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# Engine technology pathways for heavy-duty vehicles in India

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## 1. Introduction

As India works towards the development of the country's first ever regulation to reduce fuel consumption of new heavy-duty vehicles (HDVs), one of the key considerations is the availability and cost effectiveness of efficiency technologies. The primary objective of this literature review is to provide a glimpse at technology changes for diesel engines in the HDV space that are expected over the next 10 years as India transitions to world-class criteria pollutant emissions standards and improved efficiency becomes a larger focus as a result of fuel efficiency regulation.

Section 2 summarizes the engine technology pathways associated with transitioning from the current pollutant emissions standard (i.e., Bharat Stage IV in select cities, Bharat Stage III nationwide) to Bharat Stage VI, which is expected to be nearly identical to the Euro VI standard, which was implemented in the European Union starting in 2013. Section 3 reviews the efficiency improvements that are currently being deployed as well as those that are in the pipeline for the post-2020 timeframe in developed markets. The particular focus of this section is the US and Canada, where fuel efficiency regulations—specifically, engine-specific performance standards—are driving fuel-saving technology advancements in a number of areas on engines and aftertreatment systems. Finally, Section 4 summarizes the paper and discusses areas for future research.

## 2. Technology pathways to Euro VI

Europe first introduced heavy-duty vehicle emission standards in 1988. The "Euro" track was established with Directive 91/542/EEC, which defined a test protocol and set two sets of limits for new heavy-duty vehicles (Council of the European Union 1991). Starting in 2000, India implemented emission standards for HDVs that were harmonized with the Euro regulatory pathway (Central Pollution Control Board 2008). Since then, these aligned "Bharat Stage" (BS) standards have bifurcated into parallel vehicle emission standards in India: one for the vehicles registered in major cities and then a less stringent standard for the remainder of the country. At present, the current HDV emission standard for major cities is BS IV (i.e., Euro IV), and the rest of the country is at the BS III (i.e., Euro III) level. In practice, since nearly all commercial trucks are registered outside of the major cities, the BS IV standards apply primarily to urban buses (International Council on Clean Transportation and DieselNet 2014). According to sales data from fiscal year (FY) 2013-2014, the percentage of trucks and buses sold in India at the BS IV level were 3% and 27%, respectively (Sharpe 2015).

As is the case with passenger vehicle emission standards, HDV standards in India as a whole lag well behind international best practices. The United States and Europe are about ten years ahead of India. However, the Ministry of Road Transport and Highways in India recently announced that vehicle emission standards in the country will leapfrog from BS IV to BS VI in 2020 (Press Information Bureau - Government of India 2016). Assuming that this updated timeline is finalized, India will have harmonized its vehicle emission control regulations with the most stringent regulatory programs in the world.

On-road heavy-duty emission standards are designed to be technology neutral and do not require that specific technologies be used to meet regulatory levels. While manufacturers differ in the specific design parameters of the engine modifications and aftertreatment they

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use to meet the standard, in many cases their designs converge toward the most cost-effective option provided by current technology. This section lays out the typical compliance strategy to meet recent emission standards, noting the changes with each successive standard and the cases where some manufacturers employed alternate strategies.

Tables 1 and 2 summarize the technologies that have been used to achieve Euro III to VI limits for diesel engines.[1] While diesel continues to represent the large majority of sales, accounting for greater than 99% of HDVs sold in FY 2013-2014, NG market share has increased in the bus segment (9% of bus sales in FY 2013-2014), primarily driven by a ban on diesel buses in the Delhi metropolitan area, which has been in effect since 2001 (Sharpe 2015).

As shown in the tables, engine modernization in the heavy-duty sector in India requires the continued large-scale transition from mechanically to electronically controlled engines and the development of a nationwide urea infrastructure to support vehicles using selective catalytic reduction (SCR) for $NO_x$ control. In addition, OBD systems are required to ensure proper usage of the SCR systems. Although the transition to electronic controls and the introduction of SCR presents new challenges for industry and environmental regulators,

**Table 1:** Heavy-duty diesel engine emission control technology developments from Euro III to VI

| | Euro III to Euro IV | Euro IV to Euro V | Euro V to Euro VI |
|---|---|---|---|
| **Euro III technology** | • High-pressure fuel injection<br>• Electronic fuel timing and metering, including timing retard for low $NO_x$ | — | — |
| **Combustion and air-fuel controls** | • Improvements in engine combustion and calibration for PM control<br>• Turbocharging with intercooling<br>• $NO_x$ control[b]: EGR cooled | Previous technology plus:<br>• Improvements in engine combustion and calibration<br>• Multiple injection fuel system (pilot-main-post)<br>• VGT<br>• $NO_x$ control[b]: EGR cooled<br>• Higher EGR rates | Previous technology plus:<br>• VGT improvements<br>• Combustion system improvements |
| **Aftertreatment system** | • $NO_x$ control[b]: SCR systems (open loop)<br>• PM control (for EGR pathway only): DOC + PFF | • $NO_x$ control[b]: SCR systems (closed loop)<br>• Ammonia slip catalyst<br>• PM control (for EGR pathway only): DOC + PFF | • PM control: DOC + DPFs |
| **Onboard diagnostics (OBD) requirements** | OBD Stage I must monitor thresholds:<br>• Complete removal of the catalyst when fitted in separate housing from DPF or de$NO_x$ systems<br>• Efficiency reduction of the PFF or de$NO_x$ system | OBD Stage II adds the following:<br>• Monitoring of the interface between the ECU and other powertrain and vehicle electrical or electronic systems for continuity<br>• Adoption of standardized OBD systems across manufacturers and also access to repair information | • More stringent OBD threshold values and type approval based on the World Harmonized Test Cycle<br>• Adoption of in-use performance ratios<br>• Additional monitoring requirements for EGR flow, EGR cooling system, boost (turbo and superchargers) and fuel injection systems |

[a] Emissions measured over the ESC engine dynamometer test cycles, except for Euro VI, which requires testing over the World Harmonized Stationary Cycle (WHSC).

[b] $NO_x$ control through EGR or SCR is manufacturer's choice.

***Note:*** CO = carbon monoxide; DOC = diesel oxidation catalyst; DPF = diesel particulate filter; EGR = exhaust gas recirculation; ESC = European Stationary Cycle; HC = hydrocarbon; $NO_x$ = nitrogen oxides; PFF = partial flow filter; PFF = partial flow filter; PM = particulate matter; SCR = selective catalytic reduction; VGT = variable geometry turbocharger.

1 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 (g/kWh). These limits apply to both compression ignition (diesel) and spark ignition (gasoline, natural gas, or liquefied petroleum gas) engines.

**Table 2:** Heavy-duty natural gas engine emission control technology developments from Euro III to VI

| | Euro III to Euro IV | Euro IV to Euro V | Euro V to Euro VI |
|---|---|---|---|
| **Euro III technology** | • Lean-burn combustion<br>• Predetermined, open-loop fuel injection control (i.e., no feedback to the engine control unit) | — | — |
| **Combustion and air-fuel controls** | • Lean-burn combustion<br>• Closed-loop fuel injection control with oxygen (lambda) sensor instead of open-loop system | • Mixed (lean-burn and stoichiometric) or stoichiometric combustion with EGR and turbocharging<br>• Secondary lambda sensor for OBD requirements | • Stoichiometric combustion with cooled EGR and turbocharging<br>• Improved design of combustion chamber and overall system tuning |
| **Aftertreatment system** | • Oxidation catalyst | • Three-way catalyst | • Three-way catalyst |
| **Onboard diagnostics (OBD) requirements** | Same as diesel | Same as diesel | Same as diesel |

policymakers in India can learn from the compliance and enforcement experiences of other countries/regions such as the EU, United States, Japan, China, and Brazil that already have SCR-equipped vehicles on the road.

Sections 2.1 through 2.4 describe the technology pathways for diesel engines to move from Euro III to Euro VI, and Section 2.5 covers the Euro progression for NG engines.

## 2.1 DIESEL ENGINES: EURO III

Euro III and older trucks are typically fitted with direct injection technologies and turbochargers with after-cooling. In-cylinder development for $NO_x$-PM tradeoff control includes an increase in valve number (3–4 per cylinder), fuel injection technologies with higher pressures and metering control, and nozzle redesign aimed at improving the fuel spray pattern for better mixing with air and to reduce fuel dribbling at the end of the injection. Further $NO_x$ reduction is achieved by using fuel injection timing retardation during some engine conditions (to lower peak combustion temperatures). Exhaust gas recirculation (EGR) is not required for most heavy-duty engines at the Euro III and older level. EGR is an engine-based technology designed to reduce $NO_x$ emissions by lowering the peak combustion temperature by recirculating exhaust gases into the engine intake manifold. However, an important side effect of lowering the combustion temperature is reduced combustion efficiency and higher PM.

## 2.2 DIESEL ENGINES: EURO III TO IV

The Euro IV standard requires roughly an 80% reduction in PM and 30% reduction in $NO_x$, HC, and CO. There were two technical approaches to achieve these levels: 1) engine-based PM control and $NO_x$ controlled with aftertreatment devices, or 2) $NO_x$ control through EGR and PM control by an aftertreatment device—typically, a diesel oxidation catalyst (DOC) or partial flow filter (PFF).

The first strategy, which has been most commonly used in Europe, combines engine calibration for low PM emissions and does not use EGR. Low PM engine calibration requires adequate fuel atomization, through high-pressure fuel injection, and early fuel injection during the compression stroke. The fuel injection advancement results in higher combustion temperatures leading to high $NO_x$ levels that need to be addressed with aftertreatment. SCR systems using urea as a reductant with roughly 50% to 60% $NO_x$ reduction capability are required to meet the Euro IV targets (Johnson 2002). The injection advancements and combustion optimization increase the engine's fuel efficiency. From the literature, the changes in engine tuning that are enabled by the SCR system result in fuel savings that are typically on the order of 3 to 5% (Committee to Assess Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles 2010, U.S. Environmental Protection Agency 2011). A key benefit of the SCR approach is that the fuel penalty associated with EGR is avoided and can offset the costs associated with having to supply the vehicle with urea.

The second approach is tuning the air-fuel management system to produce engine-out PM with a highly soluble organic fraction, which may be controlled with DOCs or PFFs, and using cooled EGR for in-cylinder $NO_x$ reduction. The use of PFFs requires higher EGR use and lower engine-out $NO_x$ levels. This option is most useful for urban low-load heavy-duty vehicles. The technical reason for selecting EGR + DOC or EGR + PFF over SCR is that SCR systems using vanadium catalysts can have limited efficiency in low-exhaust temperature ranges typical of urban driving. The performance of SCR systems is highly dependent on exhaust temperature, the choice of catalyst, urea dosing method, and other factors. However, real-world evidence from researchers in Europe indicates that some of the heavy-duty vehicles using EGR may be underperforming in stop-and-go driving conditions as well (Ligterink, de Lange et al. 2009, Rexeis 2009). For both EGR and SCR systems to meet $NO_x$ performance expectations across the spectrum of exhaust temperatures, these systems must be designed and tested using test cycles that better encompass the full range of driving conditions—especially low engine loads. Experience in Europe provides evidence that Euro VI testing on the World Harmonized Transient Cycle, which includes a cold-start portion, has helped to mitigate the issue of underperformance at low speeds that are typical of urban driving. However, there is still the need for a robust compliance and enforcement program to ensure that emissions in the real-world from Euro VI vehicles—and HDVs of all emissions standards levels—are meeting expectations based on laboratory results.

## 2.3 DIESEL ENGINES: EURO IV TO V

Moving from Euro IV to V, only $NO_x$ is subject to a more stringent limit, which is approximately 40% lower. The options to reach this emission target are based on improvements over Euro IV technologies. The fundamental way to keep all regulated pollutants under Euro V limits is intensive air–fuel management control involving fuel injection timing, fuel injection pressure, and variable geometry turbochargers. The SCR systems have higher urea injection rates. Due to the higher urea injection rates, ammonia slip catalyst are typically required, if they were not already installed in the Euro IV system. Improved SCR reduction can be achieved if a DOC is used upstream of the SCR to provide extra $NO_2$ for $NO_x$ reduction. $NO_x$ control based on EGR may lead to an undesirable increases in PM emissions under specific speed-load conditions. Under this strategy—and depending heavily on the specific air-fuel management strategy—PM control may be achieved with the combination of a DOC and PFF or may require the use of DPFs.

In the EGR approach, the move to Euro V requires increased EGR rates and slightly increased fuel injection pressures. Moreover, increased charge pressures are needed to give acceptable air-fuel ratios at full load. For controlling particulates the use of a DPF may be required in larger engines or when the air-fuel management system is unable to maintain low PM with high EGR use during the test cycles. Sulfur levels are a key constraint on catalyzed DPFs or uncatalyzed DPFs that are used with an upstream DOC. For these systems, diesel sulfur levels must be less than 50 ppm; for optimal performance and durability, 10-ppm fuel is preferred. A more detailed discussion of the sulfur effects on aftertreatment technologies is included in Appendix A of (Sharpe, Fung et al. 2011).

## 2.4 DIESEL ENGINES: EURO V TO VI

Heavy-duty diesel engines require significant reductions in $NO_x$, PM, and HC emissions—roughly 80%, 50%, and 70%, respectively. The low PM mass value of 0.01 g/kWh and newly instituted particle number limit[2] requires the use of DPFs. As mentioned earlier, low sulfur diesel (less than 50 ppm) is required for use with catalyzed DPFs or DOC + DPF devices. HC and CO control is achieved with a DOC or using DPFs with catalyzed surface membranes. DOCs formulated for Euro VI applications are designed for improved oxidation capabilities at low temperatures. The heat generated during HC and CO oxidation can be combined with another heat source and used for active DPF regeneration. The oxidation also affects NO, which is oxidized into $NO_2$ and then used for passive DPF regeneration because $NO_2$ greatly reduces the temperature at which the trapped soot will combust. Increasing $NO_2$ generation in the DOC is an option for facilitating passive soot oxidation but requires integrated $NO_x$ control downstream of the DPF (Andersen 2008). A system diagram of the Euro VI emission control configuration is shown in Figure 1. The left-hand side of the figure shows an 'engine with or without EGR', since the various manufacturers have somewhat different strategies for what portion of the overall $NO_x$ reduction come from in-cylinder (i.e., EGR) processes versus downstream in the SCR system. Table 3 provides a summary of the $NO_x$ control strategies employed by some of the major global heavy-duty vehicle manufacturers. High-efficiency SCR systems allow the removal of the EGR system, which brings efficiency gains in various fronts: 1) it reduces PM production through more complete combustion so less post-injection of fuel is needed for active regeneration of the DPF; 2) it reduces the heat rejection of the engine so less energy is spent by the cooling system; and 3) it reduces the air-handling losses since there is no need for a negative pressure difference to drive the EGR into the cylinders. The only caveat is the need for higher urea injection rates. In one particular manufacturer example, the use of a SCR-only approach required doubling the rate of urea injection compared to the SCR+EGR system (Heyward 2014).

The significant challenge of Euro VI and the current emissions standards in the United States and Japan have prompted intensive research in multimodal combustion

2 The particle number limits have been set at $8.0 \times 10^{11}$ for the World Harmonized Stationary Cycle and 6.0 × 1011 for the World Harmonized Transient Cycle.

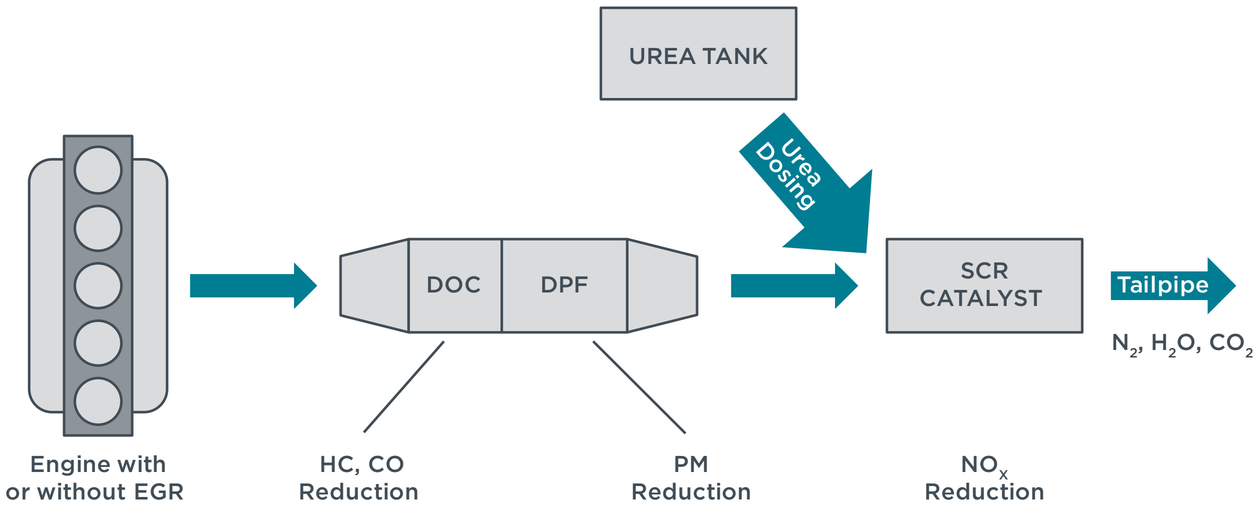


**Figure 1:** Emission control diagram for a Euro VI compliant heavy-duty diesel engine

**Table 3:** Manufacturers architectures for $NO_x$ control

| Manufacturer | Euro IV[a] | Euro V[a] | Euro VI | Reference (for Euro VI) |
|---|---|---|---|---|
| **Cummins**[b] | SCR | SCR | EGR + SCR | (Cummins Inc. 2012) |
| **Daimler** | SCR | SCR | EGR + SCR | (Daimler AG 2011) |
| **DAF** | SCR | SCR | EGR + SCR | (DAF Trucks 2012) |
| **Iveco** | SCR | SCR | SCR | (Iveco 2011) |
| **MAN** | EGR | EGR | EGR + SCR | (MAN Truck International 2015) |
| **Scania** | EGR / SCR[c] | EGR / SCR[c] | SCR | (Scania Group 2014) |
| **Volvo** | SCR | SCR | EGR + SCR | (Volvo Group 2012) |

[a] Unless specified otherwise, reference for Euro IV and V architectures: (Steffens 2006)
[b] Reference for Euro IV and V architectures: (White 2008, Cummins Inc. 2011)
[c] According to (Vialtis 2005), Scania offers both EGR and SCR configurations, depending on the size and application of the individual engine model.

engines and sophisticated in-cylinder control strategies. Multimodal engines are engines capable of keeping electronic control over many variables to achieve in-cylinder reduction in both $NO_x$ and PM emissions. Fuel injection is controlled for timing and quantity, including multiple injections in a single cycle. The flexibility of fuel injection is also accompanied with variable geometry turbochargers able to match the response of electronic fuel injection controls with the proper amount of air for improved combustion.

In terms of efficiency impacts, the presence of the DPF increases the exhaust backpressure, which comes with a fuel penalty. Moreover, DPFs that employ active regeneration must consume extra fuel to regenerate the filter. This impact can have a fairly sizeable fuel consumption penalty (up to 5%), though this is heavily dependent on the drive cycle and how often a vehicle is regenerated. Urban vehicles that operate in stop-and-go conditions typically experience a higher fuel penalty than on-highway vehicles that spend a large amount of time in steady-state driving. Since the introduction of vehicles with emissions aftertreatment that includes DPFs, manufacturers have made efficiency improvements in engines and vehicle technologies to mitigate the fuel penalties that are imposed by the DPF (Sharpe and Muncrief 2015).

## 2.4 NATURAL GAS ENGINES: EURO III TO VI

As described in Table 2 (adapted from Posada 2009), Euro III NG engines typically employ lean-burn combustion with open-loop fuel injection controls, and emission levels can be met with or without an oxidation catalyst, depending on the overall emission control design approach. Euro IV NG engines are also lean-burn, but closed-loop fuel injection controls with an oxygen sensor are required. In addition, an oxidation catalyst is needed for keeping CO and HC under their respective limits.

Natural gas engine manufacturers are combining stoichiometric combustion with a TWC to meet Euro V and VI levels. The primary challenge with stoichiometric combustion for heavy-duty applications is the high in-cylinder mixture temperatures during combustion, which leads to high production of $NO_x$, and the excessive amount of heat that must be removed. In addition to higher thermal stress, lower brake efficiency is expected because of the low compression ratio required for suitable stoichiometric combustion. EGR, a technology borrowed from diesel engine emission control technologies, is used to curb the excessive high temperature and heat production in the stoichiometric CNG engine. The EGR in the stoichiometric engine dilutes the concentration of fuel in the cylinder, which reduces the rate of the combustion reaction and lowers its temperature while keeping the air-fuel ratio at the stoichiometric value. Because part of the cylinder volume is occupied by inert recirculated gas, there is a reduction in volumetric efficiency that can be corrected by adding a turbocharger. The turbocharger recovers the loss of power that results from dilution with EGR. In most cases, the EGR requires an intercooling circuit. Because the exhaust gases from the stoichiometric engine contain negligible oxygen, a TWC can be applied as aftertreatment, which allows for $NO_x$ reduction during rich periods of operation.

## 3. Engine efficiency technology potential

Since the late 2000s, a number of studies have indicated that there is tremendous potential for efficiency gains in heavy-duty diesel engines over the 2015 to 2030 timeframe (Committee to Assess Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles 2010, Hill, Finnegan et al. 2011, Law, Jackson et al. 2011, Delgado and Lutsey 2014, Thiruvengadam, Thiruvengadam et al. 2014, Delgado and Lutsey 2015, U.S. Environmental Protection Agency 2015). This section provides a brief overview of the fuel-saving engine technology areas from these studies.

In the aforementioned studies, researchers typically use Euro VI- or US 2010-compliant engines as the baseline for their technology potential analysis in investigating what advancements are possible out to 2020 and beyond. From a technology perspective, the US 2010 and Euro VI standards are nearly functionally equivalent and require the same emissions control technologies that achieve roughly the same emission benefits. For a more detailed comparison of these two emissions standards, see Table 1 in (Blumberg, Posada et al. 2014).

Table 4 below describes the primary engine technology areas and the opportunities for efficiency improvements. The far right column gives a range of fuel consumption benefits for each technology area. These percentages are based on a US Class 8 (i.e., 15 tonnes or greater) tractor-trailer operating over a typical long-haul duty cycle that has a large degree of constant speed highway driving (roughly 100 km/hr). Altogether, the literature suggests that overall fuel consumption reductions on the order of 15 to 20%[3] compared a Euro VI/US 2010 baseline are possible in the 2025 to 2030 timeframe. In future work, we will be doing detailed analyses to estimate the efficiency potential for each of these engine technology areas for a number of representative Indian HDV types (e.g., tractor truck, rigid truck, and transit bus) over various India-specific drive cycles.

3 To estimate the total fuel-savings potential across all of the engine technology areas, the percentages in Table 3 should not summed using simple addition. Because there are complex interactions when intervening in many of these areas, more sophisticated modeling approaches are needed for estimating the overall efficiency impacts of combinations of engine technologies.

**Table 4:** Heavy-duty diesel engine efficiency technology areas

| Engine area | Description | Efficiency opportunities | Fuel savings potential from a US 2010/Euro VI baseline |
|---|---|---|---|
| **Engine friction reduction** | Engine efficiency is affected by friction losses and lubricant oil churning in bearings, valve-trains, and piston-to-cylinder interfaces. Friction losses increase with engine speed and, to a lesser degree, with cylinder pressure (i.e. torque). Friction reduction provides direct brake work gains. Since friction losses leave the engine in the form of heat, friction reduction also reduces the amount of heat dissipated through the cooling system. | • Low viscosity lubricants<br>• Piston ring designs<br>• Engine material coatings that lower friction | 0.5 – 2%[a, b] |
| **On-demand accessories** | Engine and vehicle accessories including the water pump, oil pump, fuel injection pump, air compressor, power steering, cooling fan, alternator, and air conditioning compressor are traditionally gear- or belt-driven by the engine. These "parasitic" losses, or auxiliary loads tend to increase with engine speed. Decoupling the accessories from the engine when their operation is not needed, and operating them at optimal speeds can reduce these loads. Moreover, vehicle inertia (e.g., when going downhill) can be used to operate these devices and save fuel. | • Feedback engine controls<br>• Clutches to engage/ disengage the accessories<br>• Variable speed water and oil pumps<br>• Parasitic load reduction in fuel pump<br>• Variable flow pumps | 0.5 – 4%[a, b, c] |
| **Combustion optimization** | Optimization of diesel fuel combustion, with improved injection and high-pressure systems, is in active development. Most of the losses within an engine correspond to the combustion process and are reflected in high exhaust enthalpy and heat transfer to the cooling system. Combustion optimization improves the work extraction from the combustion process and thus reduces the exhaust and heat transfer losses. Future combustion optimization may include low temperature combustion strategies. | • Higher pressure fuel injection<br>• Injection rate shaping<br>• Better atomization and distribution within the cylinder<br>• Increased compression ratios<br>• Insulation of ports and manifolds<br>• Improved thermal management | 2 – 4%[a, b, d] |
| **Turbocharger improvements** | Turbocharging technology utilizes exhaust energy to increase intake pressure and volumetric efficiency. Efficient turbocharging provides increased power density to the engine and efficient air and EGR delivery to the intake manifolds. Turbocharging systems have the ability to reduce pumping, exhaust, and coolant losses due to the increased combustion efficiency from the higher boost and improved operational range. | • Improved design and control of VGTs.<br>• Asymmetric turbocharger systems | 1 – 5%[a, b, e] |
| **Advanced engine controls** | Improved engine controls are linked to various efficiency-related engine systems namely injection, air intake, EGR, auxiliaries, thermal management, and aftertreatment systems. Model-based control for engine calibration with closed-loop controls allows real-time optimization of more engine parameters. Improvements in this technology area affect the losses in the other energy loss categories (e.g., exhaust, coolant, and pumping). | • Model-based controls<br>• Real-time optimization of various engine parameters | 1 – 4%[a, b, f] |

**Table 4:** Heavy-duty diesel engine efficiency technology areas

| Engine area | Description | Efficiency opportunities | Fuel savings potential from a US 2010/Euro VI baseline |
|---|---|---|---|
| **Aftertreatment improvements** | Several aftertreatment-related systems are directly connected to the energy loss characteristics of the engine. In a typical engine configuration with a variable geometry turbocharger (VGT), the pumping losses in the engine are increased when higher EGR rates are used for $NO_x$ control since higher exhaust backpressure is needed to drive the exhaust gases back to the cylinder intake. The diesel particulate filter also creates additional backpressure that increases with particulate soot loading. Improvements in aftertreatment technologies are interrelated with advanced controls and combustion optimization and could reduce pumping, exhaust, and coolant losses. | • Enhanced $NO_x$ and PM aftertreatment systems<br>• Dual SCR-DPF systems<br>• Reduced EGR levels | 2 – 4%[a, b] |
| **Engine downsizing** | Vehicle improvements that reduce the road load power requirements may shift the operational locus of an engine to lower efficiency regions. Replacing the base engine with an engine with lower displacement, peak torque, and peak power can force the engine to operate at higher loads where usually the optimal, high-efficiency engine region is located. | • Reduced vehicle load allows for engine with lower displacement, peak torque, and peak power | 1 – 4.5%[a, b] |
| **Engine downspeeding** | Decreasing the engine speed lowers friction losses (lower piston speeds) and pumping losses (lower air flow rates), and increases thermal efficiency. The engine torque must rise as the engine speed is reduced to keep same power capabilities. | • Reduced friction and pumping losses | 2 – 3%[g] |
| **Turbo-compounding** | Turbocompounding technologies can be mechanically or electrically actuated. In mechanical turbocompounding, exhaust flow is used to spin a turbine that connects through a mechanical transmission directly to the crankshaft. This technology results in higher torque, higher brake power output, and lower exhaust energy losses for a given fuel input. In electrical versions, exhaust flow is used to spin a turbine that is connected to an electrical generator. The electricity can be stored and then used to power electric accessories or to provide torque assist to the engine through an electric motor (in hybrid powertrains). | • Mechanical turbocompounding<br>• Electrical turbocompounding | 0.5 – 5%[a, b] |
| **Waste heat recovery** | Rankine cycle waste heat recovery systems convert heat that is typically wasted through the exhaust and engine cooling systems to useable mechanical energy. The extra mechanical power output can be fed to the crankshaft through a gearbox or can be used to generate electric power. As a result, linking such a Rankine cycle to an existing power cycle reduces the load and overall fuel input to the engine for a given system work output. | • Rankine cycle waste heat recovery systems | 2 – 8%[a, b] |

[a] (Lutsey, Langer et al. 2014) [b] Thiruvengadam, Delgado et al. (2014) [c] (Kies, Rexeis et al. 2013) [d] (Edwards and Wagner 2012)
[e] (Chebli, Müller et al. 2013) [f] (Atkinson 2013) [g] (Stanton 2013)

## 4. Conclusions

This literature review highlights the developments in engine technology that are expected as India transitions to tighter emissions standards and introduces the nation's first regulatory program to improve the fuel efficiency of new HDVs. The primary objective of this paper is to preview the upcoming evolution in engine technology so that policymakers and other relevant stakeholders in India have a better understanding of the anticipated sequence of these advancements and what these changes will mean in terms of impacts to per-vehicle pollutant emissions and fuel consumption.

As India transitions to more stringent vehicle emissions standards over the next five years, new heavy-duty engines are going to experience significant technology changes. The shift from the current national standard of BS III to BS VI starting in 2020 is going to require that manufacturers invest in a number of technologies to achieve the target brake-specific levels of $NO_x$ and PM emissions. Experience in developed markets such as the US, Europe, and Japan indicate that these engine technology changes include transitioning from mechanical to electronic controls, improvements in engine combustion and calibration, increased injection and cylinder pressures, refinement in fuel injection systems, and the implementation of $NO_x$ and PM after-treatment solutions.

The technologies for controlling criteria pollutant emissions often have efficiency impacts. For example, selective catalytic reduction (SCR), which is required to achieve the most stringent $NO_x$ levels, allows engines to be tuned for increased fuel efficiency. Moreover, the introduction of electronic controls and more sophisticated fuel injection strategies is a boon to efficiency. On the other hand, certain emission control strategies such as exhaust gas circulation (EGR) and diesel particulate filters (DPFs) often have negative fuel use ramifications.

Engine-specific efficiency standards in the US and Canada have spurred a number of advances, and the technology pathways for the next 10 to 15 years to facilitate these efficiency improvements are reasonably well understood. Moreover, regulatory progress in Japan, China, and the EU are also expected to promote the proliferation of a number of fuel-saving technologies for engines. These technology advances include improvements to combustion and air handling, reduced friction and parasitic loads, high efficiency aftertreatment, and waste heat recovery. Given the large degree of globalization in the vehicle industry, India can leverage the knowledge and experience from other markets and deploy the technologies that are best suited to local conditions.

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