all gasoline is 30 ppm for the annual refinery average and a cap of 80 ppm for all production.
8. Applies on December 31, 2011.

A.III.II Diesel Fuel Properties

Fuel Property	India Bharat Stage II	India Bharat Stage III	India Bharat Stage IV	Euro III	Euro IV	Euro V	EPA	CARB		Worldwide Fuel Charter Category 4 [2]
							Conventional diesel	Reference fuel [1]	Designated equivalent limit [1]	
Polyaromatics, vol%, max	-	11	11	11	11	8	NS	1.4	3.5	2.0
Sulfur, ppm, max	500	350	50	350	50	10	15	15	15	10
Cetane number, min	48	51	51	51	51	51	Cetane index >= 40 or aromatics <= 35%[3]	48	53	55
Density @ 15°C, kg/m^3, min	800-820	820-845	820-845	820 - 845	845	845	NS	NS	NS	820 [4]
Flash point, °C, min	NS	NS	NS	55	55	55	NS	54	NS	55
Ash content, % m/m, max	NS	NS	NS	0.01	0.01	0.01	NS	NS	NS	0.001
Viscosity @ 40°C, mm^2/s	NS	NS	NS	2 - 4.5	2 - 4.5	2 - 4.5	NS	2 - 4.1	NS	2.0 [5]

PP = Diesel pour point; NS=Not specified

1. The California regulations allow flexibility in meeting the limit on aromatics. Producers or importers could either produce a fuel that meets the designated equivalent limits, or certify a fuel formulation by demonstrating that the exhaust emission reduction of a candidate fuel is equivalent to those with the reference fuel; the "low emission" fuels typically have much higher cetane number, lower sulfur, but higher aromatics, higher polycyclic aromatics and higher nitrogen than the reference fuel.
2. Applicable to markets requiring Euro 4, Euro 5 heavy duty, US EPA Tier 2 or 2007/2010 Heavy Duty On-Highway or equivalent emission standards.
3. EPA requires either a minimum cetane index of 40 or a maximum aromatic content of 35%. Premium diesel fuel defined by National Institute of Standards and Technology (NIST) requires minimum cetane number of 47.0. It is up to individual states to adopt the NIST premium diesel requirements.
4. Can be relaxed to 800 kg/m3 when ambient temperatures are below -30°C. For environmental purposed, a minimum of 815 kg/m3 can be adopted.
5. Can be relaxed to 1.5 mm2/s when ambient temperatures are below -30°C, and to 1.3 mm2/s when ambient temperatures are -40°C.

Annexure – IV. Overview of Refining Capacity in India

This section summarizes the state of refineries in India, including current refining capacities, expansion projects and new refineries that are planned for construction in the next few years. The capability of each refinery for refining Bharat III and IV quality fuels is presented.

A.IV.I Actual and Projected Refining Capacity in India

As of April 2010 there were a total of 20 refineries in India comprising 17 in the public sector and 3 in the private sector. The total officially reported refining capacity stands at 184.4 million metric tonnes per annum (MMTPA), with a utilization capacity close to 100%, while the consumption of petroleum is 140 MMTPA, of which 56 MMTPA is diesel and 13 MMTPA is gasoline (MoPNG, 2010). India is not only self-sufficient in refining capacity for its domestic consumption but also exports petroleum products substantially. The company-wise location, capacity of the refineries and FY 2009-10 throughput as of April 2010 is given in Table 9. Declared capacity was obtained from companies' websites. The actual crude throughput was obtained from the latest MoPNG reports (MoPNG, 2010). Additional information on India fuel quality and specifications is presented in Annex A.

Table 9. Capacity of Refineries in India, as of April 2011

	Company	Location	Declared Capacity MMTPA	Actual Crude T'put MMTPA (FY 2009-10)
1	Indian Oil Corp. Limited (IOC)	Guwahati, Assam	1.00	1.07
2	IOC	Barauni, Bihar	6.00	6.18
3	IOC	Koyali, Vadodara, Gujarat	13.70	13.21
4	IOC	Haldia, West Bengal	6.00	5.68
5	IOC	Mathura, Uttar Pradesh	8.00	8.11
6	IOC	Digboi, Assam	0.65	0.60
7	IOC	Panipat, Haryana	12.00	13.62
8	IOC	Bongaigaon, Assam	2.35	2.22
9	Hindustan Petroleum Corp. Ltd (HPCL)	Mumbai, Maharashtra	6.50[a]	6.96
10	HPCL, Visakhapatanam	Visakh, Andhra Pradesh	8.30[b]	8.80
11	Bharat Petroleum Corp. Ltd (BPCL)	Mumbai, Maharashtra	12.00	12.52
12	BPCL, Kochi	Kochi, Kerala	9.50[c]	7.87
13	Chennai Petroleum Corp. Ltd (CPCL)	Manali, Tamil Nadu	9.50	9.58
14	CPCL, Narimanam	Narimanam, Tamil Nadu	1.00	0.52
15	Numaligarh Refinery Ltd (NRL)	Numaligarh, Assam,	3.00	2.61
16	Mangalore Ref.& Petrochem. Ltd (MRPL)	Mangalore, Karnataka	12.50[d]	12.50
17	Oil & Natural Gas Corp. Ltd (ONGC)	Tatipaka, Andhra Pradesh	0.078	0.055
18	Reliance Petroleum Limited (RPL)	Jamnagar, Gujarat	33.00	34.41
19	Reliance Petroleum Limited (SEZ)*	Jamnagar, Gujarat	29.00	29.00
20	Essar Oil Limited (EOL)	Vadinar, Gujarat	13.80	13.50

Total			187.88	189.02

MMTPA: Million Metric Tonnes Per Annum
(a) HPCL Mumbai official installed capacity was 5.5 MMTPA as of March 2010. Its capacity increased by 1.0 MMTPA.
(b) HPCL Visakh official installed capacity was 7.5 MMTPA as of March 2010. Its capacity increased by 0.8 MMTPA.
(c) BPCL Kochi official installed capacity was 7.5 MMTPA as of March 2010. Its capacity increased by 2.0 MMTPA.
(d) MRPL Mangalore official installed capacity was 9.7 MMTPA as of March 2010. Its capacity increased by 2.8 MMTPA.
*The SEZ refinery was added to the original Reliance Industries LTD (RIL), making the Jamnagar refinery complex the largest in the world.

Note that the total refining capacity as shown in Table 10 differs slightly from the most recent official assessment of 184.4 MMTPA. The difference might be found in ongoing refinery upgrades and capacity expansions.

The broad expansion in refining capacity was the result of the development program of the XI[th] Five Year Plan[5], which covers the years 2007-2012. Table 10 presents the list of refineries involved in capacity expansions and their current status. Once completed, the total refining capacity in India will be increased by 13.6 MMTPA, resulting in 198.0 MMTPA.

Table 10. Capacity Expansion of Refineries in India

Company	Location	Declared Capacity (2011) MMTPA	Capacity target, MMTPA	Status
IOCL	Haldia, West Bengal	6.0	7.5	No completion date announced[(a)]
IOCL	Panipat, Haryana	12.0	15.0	Completed by August 2010 (MoPNG, 2010)[(b)]
HPCL	Mumbai, Maharashtra	6.5	7.9	The project is expected to be completed by the 2nd qtr of 2010-11 [(c)]
CPCL	Manali, Tamil Nadu	9.5	10.5	Expansion of distillation unit. Completed by March 2010 (MoPNG, 2010)
MRPL	Mangalore, Karnataka	12.5	15.0	No completion date announced (MoPNG, 2010)
EOL	Vadinar, Gujarat	13.8	18 .0	70% of additional capacity has been finished. No completion date announced [(d)]

ND: No data
(a) http://www.iocl.com/AboutUs/HaldiaRefinery.aspx
(b) http://www.iocl.com/Aboutus/Refineries.aspx
(c) http://www.hindustanpetroleum.com/En/UI/RefineryNewProjects.aspx
(d) http://www.essar.com/section_level1.aspx?cont_id=fBlwNPJhC0c=

New refineries were also planned during the XI[th] Five Year Plan, as presented in Table 11. These new refineries will provide an extra 63 MMTPA processing capacity. The information available to date points toward a refining capacity of approximately 261 MMTPA by the end of 2013, or a 41.8% increase from the 2010 figure of 198 MMTPA. It should be noted that the overall petroleum consumption in India increased 3.6 % in FY2009-10 with respect to the FY2008-09. Diesel and gasoline demand grew at a faster rate during the same period, by 9.1% and 14.2% respectively (MoPNG, 2010).

[5] Two of the main objectives of the XI[th] Five Year Plan regarding the environment were to attain WHO standards of air quality in all major cities by 2011 and increase energy efficiency by 20% by 2016-17. Unfortunately, it appears that air quality in 2011 is far worse than the WHO standards, and fuel efficiency standards for 2016-2017 are yet to be finalized.

Table 11. New Refineries in India as Part of the XIthFive Year Plan(MoPNG, 2011)

Company	Location	Capacity MMTPA	Comments
IOCL[a]	Paradip, Orissa	15	Expected Commissioning: March-November, 2012. Hydrocracking unit is projected
BORL [b]	Bina, Madhya Pradesh	6	Completed in May 2011 Euro III & Euro IV fuels will be produced
HMEL [c]	Bathinda, Punjab	9	Near completion. It will produce clean fuels and petrochemicals
EOL [d]	Vadinar, Gujarat	18	18 MMTPA grassroots refinery by March 2013
Nagarjuna Oil Corp. Ltd (NOCL)[e]	Cuddalore,Tamil Nadu	15	Slated for Commissioning by the end of 2011. Euro III & Euro IV fuels will be produced
Total New Refining Capacity		**63 MMTPA**	

(a) http://www.iocl.com/Aboutus/Majorprojects.aspx
(b) http://www.borl.in/ProjectHighlights.aspx
(c) http://www.hmel.in/project_profile/current_status.htm
(d) http://www.hydrocarbons-technology.com/projects/essar/
(e) http://www.nocl.co.in/NOCL_link.asp?link=project.asp. NOCL refinery is projected to refine 6MMTPA during phase one and 15 MMTPA upon completion.

A.IV.II India desulfurization installed capacity

Refineries in India are currently refining fuels at sulfur levels corresponding to Euro III and Euro IV specifications, i.e., at 350 ppm and 50 ppm respectively for diesel and 150 ppm and 50 ppm respectively for gasoline. The refining technologies required to reach such levels of sulfur in fuels are hydrotreating and hydrocracking. Hydroprocessing, common term for both hydrotreating and hydrocracking processes, is accomplished by using high pressure hydrogen to catalytically remove the sulfur, and other contaminants from the feed hydrocarbon. The amount of hydrogen and pressure used differentiates both processes. Selection of one over the other depends on crude stocks, refinery configuration and blendstocks used.

The current installed capacity for hydroprocessing in Indian refineries gives an idea of the challenges ahead for implementing ULSF. Table12 presents the list of Indian refineries with current and projected refining capacity for ultra low sulfur fuel production (OGJ, 2010). In some cases the installed capacity is not available and only the existence of such processes is acknowledged. The installed capacity for hydrogen production is included where available. Information about fuel quality produced was obtained from companies' websites.

Table 12. ULSD Installed Capacities and Expansion Projects

Refinery	Hydro-treating		Hydro-cracking		H_2 Production 2010 MMcfd	Fuel Quality Produced
	In 2002 , MMTPA	In 2010, MMTPA	In 2002 , MMTPA	In 2010, MMTPA		
IOCL Guwahati,	-	Yes	-	-		Hydrotreater installed for low sulfur diesel
IOCL Barauni	-	Yes	-	-		Bharat III quality petrol and diesel
IOCL Koyali	-	0.42	-	ND	42.7	Bharat III and IV quality petrol and diesel
IOCL Haldia	0.2	1.1	0.2	Yes	ND	Hydrocracking project for HSD sulfur is near completion The expansion from 6.0 to 7.5 MMTPA will include the capacity to produce Bharat III petrol and diesel and Bharat IV diesel.
IOCL Mathura	-	Yes	-	Yes		Bharat III and IV quality petrol and diesel
IOCL Digboi	-	Yes	-	-		Bharat III quality petrol and diesel

Refinery	Hydro-treating		Hydro-cracking		H_2 Production	Fuel Quality Produced
	In 2002 , MMTPA	In 2010, MMTPA	In 2002 , MMTPA	In 2010, MMTPA	2010 MMcfd	
IOCL Panipat	-	Yes	1.7	1.7		Naphtha cracker unit for petrol quality upgrade
IOCL Bongaigaon	-	0.09	-	-	ND	Bharat III quality petrol and diesel
HPCL Mumbai	1.4	1.85	1.4	-	17.00	Capable of Diesel Bharat II/III Plans for Bharat III/IV petrol
HPCL Visakh	2.5	Yes	2.5	Yes	21.18	Bharat-III. Currently working on diesel BS- IV Plans for Bharat III/IV petrol
BPCL Mumbai	-	-	-	1.75	ND	Currently produces Euro III/IV fuels
BPCL Kochi	-	2.8	-	-	42.0	Bharat III and IV quality petrol and diesel
CPCL Manali	0.3	1.8 Diesel	0.3	Yes	10.0	Diesel Bharat II/III. Petrol Bharat IV upgrade. Hydrotreating and Catalytic reforming unit is being revamped. Completed by 2010.
CPCL Cauvery Basin,	-	-	-	-		ND
NRL Numaligarh	-	1.45	1.2	1.2	ND	Currently produces BS II and Bharat III HSD. Bharat IV HSD will be finished by 2010. Involves revamping of Hydrocracker, hydrogen and sulfur recovery units.
MRPL Mangalore	-	ND	-	Yes		Bharat III and IV quality petrol and diesel
ONGC Tatipaka	-	-	-	-		ND
RPL Jamnagar	-	Yes	-	5.5	ND	Produces ULSD (S<10ppm) fuel exported to the US and the EU
Essar, Vadinar	-	-	-	-		Bharat III and IV quality petrol and diesel. ULSD upon completion of current expansion

ND: No data

The information from refinery capacity expansions and the ability of many refineries to produce Bharat II and IV quality fuels suggest that the hydroprocessing installed capacity has increased, although it is difficult to quantify this growth due to lack of available data on hydroprocessing developments in India. According to the Oil and Gas Journal survey (OGJ, 2010), the total installed capacity in India for hydrotreating and hydrocracking is equivalent to 6% and 5%, respectively, of the total crude refining capacity, as can be observed in Table 13. In European countries, where ULSF is already available, the national installed capacity for hydrotreating is above 65% of the total installed refining capacity; the national installed capacity for hydrocracking is, in general, below 10% of the total crude refining capacity.

Table 13. 2010 Sulfur limits, Installed refining capacity and hydroprocessing capacities as a percentage of total crude refining capacity (from OGJ, 2010)

Country	Max. Sulfur level Gasoline/Diesel, ppm	Crude Refining Capacity, MMTPA	Processing capacity Cat. Hydrotreating	Processing capacity Cat. hydrocracking
India	150/350*	184	6%	5%
China	150/350*	340	8%	3%
France	10/10	99	67%	4%
UK	10/10	93	68%	2%
US	30/15	888	78%	9%
Germany	10/10	121	84%	8%
Japan	10/10	231	100%	4%

* Nationwide values. Selected cities have 50 ppm limit

Annexure – V. ULSF production: Technologies and Cost

Homogenizing the sulfur content for fuels around the country and reaching ultra-low sulfur levels are the next steps for introducing the best available emission control technologies and obtaining the best benefits from vehicles on the road. Achieving Bharat IV countrywide, and moving towards ULSF would require technology improvements and additional cost of production that would be reflected at the pump.

This section describes the technology required for ULSF refining and the additional cost. The technology section describes the sources of sulfur and the technology required to remove it. The cost information is based on previous studies developed in the US and Asia, and are presented here as reference.

A.V.I ULSF Refining Technologies

Refining, the process of converting crude oil into products of commercial value, is done through different physical-chemical methods that can be organized in three main categories: Distillation, Conversion, and Treatment and Formulation. Distillation separates hydrocarbons in a series of products like gas oil, kerosene, naphtha, gasoline (light naphtha) and gas. Diesel is obtained later on from gas oil via conversion processes. Treating methods are designed to provide final product qualities in high-end fuels. Diesel and gasoline sulfur quality is achieved in treatment processes known as hydrotreating and hydrocracking (Speight, 2007).

A.V.I.I Sulfur in Fuels and Hydroprocessing

Most of the sulfur in crude oil is in its heaviest components. During the process of distillation and cracking of crude oil, some of the heavy compounds are broken up (cracked) into smaller compounds, carrying the sulfur into diesel, gasoline and other light products.

Since most of the refinery blendstocks after distillation used for diesel production come from the heavier fractions, diesel naturally contains large amounts of sulfur, and its removal requires additional processes, such as cracking and treatment, i.e. hydrocracking and hydrotreating (EPA, 2004).

The case for gasoline is different. Although in theory ultra low sulfur gasoline (ULSG) might be obtained from reforming the straight run, which contains around 100 ppm sulfur, the economics of the refining process force the blending with other high-sulfur content blendstocks that otherwise would be wasted (EPA, 1999).

Hydroprocessing is used for sulfur removal from refinery blendstocks. By cracking (breaking large hydrocarbon molecules into smaller ones) and hydrogenation (adding hydrogen) the sulfur present in the feed hydrocarbon is converted to H_2S, which can be readily separated from the heavier oil. Hydroprocessing is accomplished by using high-pressure hydrogen to catalytically remove the sulfur, and other contaminants from the feed hydrocarbon (Speight, 2007).

Hydrotreating is used for improving product quality without changing the boiling range. In this case, only the least stable materials, like sulfur and nitrogen and some hydrocarbons, are attacked by hydrogen. Hydrocracking is a thermal decomposition process where the hydrogen assists in removing foreign species and in reducing the coke formation during the thermal cracking (Speight, 2007). Hydrocrackers consume more catalyst, operate at higher pressure, achieve higher conversion rates, produce more light and high value products and are more complex and expensive to operate than hydrotreaters (Robinson & Dolbear, 2007).

A.V.I.II Refinery Options

The refining process is designed for meeting specific local demands for gasoline, diesel, jet fuels and others hydrocarbons derivatives. In this section the most common refinery options for improving fuel quality in the US, Europe and Asia are discussed.

A.V.I.II.I Gasoline

The desulfurization process for gasoline can be accomplished before or after the fluid catalytic cracker (FCC). Before the FCC, it is called FCC feed hydrotreating, while afterwards it is called FCC gasoline hydrotreating. FCC feed hydrotreating works at high pressures and temperatures and improves the FCC yield by improving the FCC catalyst conversion efficiency, producing large fractions of gasoline and diesel. High capital and operational costs of FCC feed hydrotreating have driven the adoption of the FCC gasoline hydrotreating unit. This unit only treats the gasoline produced by the FCC, which represents 50%-60% of the FCC feed. In addition, this unit operates at lower temperatures and pressures than FCC feed hydrotreating, which implies lower operational costs.

According to the Purvin and Gertz study (2000), the reduction in gasoline sulfur level from 50 to 10 ppm is possible with modifications in the FCC. It is expected that the FCC gasoline hydrotreating process would induce some loss of octane and that should be addressed. Again, the report signals that in case the refinery does not have the ability to increase FCC refining capacity, then the installation of a brand new FCC gasoline hydrotreater is required. High sulfur crude implies that the refinery might need sulfur removal upstream and downstream from the FCC (Purvin & Gertz, 2000).

A.V.I.II.II Diesel

In Europe and Asia, where demand for diesel is higher than gasoline, the refining strategy employs a combination of partial hydrocracking and fluid catalytic cracking (FCC) to produce very-low-sulfur fuels. In this scheme a partial conversion hydrocracking unit is placed after the FCC unit to convert the vacuum gas oil to light products (distillate, kerosene, naphtha). The distillate product is low in sulfur, below 200 ppm, and has a cetane number of about 50. The cracked blendstocks produced in the FCC unit are also lower in sulfur and higher in cetane.

Sulfur reduction in diesel from 350 ppm to maximum 15 ppm can be achieved by upgrading hydrotreater units via physical changes or changes in operating conditions. The upgrade includes more active catalysts, higher pressure and temperatures, or building of new hydrotreating units. Two-stage hydrotreating is the preferred technology for deep desulfurization due to the removal of H_2S in the first stage, which reduces the risk of recombination in the second stage (EIA, 2001). If the diesel blendstock includes some light cycle oil (LCO) or if the crude slate has high sulfur content, the refinery would have to install in a high pressure hydrotreating unit operating at 1300-1400 psi (Purvin and Gertz, 2000).

A.V.II. Capital and Incremental Costs

The cost associated with fuel sulfur reduction depends on input, output and installed equipment. Input costs are defined by the crude quality, type of blend components, and sulfur, aromatics and boiling range of those blend components. The output refers to the volume of ULSF produced and other products that defines the installed capacity. Installed capacity, the most important parameter, defines whether a refinery can increase its capacity by renovating an existing unit or by building a new one. Equipment includes the catalytic reactor, the reformer reactor to produce hydrogen, sulfur accumulation units and tankage for segregating fuels.

Capital costs and incremental costs for different levels of fuel sulfur reduction were studied by consultants and governmental agencies staff. The main assumptions, capital cost values and incremental costs in cents per liter are presented below.

A.V.II.I Asian Reports

The Asian Development Bank (Enstrat Int Ltd, 2003) and the International Council on Clean transportation (Blumberg, Kebin, Yu, Huan, & Yamaguchi, 2006) sponsored studies aimed to finding the cost of sulfur reductions for refineries in Asia with very different results.

The main objective of the ADB study was to identify technology requirements and costs for reducing diesel sulfur levels in India and other Asian countries from 3000 ppm down to 10 ppm, including the steps for 350 ppm (Euro III) to 50 ppm (Euro IV) and 10 ppm (Euro V/VI). When the ADB study was done there were 16 refineries operating in India. The desulfurization technologies assumed are medium and high-pressure hydrotreating, and hydrocracking. Sulfur levels of 350 ppm are achieved with medium and high-pressure (P>50 bar) hydrotreating units and 50 ppm levels require new or expanded hydrocracker units. A reduction from 50 to 10 ppm requires more severe hydro-processing conditions, higher H_2flowrate and higher utilities consumption, including catalyst consumption.

Based on the capacity of Indian refineries in 2002 and the cost of technology required to obtain ULSD, the study calculated the average investment costs required for upgrading and the incremental cost per liter of diesel. The average investment costs required for installing medium and high pressure hydro treating, and hydro-cracking units, assuming a throughput of 1.0 MMTPA each, are $107MM, $140MM and $278MM, respectively, corrected to $US 2011 values (Enstrat Int Ltd, 2003). Incremental fuel cost from 350 ppm to 50 and 10 ppm was found to be about the same, around 0.9 Rs/liter. It is clear the largest investment cost is incurred for installing new hydrotreating and hydrocracking units. Once that initial investment is done, the cost of increasing the process capacity or changing process conditions for lower sulfur level output is very small (Enstrat Int Ltd, 2003).

The ICCT, Tsinghua University and Trans-Energy Research Associates collaborated for a cost-benefit analysis for cleaner fuels and vehicle emissions in China (Blumberg, Kebin, Yu, Huan, & Yamaguchi, 2006). This fuel sulfur reduction study evaluated the cost increase from Euro 2/II levels (500 ppm) up to Euro 5/V (10 ppm). This study shows an incremental cost of 0.09 Rs/L for reducing sulfur levels in diesel from 350 ppm to 50ppm, and 0.31 Rs/L from 50 ppm to 10 ppm. For gasoline the incremental cost from 150 ppm to 50 ppm is 0.05 Rs/L, while the cost to move to 10 ppm is over four times as high at 0.22 Rs/L.

A.V.II.II US Reports

The Energy Information Administration (EIA) conducted a study for reducing on-highway diesel sulfur levels from 340 ppm average to 15 ppm max (EIA, 2001). The cost assessment included the cost of new and revamped distillate hydrotreating units. The results of the study show that for a refinery with a high hydrotreater capacity range, high sulfur feed content range and high percentage of cracked stock range, the additional cost of ULSD is around 0.4-0.9 Rs/L when moving from 350 ppm to S<10 ppm.

Another US study on impact assessment (RIA) of the heavy-duty standards and diesel fuel by EPA assumed sulfur level reductions from 340 ppm (average, 500 ppm max) down to 10 ppm max (EPA, 2000). Costs were based on desulfurization of diesel by hydrotreating process operations and capital cost information received from conventional distillate desulfurization technology. The US scenario was estimated assuming that some refineries have an installed capacity for 340 ppm sulfur production, and that achieving the 10 ppm sulfur level would require revamping capacity of desulfurization and building new process units. The incremental fuel cost for reducing sulfur levels from 340 ppm to 10 ppm was 0.5-0.6 Rs/L.

In addition, the EPA impact assessment study for the Tier 2 emissions standards and gasoline sulfur requirements (1999) estimated the cost of implementing the 30 ppm average sulfur limit from 120 ppm in gasoline. The increase in hydrogen capacity was evaluated and included in the cost analysis. Including depreciation and project lifetime, the incremental cost for gasoline hydrotreating was estimated at 0.26-0.28 Rs/L, after correction for inflation.

A.V.III Cost Summary

Table 14 gathers cost estimates of desulfurizing diesel and gasoline in various countries reported by previous studies. All prior studies indicate that producing ULSD from 350 ppm sulfur levels would incur minimal cost increases of not more than 2.1 ¢/L or 0.9 Rs/L. It is evident that gasoline desulfurization is less expensive that diesel desulfurization, with incremental costs of no more than 0.3 Rs/L when reducing the sulfur levels from 120 to 30 ppm. This can be attributed to the fact that gasoline production involves lighter blendstocks that carry less sulfur than the heavier blendstocks used for diesel production.

The specific cost depends on the assumptions made with regard to crude sulfur levels, refinery configuration and the desired levels of sulfur reductions. The ADB study shows an insignificant cost increase for reducing the sulfur from 50 ppm to 10 ppm, while it represents the largest cost increase according to the ICCT sponsored study in 2006 for China. However, the incremental costs estimates from various studies for transitioning to ULSF by reducing sulfur level from 500 ppm to 10 ppm appear to fall in the same range, below 1.0 Rs per liter for diesel and below 0.3 Rs per liter for gasoline.

For diesel, the cost span for improving sulfur content from 350 ppm to 50 ppm is somewhere between 0.4 and 0.9 rupees per liter; further improving the sulfur content to 10 ppm was estimated at a cost between 0.005 and 0.31 rupees per liter. The difference in this last estimate is difficult to identify given that little information on assumptions were provided.

Capital investments are very different depending on the baseline refining technology available at the time of implementation. Capital investments for ULSF production are lower if there is an already available hydroprocessing capacity installed. As an example, in the US the costs for sulfur reduction from 1998 levels to current levels were lower compared to those estimated for Asia given the large installed capacity for hydrotreating already in place in the US at that time, which was equivalent to 56% for of the total installed refining capacity, compared to 8% reported for a typical Asian Country in 2002 (EnstratInt Ltd, 2003). Another reason for the elevated capital costs might be related to the inability to obtain accurate cost information. The US EPA has the ability to gather such information from technology vendors, while the consulting firms rely on experience and general approximations to provide investment costs.

Table 14. Summary of cost increase for diesel and gasoline fuels

Source	ppm level	Capital costs (1.0 MMTPA), $US Millions	Incremental cost, ¢/L	Incremental cost, Rs/L	Comments
Diesel					
Blumberg et al., 2006	500 to 350	-	0.3	0.13	China
Blumberg et al., 2006	350 to 50	-	0.2	0.09	China
Enstrat Int Ltd, 2002	350 to 50	$208	1.99	0.88	India
Enstrat Int Ltd, 2002	350 to 10	$209	2.00	0.89	India
EPA, 2000	340 to 15	$52	1.1-1.3	0.49-0.58	US
EIA, 2001	340 to 15	-	0.9-2.1	0.41-0.94	US
Enstrat Int Ltd, 2002	50 to 10	$1.3	0.012	0.005	India
Blumberg et al., 2006	50 to 10	-	0.7	0.31	China
Gasoline					
Blumberg et al., 2006	500 to 150	-	0.2	0.09	China
Blumberg et al., 2006	150 to 50		0.1	0.05	China
EPA, 1999	120 to 30	$44	0.58-0.63	0.26-0.28	US
Blumberg et al., 2006	50 to 10	-	0.5	0.22	China

* Capital investment includes all refineries within the US

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